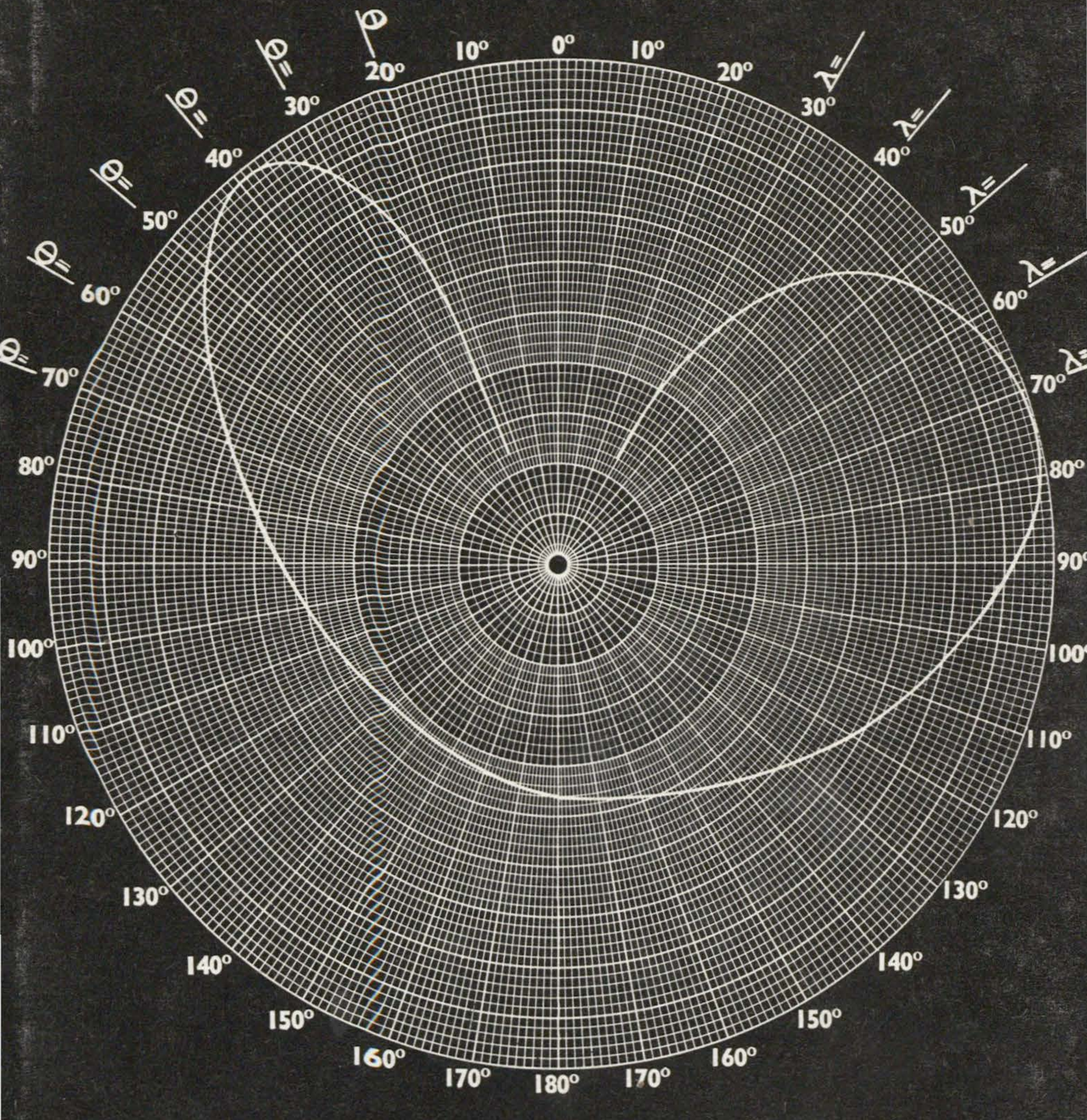
DESIGN FOR FAST SAILING

Edmond Bruce & Harry Morss



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AYRS

DESIGN FOR FAST SAILING

RESEARCH AFLOAT AND ASHORE

by

EDMOND BRUCE and HENRY A. MORSS, JR.

Edited by:

JOHN MORWOOD

First Edition: 1976

Published by:

The Amateur Yacht Research Society,

Hermitage, Newbury,

Berkshire, England.

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PREFACE

What should be in a preface? There are many things we should like to put into ours. First, there is the background. That begins with one man, John Morwood, founder of the Amateur Yacht Research Society, editor and guiding star of its wide-ranging publications and projects. Always he has had an unfailing interest in boats and those who sail them. He has effectively stimulated a great deal of exciting research. We are eternally grateful to him.

As articles were published over the years in the quarterly publications of the AYRS, it became apparent that there was a need to combine them by topic into special issues. Publication No. 13, "Self-Steering", was the first of a growing list of these. This book is another. A companion publication is being planned, entitled, probably, "Yacht Research by Amateur Yacht Research Society Members" (other than the present authors).

Our researches, which have extended through a period of years, have been a non-professional hobby. Many of them have been separately reported as articles or letters in the publications of the AYRS to obtain comments and criticisms on their reasonableness and accuracy from the world-wide, capable readership of the Society.

At times, in our work, theories preceded experiments. Sometimes the experiment was first, followed by hoped-for, plausible explanations of the results. Unless both of these factors exist and confirm each other, there is uncertainty. Either one alone is seldom convincing. (The development of theory in this book does not use mathematics beyond high-school level.)

The reader will find in this volume not only earlier material which both authors have had published by the AYRS but also new material not previously printed. Reprinted items have been updated as necessary. Symbols and terminology have been brought into uniformity consistent with current practice.

The authors make no claim that all of the contents of the book are original with them. We have drawn heavily on the AYRS publications and have talked over countless aspects of theory and performance with many people in England and in America. We thank them all sincerely.

It is neither the purpose nor the intent of this book to be a textbook. What we do try to do is to put together, cohesively and clearly, a synthesis of an overall approach to certain aspects of design, especially design for sailing at high speeds, which relies on and emerges from what may be looked on as the components of the picture in many of the older articles.

The criteria for sailing at speed and the means of meeting them, along with some estimate of the results which can be expected at the present state of the art, are now stated succinctly. These criteria are:

1 Elimination of the "hull-speed" restriction.

2 Enhancement of sail-carrying capacity.

3 Reduction of drag angles and improvement of rig and hull force coefficients by careful attention to refinement. Through many details this leads to the best design of hull and underwater foil that can be devised and then a calculation of the sail area needed for the desired performance. It may call for varying the sail area for best results at different angles of sailing.

Thus it appears that a craft can now be designed which will outperform existing boats. There will be rapid advances in the very near future.

E.B.

Oct. 1973 H.A.M., Jr.

OBITUARY

EDMOND BRUCE

died peacefully on November 28, 1973

Aged 74

ACKNOWLEDGEMENTS

This book is composed of wonderful articles by the late Edmond Bruce or of articles by Harry Morss in the same tradition and style, though more mathematical and abstract. Finally, I have tried to tie down the information into a practical sailing boat, though my original article was severely changed by both Edmond and Harry.

Many people have been involved in getting this work ready for printing. Edmond worked alone both at his many years of test tank work and carefully typed out articles for us. Each of even his private letters was a masterpiece of exposition of the complex ideas he was so simply setting forth. Poor Edmond worked alone. Harry and I got, and are grateful for, a great amount of help from our wives, Betty Morss and Pat Morwood.

Mrs. Maureen Martin re-typed the whole book except for original articles, making all the corrections wanted by Edmond and Harry in articles already published in the AYRS.

Finally, we have to thank all the AYRS members both for giving us their support and for that "feed-back" to our authors which means so much to people who are doing their lonely work either in the test tank or at the typewriter.

J.M.

SYMBOLS USED IN THE BOOK

A	Area
A_S	Sail Area
A_W	Wetted surface area of hull, usually in sq ft
B	Beam
C	Coefficient
C_D	Coefficient of Drag
C_F	Frictional Coefficient
C_L	Coefficient of Lift
C_P	Pressure Coefficient, also Prismatic Coefficient
C_R	Coefficient of Resistance
C_S	Total Sail Coefficient (usually for entire rig and everything else above the water exposed to the moving air). Defined as:— $F_S/(\rho/2)\ A_S\ v^2$ with F_S in pounds, ρ in slugs per cubic foot, A_S in sq ft, and v in feet per second
C_{SD}	Sail Drag Coefficient
C_{SL}	Sail Lift Coefficient
C_T	Total Coefficient
CB	Centreboard (Sometimes C.B.)
CE	Centre of Effort (Sometimes C.E.)
CLR	Centre of Lateral Resistance (Sometimes C.L.R.)
CR	Centre of Resistance (Sometimes C.R.)
D	Drag, or Draft
D_F	Frictional Drag
D_H	Drag of Hull
D_P	Pressure Drag
D_S	Drag of Sail
F_F	Frictional Force
F_H	Resultant or Total Hull Force
F_P	Pressure Force
F_S	Resultant or Total Sail Force
k	A proportionality factor, not necessarily constant
K_H	Total Hull Force Coefficient, defined as $100\ R_T/W^{2/3}\ V_B^2$ with R_T and W in lbs, V_B in knots
K_{HF}	Hull Frictional Coefficient, or forward component of K_H
K_{HP}	Hull Pressure Coefficient
L	Lift, or Length
L_{av}	Average Length
L_F	Frictional Lift
L_H	Lift Component of Total Hull Force
L_P	Pressure Lift
L_S	Lift Component of Total Sail Force
L/D	Lift/Drag Ratio
LWL	Load Water Line Length (Sometimes L.W.L.)
P	Power
R	Resistance (total), or Radius

R_F	Frictional Resistance
R_P	Pressure Resistance
R_T	Total Resistance
$\frac{R}{W}$ in %	Ratio of total resistance of hull to weight of hull expressed in per cent
R_e	Reynolds' Number = $vL/(\mu/\rho)$
v	Speed, in feet per second
V	Speed, usually in knots
V_A	Speed of Apparent Wind in knots
V_B	Speed of boat through water in knots
V_L	Speed made good to leeward, in knots
V_{MG}	Speed made good to windward, in knots
V_T	Speed of True Wind in knots
$\frac{V}{\sqrt{L}}, \frac{V_B}{\sqrt{L}}$	Modified Froude Number
W	Weight or displacement, usually in pounds
α	Angle of Attack
β	Angle between apparent wind and course
$\beta - \lambda$	Angle between apparent wind and boat's heading
γ	Angle between true wind and course
δ	Drag Angle
δ_H	Drag Angle of Hull
δ_S	Drag Angle of Sails, Rig, etc.
λ	Leeway Angle, the Angle of Attack of the Hull (the angle between the boat's heading and her course)
ϕ	Angle between Resultant Sail Force and Course = $90° - \delta_H$. (In towing tests, this is the "towing angle")
μ	Viscosity
μ/ρ	Kinematic Viscosity. (For clean, fresh water at 70°F, it is $1{\cdot}05 \times 10^{-5}$; at 60°F, $1{\cdot}21 \times 10^{-5}$; and at 50°F, $1{\cdot}41 \times 10^{-5}$)
ρ	Density
ρ_A	Density of Air (0·0024 slugs per cubic foot)
ρ_W	Density of Water (1·99 slugs or 64 lbs per cubic foot for salt water, 1·94 slugs or 62·4 lbs per cubic foot for fresh water).

PART ONE

SAILING PERFORMANCE FACTORS

CHAPTER I

THE PHYSICS OF SAILING CRAFT AS REVEALED BY MEASUREMENTS AT FULL SIZE

Reprinted from AYRS 40, July 1962

by Edmond Bruce

SECTION I
MEASURING SAIL FORCES BY TETHERING A SAILING CRAFT

In measuring the forces of a wind of known velocity on a sail, in magnitude and direction, and also in measuring the centre of wind pressure, the employment of a wind tunnel and a model sail is highly desirable. A calibrated wind tunnel has the advantage of providing a uniform cross-sectional flow of air at a measured constant velocity. This shortens the time required to make measurements and promotes confidence in their accuracy.

Few of us have access to a wind tunnel. One large enough to measure a full size sail (to avoid scaling corrections) would be prohibitively expensive. If we are willing to exchange considerable experimental time and patience for the obvious conveniences of a wind tunnel, nearly the same results can be achieved using natural winds by properly tethering the boat afloat to some fixed object. A single restraining line is used which includes a spring scale. Further essentials are a wind velocity meter, a wind directional vane and two adjustable, concentric, azimuth circles mounted under the vane.

In carrying out the measurements, which will be described, a startling lesson was learned. The windage forces on the hull and on the rigging, which are necessarily superimposed on the air foil characteristics of the sail, markedly modify the overall results. These parasitic windage forces are sufficiently great, particularly in windward sailing, so that it may be more profitable, in many cases, to reduce windage rather than improve upon reasonably good sail characteristics. Obviously, when on a running course, such parasitic windage can be helpful rather than harmful.

The Apparent Wind

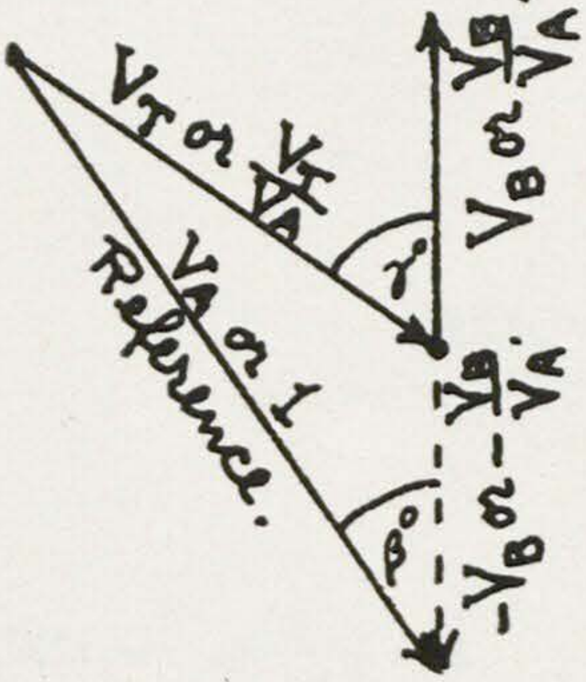
A designer may desire polar diagrams of how fast a sail-boat can travel in theoretical true winds of named magnitude and direction. True wind has the advantage of being unchanged by the speed and heading of the boat.

An observer aboard a sail-boat is deceived. The apparent wind he encounters can differ markedly in direction and speed from nature's actual wind. This is due to the speed and direction of the boat's progress.

It is a fact that a sail-boat sails in an apparent wind partly of its own making. We are dealing with Einstein's theory of relativity but let this not frighten us.

To an observer at a fixed position in space events appear to be different than they do to an observer moving with the event. This is a case of the relativity of motion.

It simplifies the presentation of the experimental data to deal with the apparent wind as a reference rather than the true wind since this is the wind encountered by the sail. The effects of the speed of the boat are included, although this speed may not be known. In fact, hull speed is unknown until the characteristics of the hull have been separately studied.



Vector Equation:

$$\overline{V_A} = \overline{V_T} - \overline{V_B}$$

Trigonometric Equation:

$$\frac{V_T}{V_A}\cos\gamma^\circ + \frac{V_B}{V_A} - \cos\beta^\circ = 0.$$

$$\tan\gamma^\circ = \frac{\sin\beta^\circ}{\cos\beta^\circ - \frac{V_B}{V_A}}$$

Fig. 1

V_B is boat's speed through water (including current).
V_A is apparent wind velocity.
V_T is true wind velocity
β° is apparent angle between boat's course and the apparent source of wind.
γ° is true angle between boat's course and the direction of the true wind's source.
Note: Dividing all vectors by the scalar of V_A simplifies the task of plotting.

While not required in the present discussion, the process of converting apparent wind to true wind or vice versa, both in direction and magnitude, is shown by the vector diagram in Fig. 1. If one divides all the indicated speeds by V_A (the velocity of the apparent wind) a dimensionless form is obtained which will make possible representation of the solutions by fewer curves. While apparent wind will be our reference for these sail studies, the frame of reference can be transformed to the true wind after force versus speed measurements, for various points of sailing, have been made on the sailing hull by towing.

The Force of the Wind on a Sail

Fig. 2 shows a plan view vector diagram of the various forces encountered by a cat-rigged dinghy sailing to windward. In the present discussion, our principal attention will be on the force exerted on the sail by the apparent

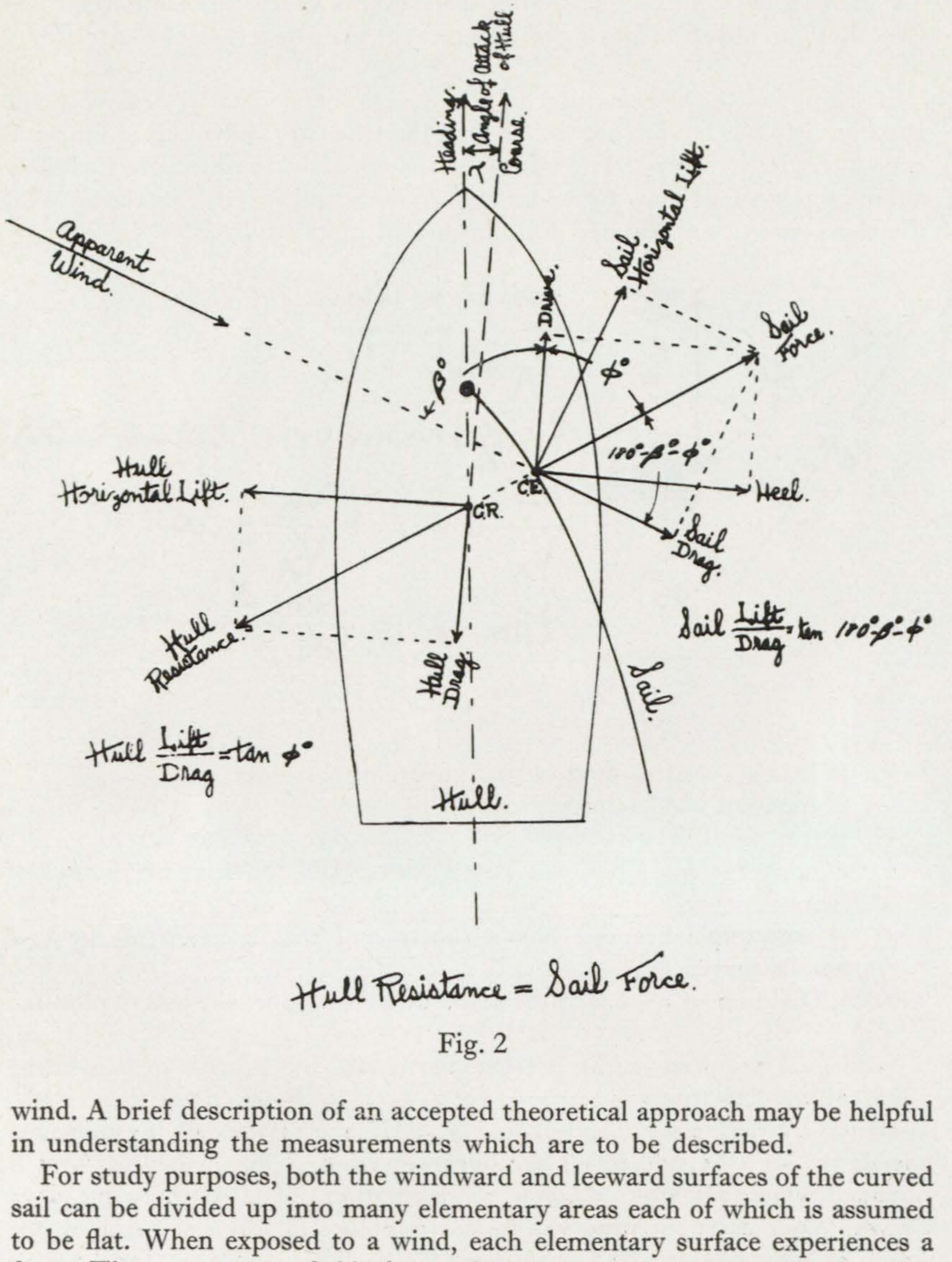


Fig. 2

wind. A brief description of an accepted theoretical approach may be helpful in understanding the measurements which are to be described.

For study purposes, both the windward and leeward surfaces of the curved sail can be divided up into many elementary areas each of which is assumed to be flat. When exposed to a wind, each elementary surface experiences a force. The component of this force which is normal to the surface is called pressure. The tangential component of this force is called friction. In the case of air on a properly trimmed sail, the frictional forces are small compared to the pressures.

On striking the windward side of a sail, the free air is decelerated. On the lee side of a sail with convex curvatures, the wind accelerates to fill in lower pressure voids beyond bends. This increased velocity at lowered pressure is known as "Bernoulli's principle" for non-turbulent flow. The windward surface pressures are positive, in respect to the surface, due to air deceleration. The lee pressures are usually negative as a result of air acceleration. This results in a partial vacuum on the lee side. In windward sailing, the lee pressures are large and nearly dominate the situation. While not a highly scientific explanation, the lee negative pressures "pull" the boat forward while the windward positive pressures push the boat forward.

Summing up or integrating all the elementary vector forces on both sides of the sail produces an equivalent single directional force acting at a single location known as the "centre of effort" of the wind on a sail. This is the equivalent sail force having direction and the location marked 'CE' shown in Fig. 2. It is this force that will be measured in the experiments to be discussed.

Theoretically, pressure forces vary as the square ot the initial wind velocity at all points. This comes from a physical law of motion which stated in our terms becomes: Mass of air per second multiplied by the change in air velocity per second $\begin{matrix}\text{(acceleration)}\\\text{(deceleration)}\end{matrix}$ equals the developed force. Now the mass of air per second is proportional to the cross-section of air intercepted by the sail multiplied by the relative air velocity. Thus we see from the above statement that to obtain force, the velocity of the air is multiplied by itself, or some fraction thereof, giving a result that is proportional to the initial wind velocity squared.

An understanding of why the velocity squared is proportional to the force is important because data will be obtained with wind which will be varying continually in strength. This would destructively complicate our experiment if it were not for the fact that sail force divided by the wind velocity squared is approximately constant for any given positioning of the sail. Not only is this the theoretical derivation but it will be proved experimentally through a series of simultaneously measured sail forces and wind velocities for each sail position.

A component of the resultant sail force resolved in the direction of wind flow is called "drag" in aerodynamics. The other component resolved perpendicular to the wind flow is called "lift". We will retain this accepted term although lift is lateral, in the case of a sail, rather than vertical. These component forces are indicated in Fig. 2. They should not be confused with the "drive" and "heel" components of the sail force which are indicated also.

Referring again to Fig. 2, one sees that the total sail force is equal and opposite to the total force of hull resistance. This is in accord with the physical law which states that for every action there is an equal and opposite reaction.

In problems where events vary with time, there exist what are known as "transient" state and "steady" state solutions. In the transient case, for our problem, the propelling force equals and opposes a sum of two forces. One is the force which accelerates the mass of the boat when under way. The other is a force which is the momentary water resistance. This second is actually a force which accelerates masses of water due to the boat's motion. If one waits while the boat accelerates from a standing start until there is no longer any acceleration, the hull's water resistance alone just equals and opposes the sail force. The steady state case thus has been achieved. This is the circumstance that now will be simulated and measured since a tethered boat has no acceleration.

Measuring Equipment and Method

A boat mooring is selected which has a good wind fetch in most directions. A substantial buoy or small boat is attached to the mooring and the sailing dinghy is in turn tied to this. The reason is to hold the dinghy with a line that is horizontal.

The desired point of attachment of the line to the dinghy must be at CR or better still on the windward rail in line with the points marked CR and CE, in Fig. 2. CR is an abbreviation for the centre of resistance of the hull. There exists a fore and aft range of possible attachment positions, for a fixed sail trim, that stably controls the angle of attack and angle of hull heading in respect to the wind. Beyond this range, the hull will unstably circle the mooring, forcing both a tack and a gybe or vice versa to reestablish position. Attachment to the windward rail with a G-clamp proved satisfactory. Use of a short line limits the hull travel and also the restabilisation time should the wind change direction.

The tension and its direction, in respect to the wind, in the restraining line simulates the total hull resistance of the dinghy when under way. It is equal and opposite to the total sail force.

Since the boat is not moving, the apparent wind and the real wind are identical in direction and magnitude.

The centre of wind effort, marked CE in Fig. 2, can be obtained by graphically projecting the restraining line to the boom. The resulting intersection with the boom gives the location of the centre of effort, in a horizontal plane, by the distance of this point measured from the mast.

The problem also requires the measurement of the angle of attack of the sail to the wind and the measurement of the velocity of the wind. Descriptions of these measurements will now be given.

The instrumentation layout is designed for one man operation aboard the boat having the sail being tested. Fig. 3 is a diagram of the arrangement used and Fig. 4 is a photograph of the layout. Two rotating azimuth circles are mounted concentrically under a counter-balanced wind vane.

It is customary to measure wind angles of attack to the geometric chord of a curved surface. The boom is a good approximation of this chord. For this reason, the inner circle of Fig. 3 is manually rotated so that its zero index line is parallel with the cleated boom of the sail. This is accomplished by adjusting the angle, indicated by the keel arrow, shown in the diagram, to equal the boom angle which has been marked along the boat's rail. The angle of attack of the sail can be read directly by the wind vane's indication on this inner azimuth circle. Adding the angle of attack to the boom angle gives the hull's heading in respect to the wind's source.

The outer azimuth circle, of Fig. 3, is so arranged that the restraining line pulls it around causing its zero index to be aligned with the restraining line.

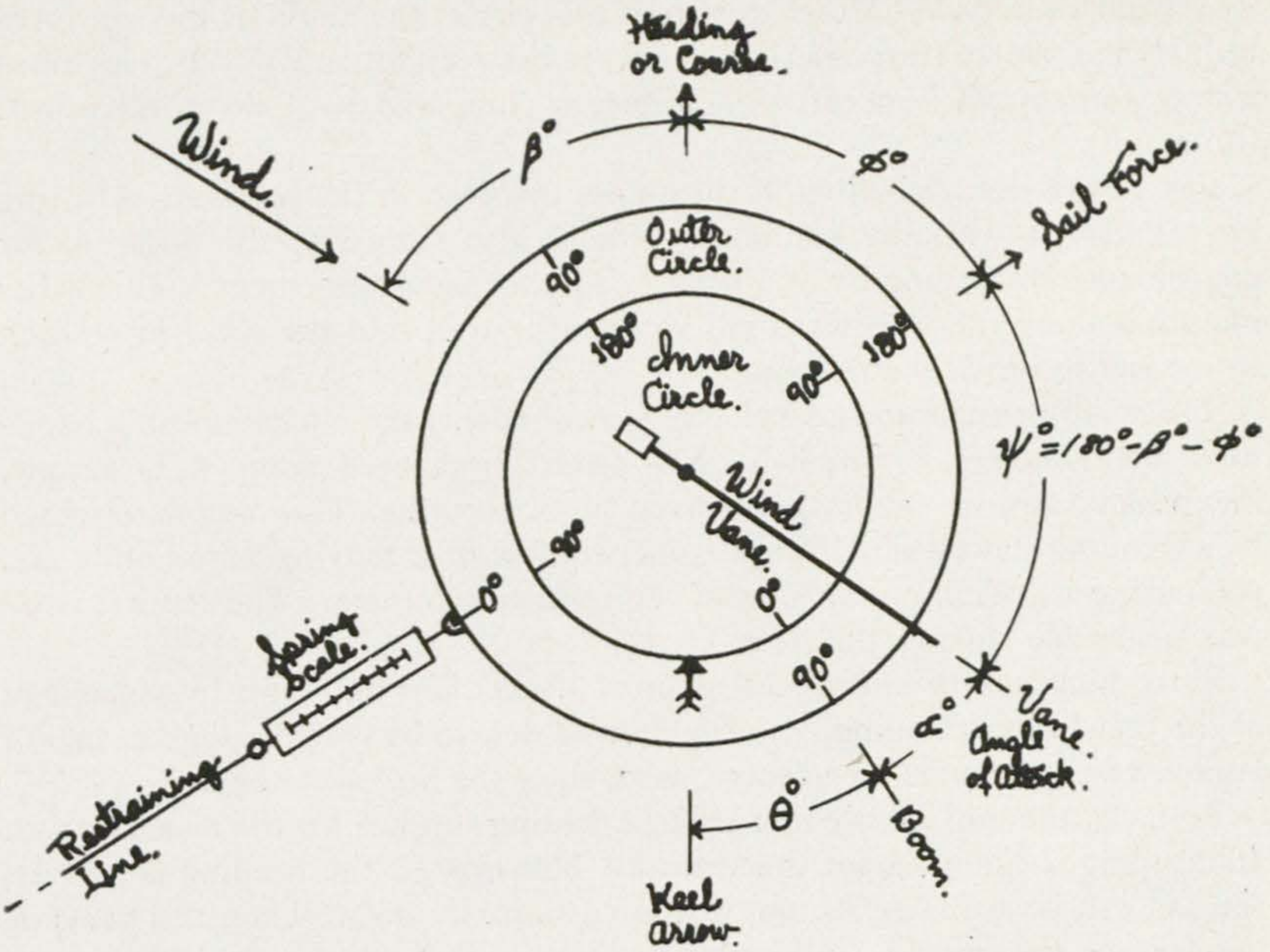

Heading or Course.
Wind.
β°
φ°
Sail Force.
Outer Circle.
90°
180°
Inner Circle.
90°
180°
ψ° = 180° - β° - φ°
Wind Vane.
90°
0°
0°
Spring Scale.
90°
α°
Vane Angle of Attack.
Restraining Line.
θ°
Boom.
Keel arrow.

Fig. 3

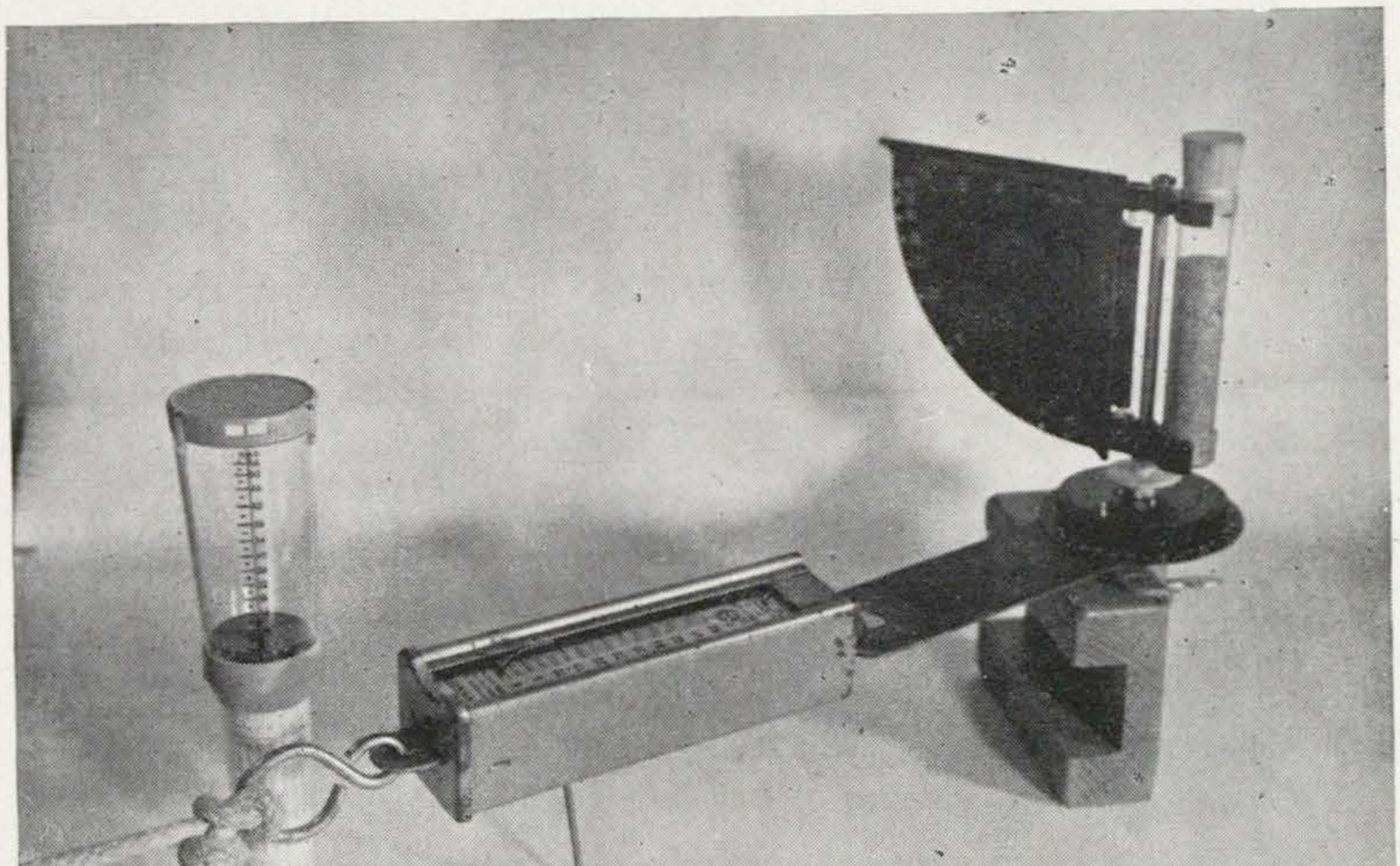


Fig. 4

The wind vane position then reads on this circle, the angle of the sail force to the wind source (direction). It is always between 90 and 180 degrees since a drag component is negative in direction compared with the wind source (direction).

Fig. 3 includes a labelling of the angles involved in the problem. A spring scale in series with the restraining line is also shown at this location for convenience in reading by one person. The whole arrangement is adjustably mounted along the windward rail so as to be well into the wind in relation to the sail or other obstruction.

The wind's instantaneous velocity is read at this same location on a hand-held anemometer. A Swedish "Elvometer" was used since it is simple, inexpensive and its calibration proved to be accurate. This was determined by extending it well out from a front window of a moving automobile and comparing its reading with that of the car's speedometer. The natural wind was negligible during this test.

Small boat sailors control the amount of heel and hull trim by placement of the crew. Heel the dinghy to the desired degree by weight alone in lieu of lateral water pressures on a centreboard, since the hull is stationary.

Actually, the hull is little more than a floating support for the mast and sail. Its heading is unimportant theoretically. However, if the heading is correct, the sail can be trimmed as one would customarily do it. Then the parasitic windage on the rigging, hull and crew is properly included in the measurements. No centreboard or rudder is necessary since the boat is not moving. In fact, readings are more quickly stabilised without them.

Fig. 5 shows a sequence of balanced relationships between the dinghy's heading, boom position and restraining line attachment location for beating, close and broad reaching and also running. The direction of the restraining line, in respect to the wind, is shown for these adjustments. This angle will be quite stable in spite of wind velocity fluctuations. Even changes in wind direction cause the whole system to rotate around the mooring without altering the relative angular relationships.

Note, in Fig. 5, that the boom is always roughly perpendicular to the restraining line. The tangent of the angle of the restraining line to the wind flow equals the lift-drag ratio of the sail for each adjustment. When the boat has been manoeuvred to the most windward position possible without luffing, the sail's lift-drag ratio becomes a criterion of the sail's windward merit. The lift-drag ratio of the hull is made infinity by the action of the restraining line.

Simultaneous readings of wind velocity and restraining force will be used to calculate the standard sail coefficients for each given angle of attack of the sail after being corrected for the parasitic windage of hull and rigging. It would be erroneous to attempt this before the windage corrections because such coefficients pertain to a unit area of the sail.

We have in our possession a simple experimental arrangement, at little cost, which is equivalent to a complicated wind tunnel. What is needed is quite a little patience so that various strengths of reasonably steady winds are encountered. All readings must be taken simultaneously.

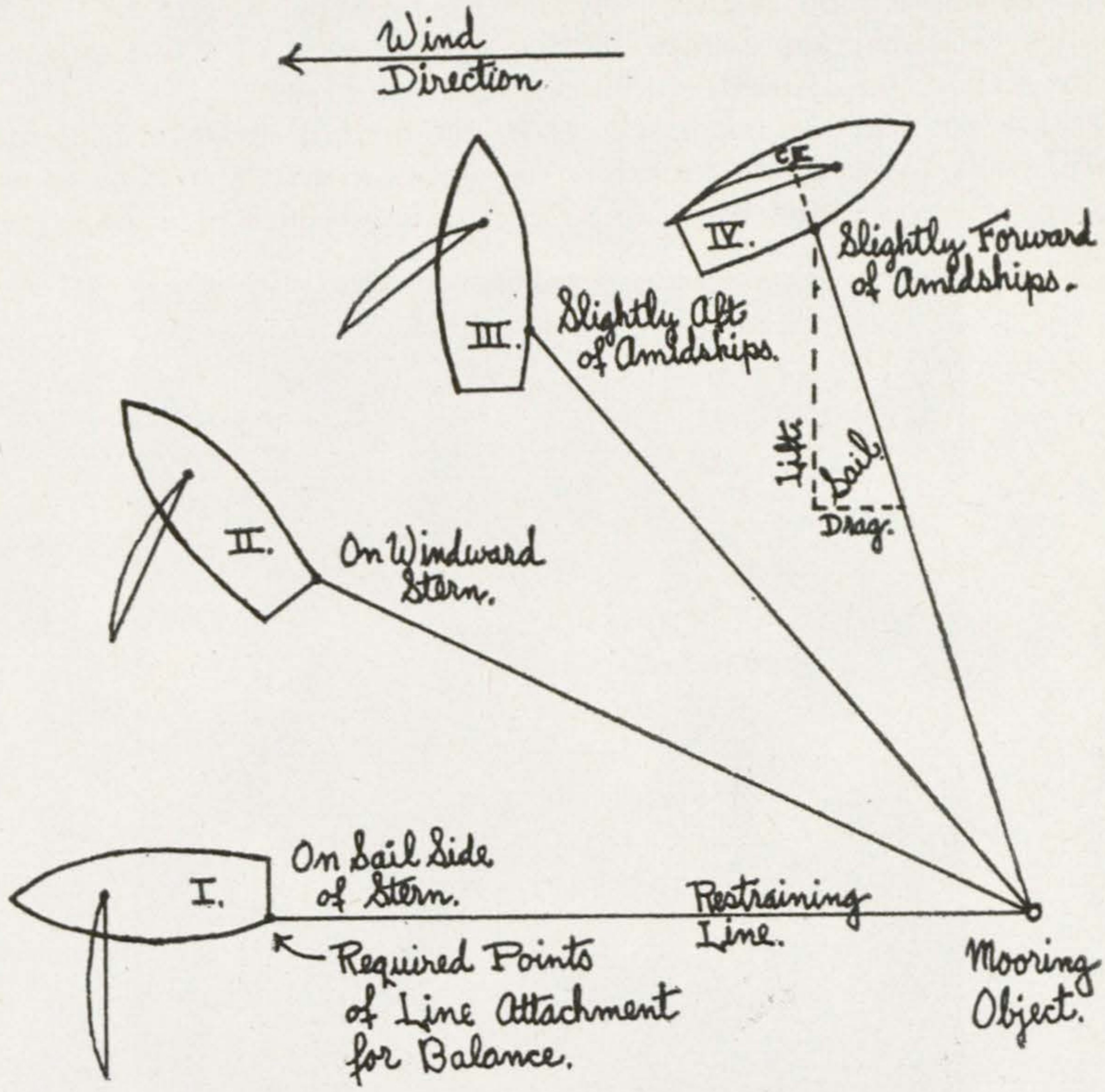


Fig. 5

I have done fascinating sailing for hours in the above fashion. My neighbours must think I am crazy and getting nowhere.

Sail Measurements

The dinghy selected, for an example of the sail tests being described, is the cat-rigged Twelve-Foot International One-Design used by the United States Coast Guard Academy. It has a centreboard type hull of fibreglass construction, and was built by the "Anchorage" of Warren, Rhode Island. A loose-footed Dacron sail "measured" at 72 sq ft is used. This results from a luff of 16 ft and a foot of 9 ft. Its actual area, including roach, is 80 sq ft. This sail contains two short battens and is mounted on a rotatable streamlined aluminium mast. Other statistics are: LOA 12 ft. Beam 56 in. Draft (CB down) 4 ft. Total weight with Mast, Boom, Rigging and Sail 207 lbs. A photograph of the dinghy during tests appears as Fig. 6.

The first step in the measurement programme is to select the best range for the spring scale to promote reasonable accuracy in the measurements of force. The scale should be no larger than necessary. This gives larger deflections which can be read with a reduced percentage of error.

For winds forming occasional white-caps on the water, the velocity is about 12 statute mph. Tables show that the force per square foot of area for this wind may approximate 0·6 lbs. For 80 sq ft of actual sail area a 50 lbs scale seems desirable within this light wind range.

I have not had too much success in obtaining accurate measurements when winds are well into the white-cap stage on the water. The constant surging of waves causes fluctuating force readings which must be averaged

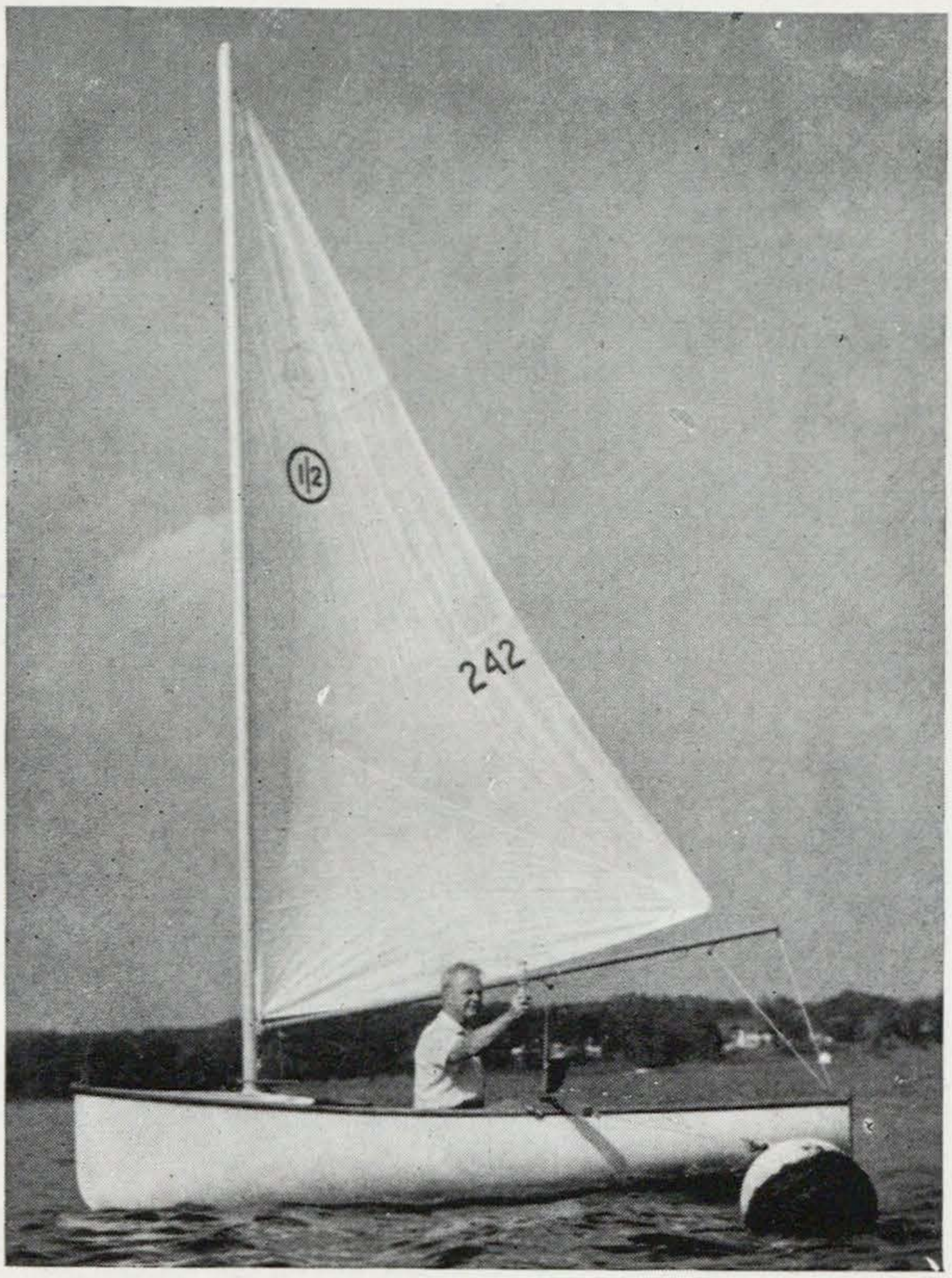


Fig. 6

to be of any value. Building a wave barrier would improve the situation but I have not done this. I keep at hand a second spring scale with a range up to 200 lbs for use with larger sails.

Wind velocities increase with height for initial distances above the water due to surface friction. It is desirable that wind velocities be used which occur at the sail's elevated centre of area. In using the hand-held anemometer, readings are obtained for wind at about 4 ft above water. This occurs because of the need to have within vision simultaneous readings of sail force and wind velocity. Unless these readings are positively simultaneous, the plotted points will be scattered and poor curves will result. By use of the anemometer and a selected reading on the spring scale, it was found that the wind velocity at the height of the centre of sail area at 8 ft compared with the convenient measuring height of 4 ft is a ratio of 1·20. The presence of the hull increases the lower reading somewhat, otherwise this ratio might be larger. All readings of wind velocity obtained at the lower level are multiplied by this ratio before use.

To gain experience with the sail measuring techniques outlined a near running course is measured first. The readings on this course are less sensitive to fluctuations in wind direction.

The boom adjustment and restraining line attachment point are approximately as shown in Fig. 5 for the hull heading marked II. Refinements of these preliminary adjustments are made during the experiment to obtain more precisely the desired angle of attack of the sail and the hull heading.

The dinghy previously described cannot have its boom placed at 90 degrees to the keel due to interference by the stays supporting the mast. Even at a boom position of 60 degrees, a lifting boom causes the stays to cut into the belly of the sail. To prevent this and to avoid spilling wind out of the upper part of the sail, a boom vang is provided. The first experiment will be to see how valuable is a boom vang for a near running course.

The boom out-haul adjustment of the sail is so placed as to provide an arch in the sail of 7 per cent of the sail foot. This selection of arch is arbitrary. Finding the optimum degree of sail arch for various wind strengths will be left to the reader as well as many other interesting studies that may come to mind. One such study might be the merit of a rotating, stream-lined mast. The current writing is intended to cover examples of the experimental method rather than the experiments themselves.

Table I is the data for the boom-vang study. The sail force and related

TABLE I

Study of Boom Vang

Test	Measurements						Calculations			
	Boom to keel	Angle of attack	Force to wind	Wind MPH	Total force in lbs	CE feet from Mast	Heading to wind	Force to boom	Force to keel	Total F_S / MPH²
No Boom Vang	50°	100°	170°	6	12	3·5	150°	110°	160°	0·33+
				7	16					0·33–
				8	21					0·33–
				9	27					0·33+
				10	33					0·33+
With Boom Vang	50°	100°	170°	6	15	3·5	150°	110°	160°	0·42–
				7	20					0·41–
				8	27					0·42+
				9	34					0·42
				10	42					0·42

$$\text{Ratio } \frac{0{\cdot}42}{0{\cdot}33} = 1{\cdot}27$$

parameters are recorded without and with the vang for a series of wind velocities. Measurements are on the left and relevant calculations are on the right. This table is self-explanatory. The reader may want to draw the situation diagram to help his understanding.

Note the following results:

a For each condition, the ratio of sail force divided by the wind velocity squared is substantially constant within experimental error, for varying wind velocities. This confirms the previous prediction.

b For a given wind velocity, the vang increases the overall sail force plus parasitic windage by 27 per cent on this near running course.

The vang will be employed throughout the remaining measurements. It becomes slack, however, on close-winded courses due to the down-pull that is possible with the main sheet alone.

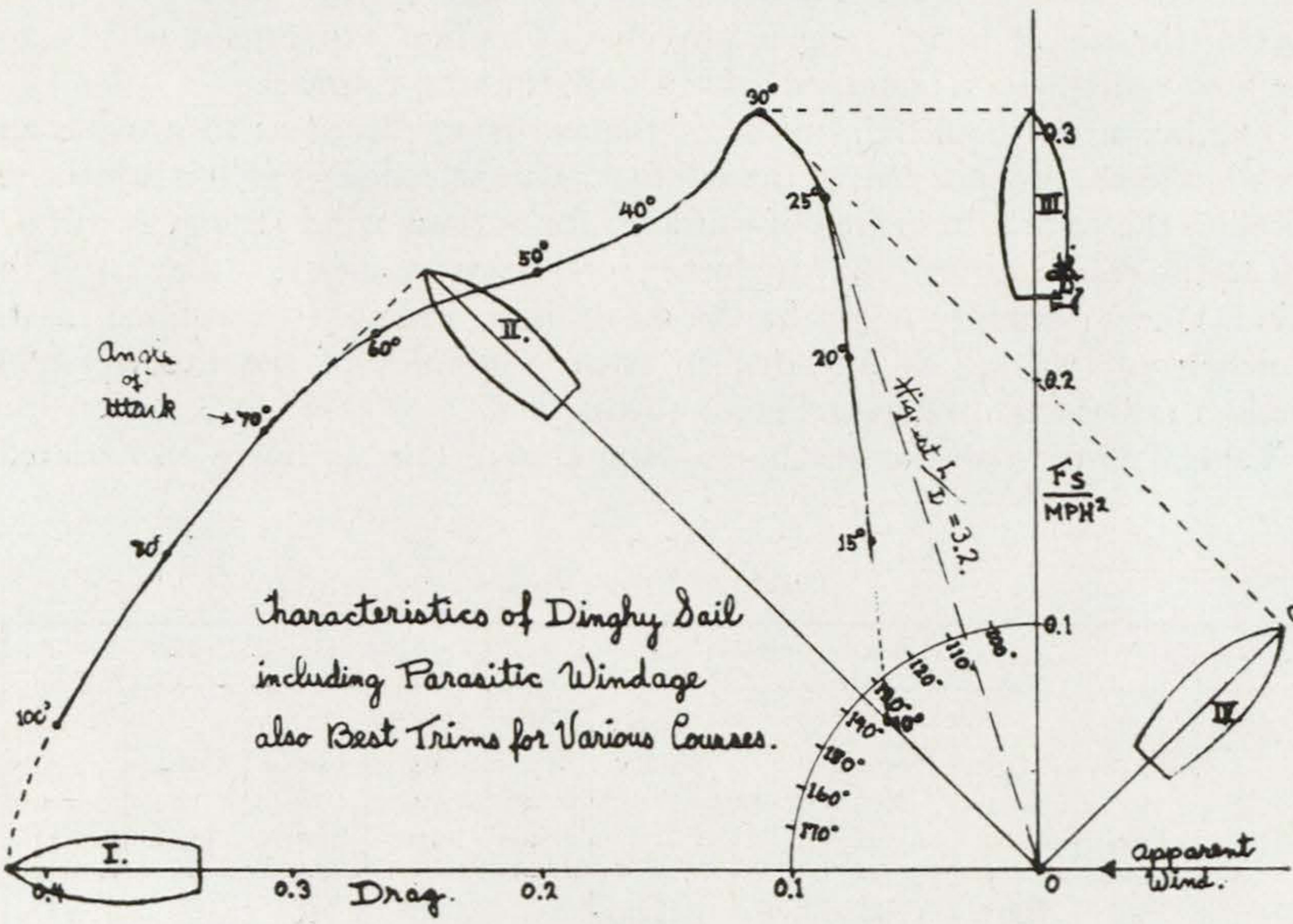


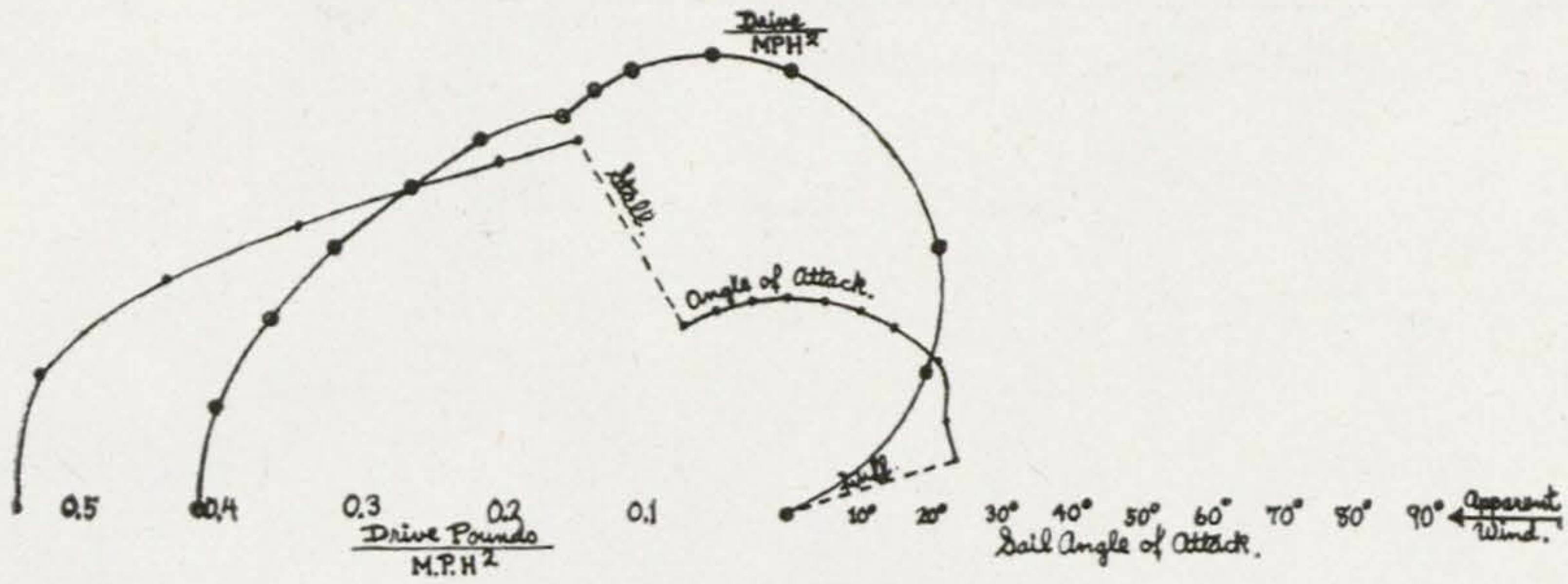
Fig. 7

Fig. 7 is a polar plot of data for a range of ratios of total sail force over wind velocity squared versus various force directions in respect to the source of wind. The sail angles of attack are marked adjacent to each point. Control of the force angles is accomplished largely through the location of the point of attachment of the restraining line. The directional force includes all windage on hull, rigging, etc. It is the overall force that drives the boat and not the sail force alone. The separate sail force will be determined later.

Each point in Fig. 7 is the median or middle measurement obtained from repeated tests when arranged in ascending magnitude. This is considered to be more accurate than averaging the data since it throws away bad measurements instead of disadvantageously including them in an average.

Fig. 7 also shows the boat at various headings in respect to the wind. One wishes a sail adjustment that will give the largest possible component of wind force in the desired direction of travel. This sail adjustment can be obtained by graphically erecting the tangent to the curve, perpendicular to the course, which produces the greatest driving component along the desired course as shown. For example, boat IV sailing at 45 degrees to the apparent wind has a ratio of drive over wind velocity squared of 0·14 maximum when the sail angle of attack is 30 degrees. The same type of graphical solutions are shown for the other courses as well.

Fig. 7 indicates that the highest possible lift-drag ratio of this sail when including all parasitic windage is 3·2 for an angle of attack of 25 degrees. This ratio is disappointingly small in view of known air-foil ratios of 20 or more. We will shortly see that it is largely the fault of the parasitic windage.



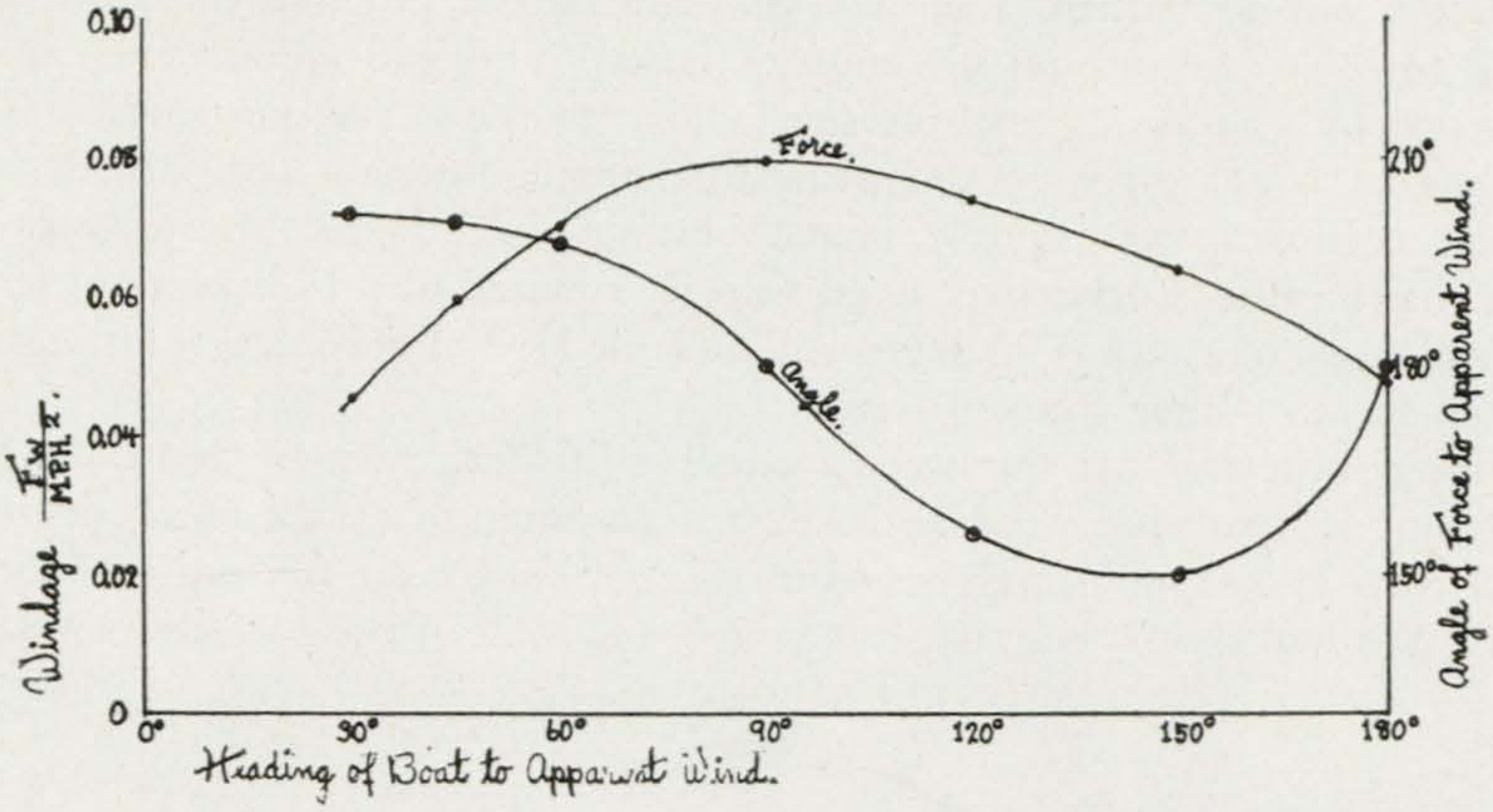
Summary
of
Best Ratios of Drive over Wind Velocity Squared
and
Optimum Angles of Attack for Sail
for
Various Courses to Apparent Wind.

Fig. 8

Fig. 8 shows a graphical summary of the best sail angles of attack (boom to apparent wind flow) for various boat courses in respect to the apparent wind. These values are for the amount of sail arching and adjustment of the boom vang as stated. Fig. 8 also summarises the best ratios of forward driving force over wind velocity squared versus these same boat courses. If the boat speed were known and the wind velocity converted from apparent to true, the drive in the windward quadrants of the cardioid shaped diagram would be increased and in the leeward quadrants decreased.

Note that the boat courses in Fig. 8 are assumed. A high course only can be achieved when the lateral lift-drag ratio of the hull is sufficient to support the force demands of the sail. See Chapter IV for a discussion of this sail versus hull relationship in achieving high pointing.

In view of the low value of the overall maximum lift-drag ratio discussed above, measurements of the contribution of parasitic windage to this situation



Parasitic Windage versus Heading.

Fig. 9

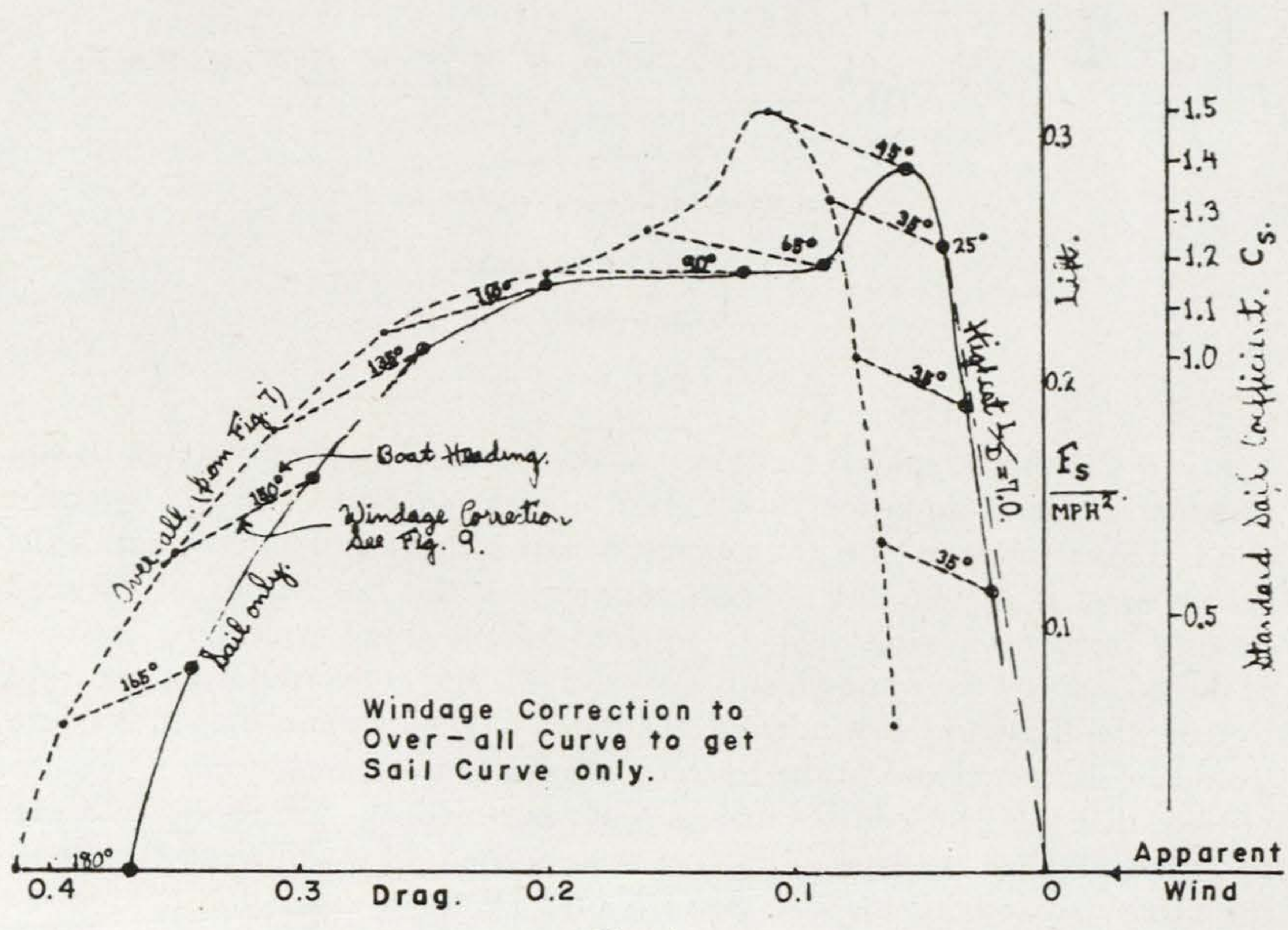


Fig. 10

were desired. Fig. 9 is a plot of boat heading versus directional force data in which the sail has been removed from the spars to obtain the parasitic windage alone.

The polar graph in Fig. 10 shows the vector subtraction of parasitic windage from the total to give the true characteristics of the sail alone. The directional windage correction used at each point of the overall curve was determined by the keel's angle to the wind when that overall measurement was taken. This correction, given in Fig. 9 is really the vector sum of the hull's windage and the rigging's windage. The latter is down wind while the former is more or less perpendicular to the keel. While these two windages can be separated by additional experiments on the hull with mast and rigging removed, it was not necessary to do this for our present purpose.

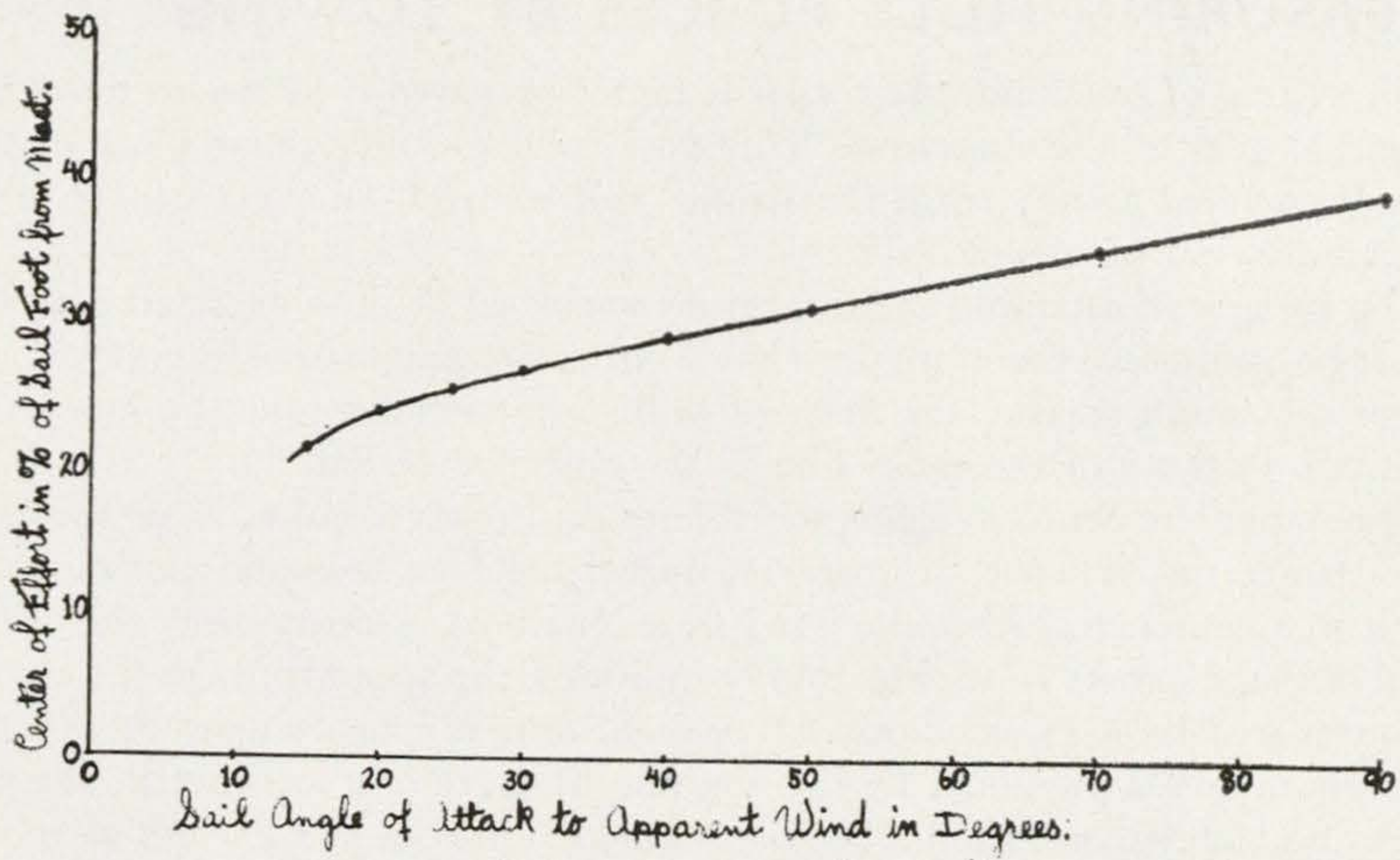
The right column of Fig. 10 shows a scale of the sail coefficients of the standard type commonly used. These are obtained from the formula,

$$C_S = \frac{F_S}{(\rho/2)\,A_S\,.\,v^2} = 4{\cdot}83\,\frac{F_S}{MPH^2}$$

where F_S is sail force in pounds.
ρ is air density of 0·0024.
A_S is actual sail area in square feet.
v is apparent wind velocity in feet per second.

These coefficients should be applied solely to the "sail only" curve.

Fig. 11 is a graph of the location of the centre of effort, CE, on the sail as a function of the sail's angle of attack to the apparent wind. The centre of effort location is expressed as per cent of the foot of the sail and is measured from the mast.



Center of Pressure (Effort)
versus
Angle of Sail Attack.

Fig. 11

Remarks

We see, in Fig. 10, that there is no reason to be disappointed in the lift-drag ratio of the sail alone. This turned out to be a maximum of 7·0, a reasonable value for a cloth sail. However, the fact that the overall lift-drag ratio including windage is a maximum of only 3·2 was disturbing to the writer. It teaches that for high pointing one must be particularly careful of the hull windage of sail boats. This is greater in magnitude than the windage of rigging. It is obvious that improvement in the sail proper, for better windward performance, would be nearly a waste of effort unless this windage situation is cleaned up.

An error analysis of the data, by known engineering methods, indicates that the experimental error can be as much as ± 15 per cent. This seems too large for accurate comparisons of different sails on an absolute numerical basis. However, relative comparisons, such as the described boom vang study should prove to be more accurate. The writer plans to improve on the instrumentation so that the value of $\frac{Fs}{MPH^2}$ is given by a single meter. This value is quite constant with varying strengths of wind, therefore greater accuracy should be obtained.

I hope the described inexpensive method of sail measurement will be attempted by a number of readers of AYRS. If so, publication of their results in the AYRS periodical will be helpful to many members in obtaining a better understanding of sail performance. It will fill a void that at present exists in information on cloth sails for sailing craft.

PART II
MEASURING HULL FORCES BY TOWING

In a writing of this kind, the reader is better prepared if he has in mind the eventual goal of the discourse. This goal is to produce polar plots of the *maximum speed possible*, with the sailing craft at hand, on every course to an apparent wind of named velocity.

To be sure of attaining the maximum speed, all of the interrelated details must be optimised, therefore these need our close examination. To determine these maximum speeds, the detailed hull characteristics must be known in addition to those of the sails. This is the objective of Part II.

The apparent wind is again the reference direction rather than the true wind since this is what an observer aboard the boat sees and can measure with an anemometer. Also, the wind vane on a boat measures only the direction of the apparent wind. For these conditions, the speed through the water, as measured by a Pitot or other type indicator, can be compared with the maximum speed predicted by the analysis. If there is a mis-match, the sail trim and boat balance should be re-examined. This can be a "secret weapon" in winning races.

Obviously different boats can be compared by their analyses without actually racing. In fact, these may be their greatest value. They give a good detailed insight to aid in the improvement of the breed. For the larger sailing craft, hull data obtained from model tests, rather than full size, have proved far less laborious and extremely helpful.

Measuring Method

The writer has obtained forces versus speeds by towing the hull of the International 12 ft dinghy, without sail, which was described in Part I. These were measured with a crew of two when the wind was calm, on various wind angles, in respect to the tow line, by the method that was described by the writer for models in AYRS No. 30. This appears as Chapter XIX in this book.

To simulate a real wind, the towing line was attached to the dinghy, without its sail, at a point which corresponded closely to the centre of effort, CE, of the wind on the sail. For good balance, this CE should be aligned, in the horizontal plane projection, with the hull's centre of resistance, CR, as shown in Fig. 2. Actually, in the hull test, it is the horizontal plane location of CR that is experimentally measured.

Once this CR is determined, it teaches us how to accurately balance the boat through mast position tuning or centreboard readjustment. These should be arranged so that the previously measured distance of the CE away from the mast coincides vertically in horizontal plane alignment with this CR of the hull.

The method of attaching the towing line is shown in Fig. 12. Note in the

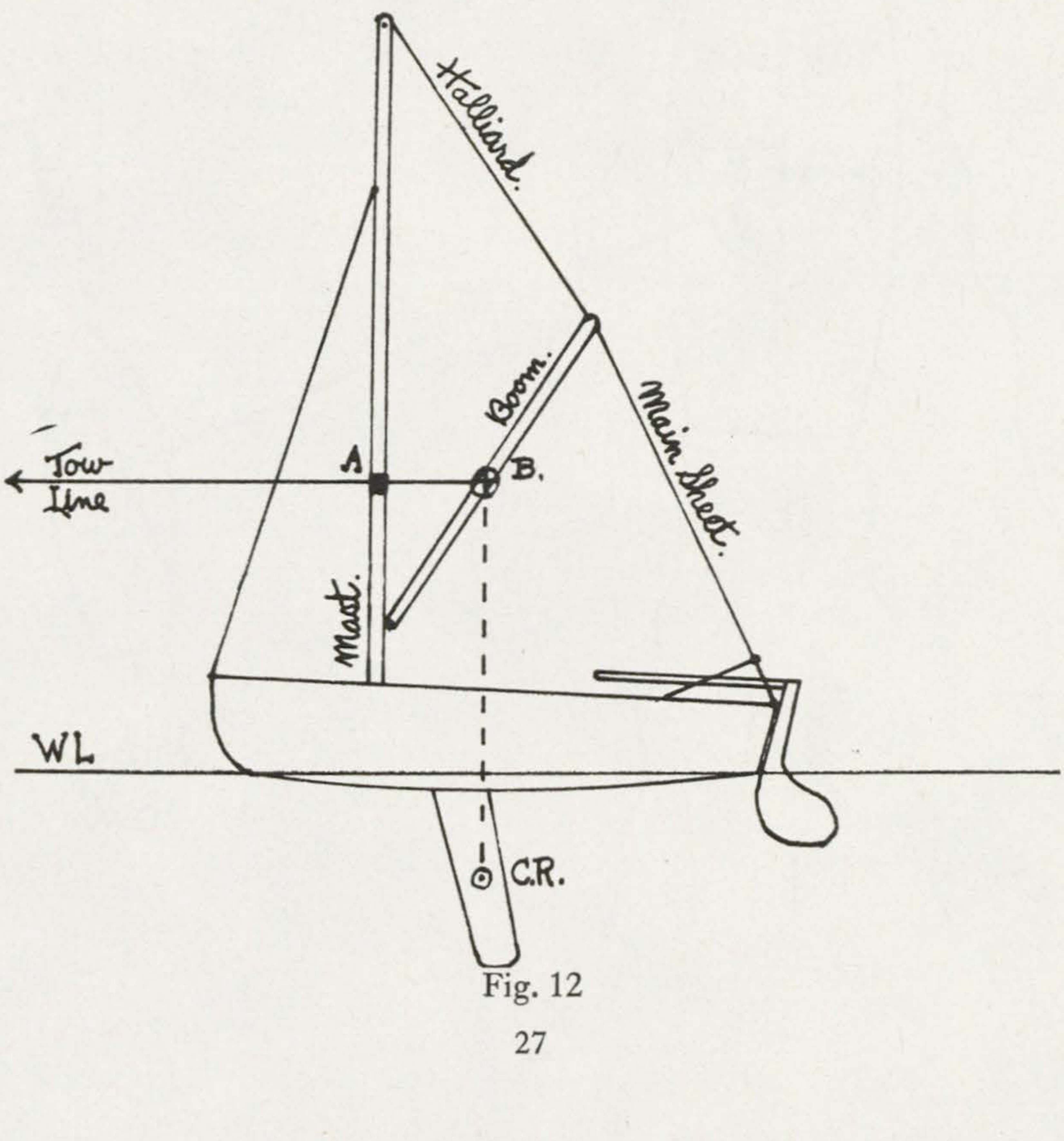


Fig. 12

sketch how the boom is cocked at an upward angle with the help of the sail halliard attached to the outward end of the boom. The towing line is tied to this boom at a point of equal height to a stripe marked on the mast. This stripe is at the distance of the sail's centre of area above the boom goose-neck which is one-third the measurement of the sail's luff.

Counter-pull to the tow line is provided by the mast and main sheet. This sheet to the boom controls the simulated position of the sail. The boom should swing around the mast so as to be roughly perpendicular to the towing line.

For a given positioning of the centreboard, the vertical angle of the boom is adjusted, during a towing test, so that the point of towing line attachment is spaced from the mast by a distance that will give balanced towing. This

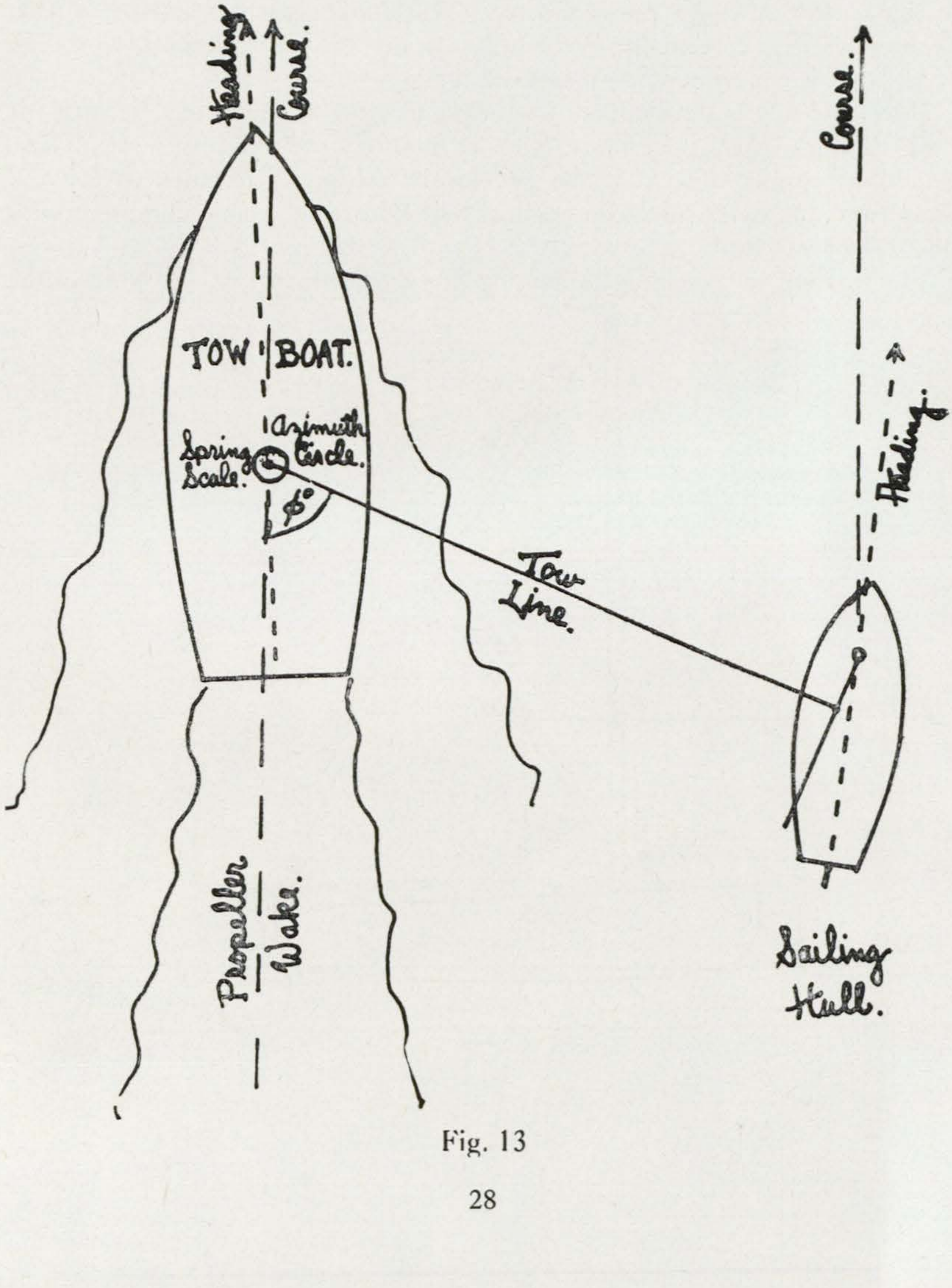


Fig. 13

distance should be measured and recorded. Balance is determined by a centre-line position of the helm which still maintains the desired course. When on a running course, this situation was only possible by placement of the crew so that the boat is heeled to windward or away from the tow line. This places the off centre-line CE in vertical alignment with CR. Many a dinghy race has been won by this manoeuvre. Incidentally, it reduces wetted surface on beamy hulls.

When towed under the conditions described, the helmsman has the satisfying feeling that he is sailing in an actual wind. There is one exception. He never "luffs". Excessive heeling is cured by steering toward the tow boat. Since most courses place the sailing dinghy well abeam the tow boat and on the same course, the harmful disturbances of the towing boat's propellor wake, to the force measurements, are avoided. Fig. 13 is a sketch showing the position of the sailing hull, on a simulated windward course, in relation to the tow boat. The courses made good by both boats are parallel after stabilisation.

The photograph of Fig. 14 shows the measuring equipment aboard the tow boat. It consists of a spring scale capable of several revolutions of its pointer. An azimuth circle indicates the angle of the tow line to the course of both boats.

Notice that the method outlined not only is capable of measuring force versus speed for various courses but includes in these measurements the

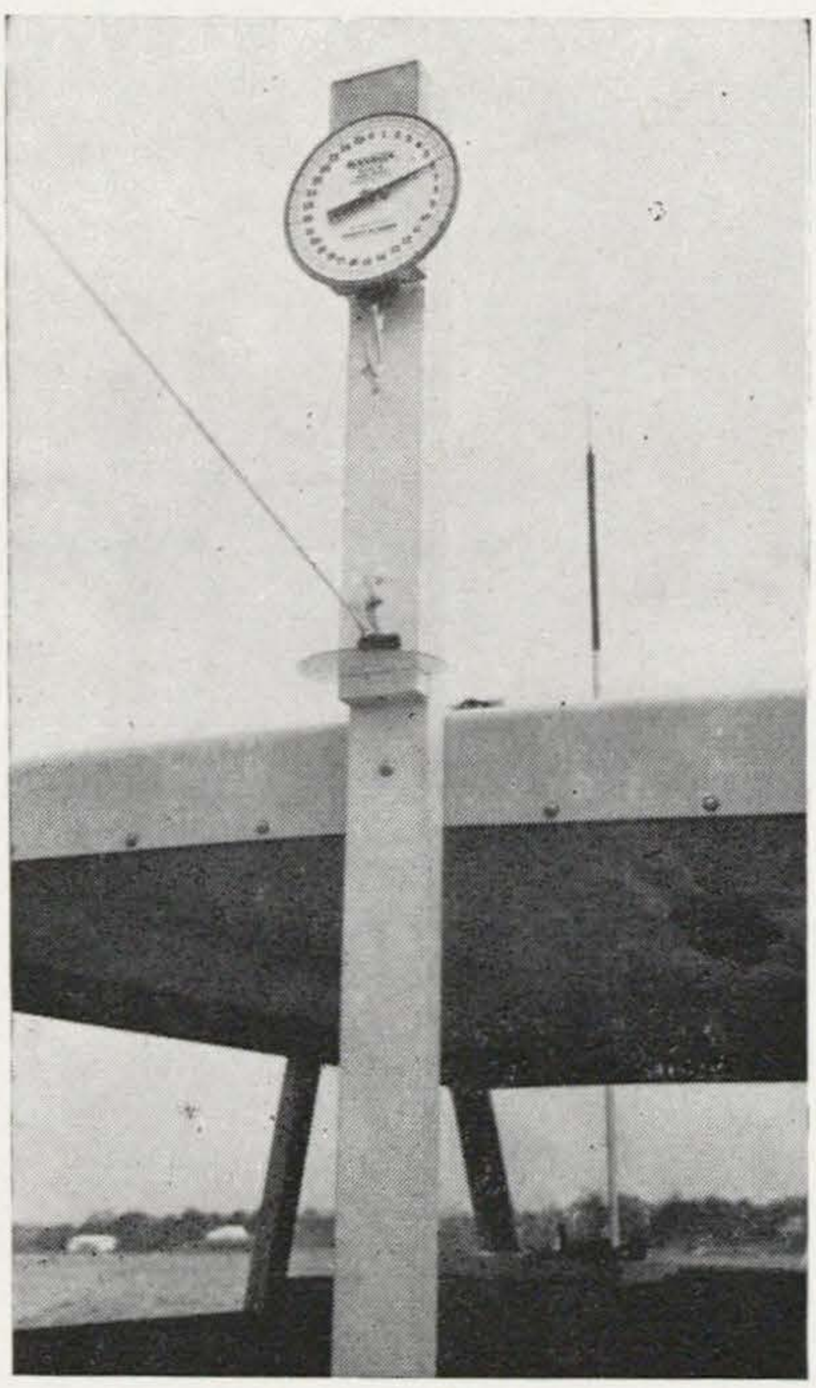


Fig. 14

effects of the sailing craft's lateral stability or sail carrying ability. Actual sailing conditions are simulated quite completely.

Hull Measurements

The 29-ft tow boat, used in these experiments, was designed for high speed planing in rough water. For longitudinal stability and easy steering, under these conditions, a full length "wine glass" shaped keel is provided. This keel and the weight of the boat proved excellent in avoiding leeway angle in the towing tests which simulated windward sailing. Pelorus sights on the wake measured leeway angles less than two degrees.

The dinghy with a crew of two was first towed astern. Then two-way speed-calibrating runs were made over a measured nautical mile. A specially made low range speed indicator was calibrated and the engine RPM noted, for the towing load, at the desired low speeds. This speed indicator consisted of the measured drag of a floating, two-foot length of $\frac{1}{8}$ in diameter, waxed, woven line towed by a thin Nylon thread.

Next, the dinghy crew were requested to work out to windward as much as possible by any adjustment means whatever for several selected speeds of the towing boat. Fig. 15 is a graph of the results. The highest lift-drag ratio before stalling measured to be only 3·5, whereas 5·0 is a good value but not rated as excellent. Since the centreboard of this dinghy already has an

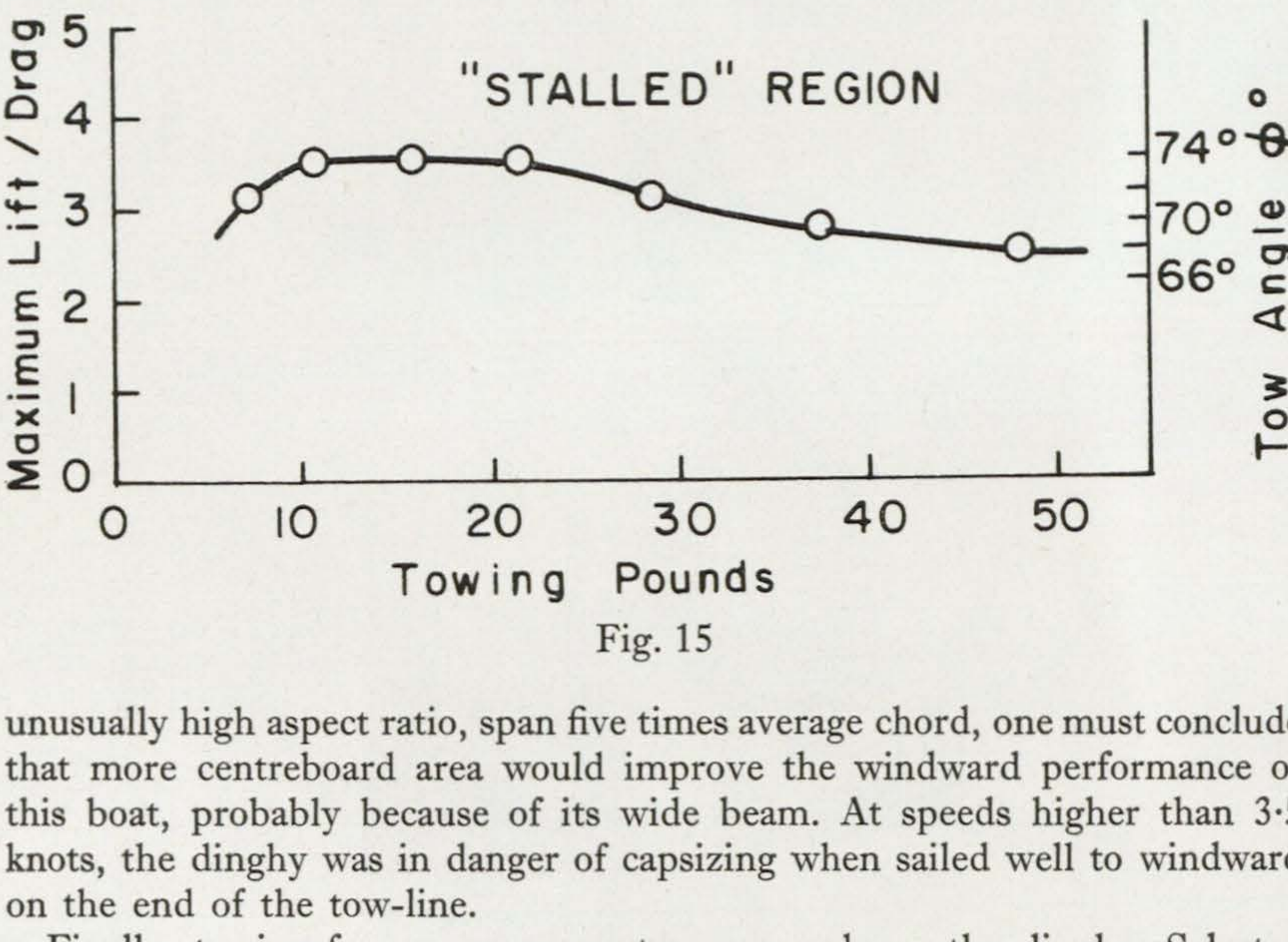


Fig. 15

unusually high aspect ratio, span five times average chord, one must conclude that more centreboard area would improve the windward performance of this boat, probably because of its wide beam. At speeds higher than 3·5 knots, the dinghy was in danger of capsizing when sailed well to windward on the end of the tow-line.

Finally, towing force measurements were made on the dinghy. Selected fixed speeds were carefully maintained as the dinghy gradually worked out to windward. Simultaneous readings were taken of the towing force and its angle to the course, at the instruments aboard the tow boat, when signalled to do so by the dinghy crew. The crew of the dinghy, at the same time,

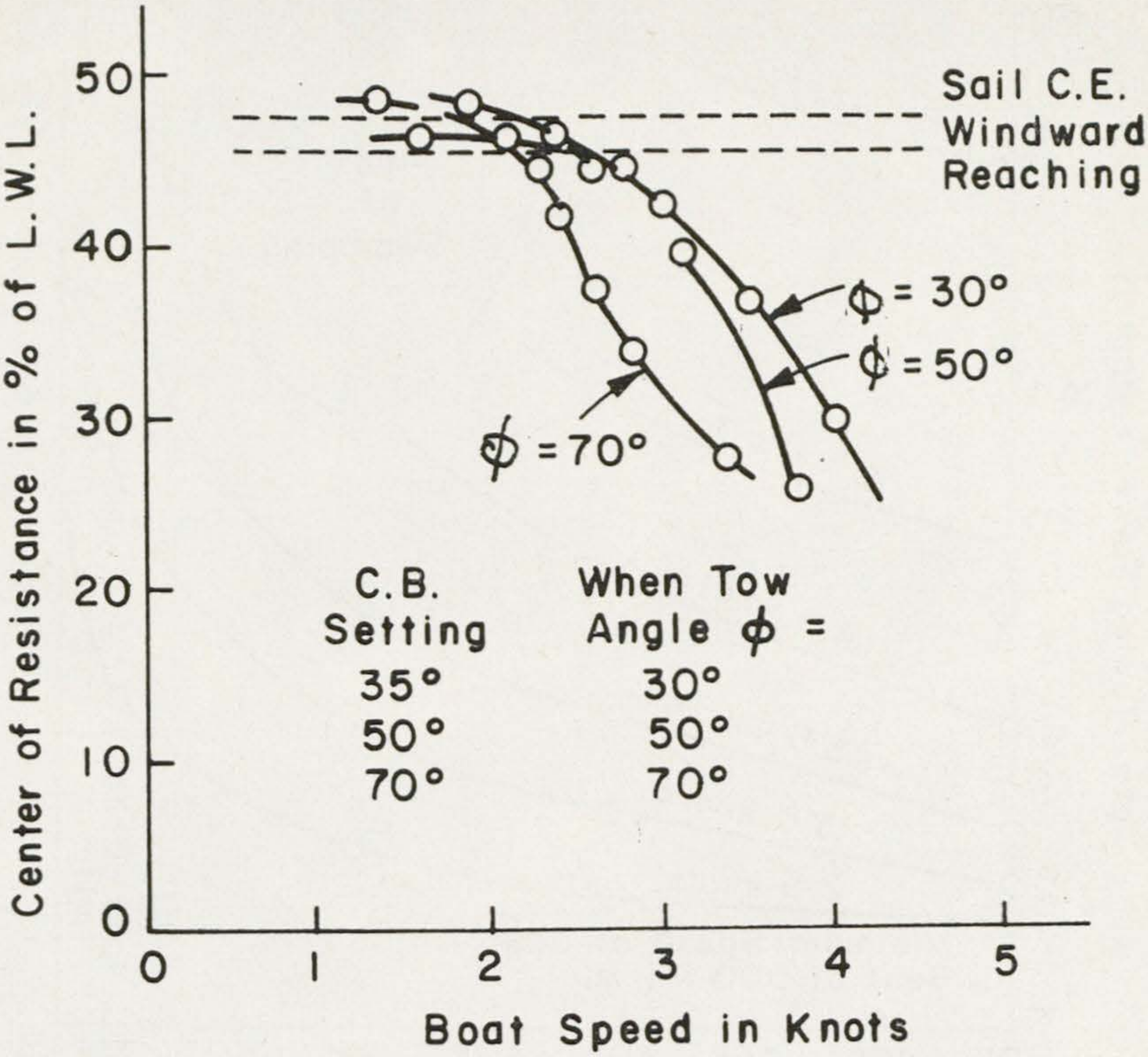


Fig. 16

measured the positions of the hull centre of resistance and centreboard settings each time hull balance had been achieved for the course.

Fig. 16 is a summary of the positions of the centres of resistance of the hull. Fig. 17 is the graphed summary of the towing forces. We now have all the hull data that is necessary to determine the overall optimum performance of the dinghy with its weight of crew.

PART III
COMBINED FORCES OF SAIL AND HULL TO OBTAIN SPEED

The sail information of Part I now will be combined with the hull information of Part II to obtain the overall characteristics of the tested sailing dinghy.

First, the maximum possible pointing ability of this dinghy will be examined. Next, the maximum possible speeds on various courses to the apparent wind and in several wind strengths will be determined. For further edification, this will be converted to refer to a fixed velocity, true wind as the course reference direction. Finally, the adjustments necessary for the greatest component speed directly toward the source of wind will be obtained.

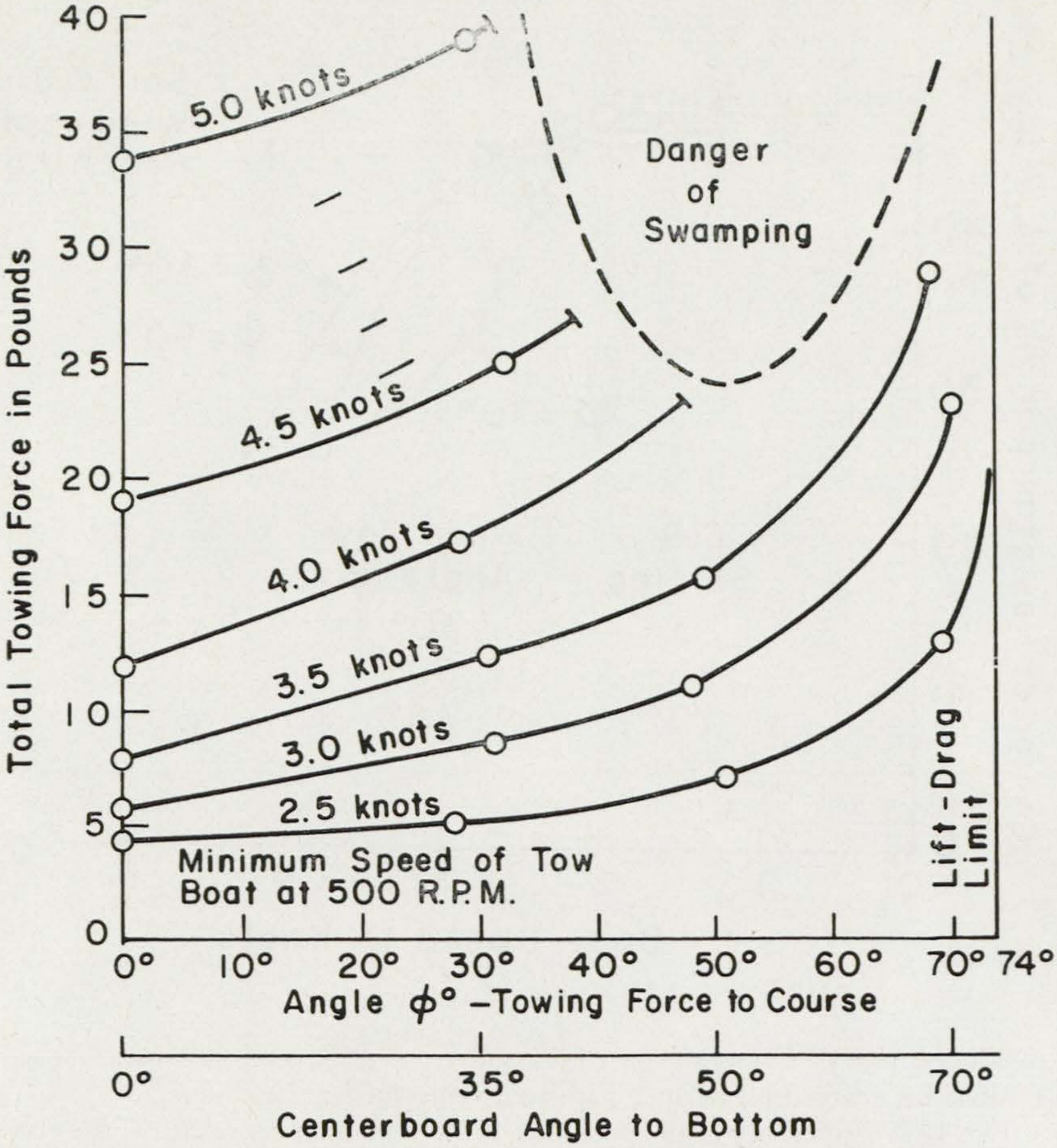


Fig. 17

Pointing Ability

Fig. 15 indicates, for the dinghy hull alone, that the maximum possible angle $\phi°$ between towing force and the achieved course is 74 degrees for total sail forces between about 10 and 22 lbs. For the angles shown in Fig. 2 the sail ratio of Lift/Drag equals tan $(180° - \beta° - \phi°)$ for all points of sailing. (See writer's article in Chapter II). Fig. 7 indicates that the maximum overall Lift/Drag of the dinghy sail including windage was 3·2. Thus 3·2 equals tan $(180° - \beta° - 74°)$. Trigonometric tables give tan $72{\cdot}6° = 3{\cdot}2$. Then $180° - \beta° - 74° = 72{\cdot}6°$ and $\beta° = 33{\cdot}4°$ which is the least angle of course to the apparent wind that this sail and hull combination can theoretically point without luffing or excessive side slipping.

An actual sailing test of the dinghy showed a wind vane to centreline minimum angle of 29 degrees was the highest pointing into the wind that was achieved. Since the leeway angle of the wake measured 5 degrees, the sum of 29 and 5 gives 34 degrees. (See Fig. 2.) This experimentally confirms the above analysis as to pointing ability in respect to the apparent wind.

Pointing ability is of particular value in getting by an obstruction or mark on a windward course. While it is a problem in angles and is near stalling speed, the minimum pointing angle is a good figure of merit between boats of nearly equal sail areas and hull weights, one-design classes for example. When sailed somewhat broader, a boat of high pointing ability foots faster than a boat of less high pointing capability when both are on the same course, in the forward quadrant.

Maximum Speed for a Course

In Fig. 16, the intersections of the solid curves of CR with the dotted curves of CE show the boat speeds for perfect balance. Satisfactory balance occurs up to nearly 2·5 knots. Beyond this, the curves show that less centreboard angles than indicated should be used for balance on all courses. This is due to waterline area dissymmetry when heeling.

In using Fig. 17, to help determine the maximum boat speed on a selected course, it should be observed that boat speed is plotted versus a towing force which is usually at some angle to the course. It is *unnecessary* to resolve this force into a component along the boat's course as will be seen in the following:

The towing force of Fig. 17 equals, in magnitude and direction, a sail plus parasitic windage force plotted in Fig. 7 in the form of $\frac{F_S}{MPH^2}$ versus angle to the apparent wind. This latter information must be resolved to be in an angular relation to the boat's course to achieve a speed solution with the aid of Fig. 17. This process will be illustrated step-by-step in the following example:

It is desired to know the maximum speed possible, with our sailing dinghy, on an achieved course which is at an angle of 90-degrees to an apparent wind blowing at 10 statute miles per hour.

A boat course at 90-degrees to the apparent wind has been drawn in Fig. 7. The maximum possible speed along this course is when the sail angle of attack is adjusted for the largest component, of the total force of sail and windage, along the desired boat course. This is obtained graphically as drawn in Fig. 7. It was done by erecting a perpendicular to the course which is also tangent to the curve of $\frac{F_S}{MPH^2}$.

The above graphical construction shows that the angle of attack (boom to apparent wind) should be 30 degrees. It also shows that the length of the vector $\frac{F_S}{MPH^2}$ measures 0·328 and is at an angle of 111-degrees to the apparent wind. Now the desired angle of this force to the course is $111° - 90° = 21°$ as sketched in Fig. 7.

Since we are concerned with a 10 MPH apparent wind, $\frac{F_S}{10^2} =$

0·328 and F_S = 32·8 pounds total sail force.

Plotting on Fig. 17 the above force of 32·8 lbs at a towing angle of 21-degrees to the course, we find that the boat speed required is a little less than 4·9 knots obtained by interpolating between the curves. All other courses can be solved in a similar fashion. These results appear in Table II and have been plotted in Fig. 18. This polar plot indicates the maximum speeds and sail adjustments versus courses for apparent winds of 5 and 10 MPH. This information has been the principal objective of this article.

TABLE II
Summary of Results

Assume			Obtain from Fig. 7					Obtain from Fig. 17	
Apparent wind		Course to apparent wind	$\frac{F_S}{MPH^2}$	F_S	Sail angle of attack	Force angle to apparent wind	Force angle to course	Boat speed	CB angle to bottom
MPH	knots	Degrees	—	Pounds	Degrees	Degrees	Degrees	Knots	Degrees
*		*		**			**		
5·0	4·3	34			27			0·0	74
		45	0·323	8·1	29	110	65	2·0	65
		60	0·328	8·2	30	111	51	2·65	51
		90	0·328	8·2	30	111	21	3·1	25
		135	0·357	8·9	70	150	15	3·3	18
		180	0·414	10·4	90	180	0	3·8	0
10·0	8·7	34			27			0·0	74
		45	0·323	32·3	29	110	65	4·0	65
		60	0·328	32·8	30	111	51	4·5 Swamp Danger	51
		90	0·328	32·8	30	111	21	4·9	25
		135	0·357	35·7	70	150	15	5·0	18
		180	0·414	41·4	90	180	0	5·2	0

*Substitute in Fig. 7.
**Substitute in Fig. 17.

The method of obtaining boat speed from the *apparent* wind velocity and boat course has been covered above. However, it is quite tricky to get the boat speed from a *true* wind and course. For a given true wind velocity and boat course, the boat speed must be postulated and the apparent wind velocity and angle to the course determined by means of Fig. 1. From this apparent wind, the boat speed is recalculated, as before, and the error from the postulated speed noted. This error is then reduced to zero by successive postulations and calculations. Fig. 19 is a polar graph of the results assuming a fixed 10 MPH true wind. A graphical method of solution is possible also. However, it appears to be more time-consuming than the method cited.

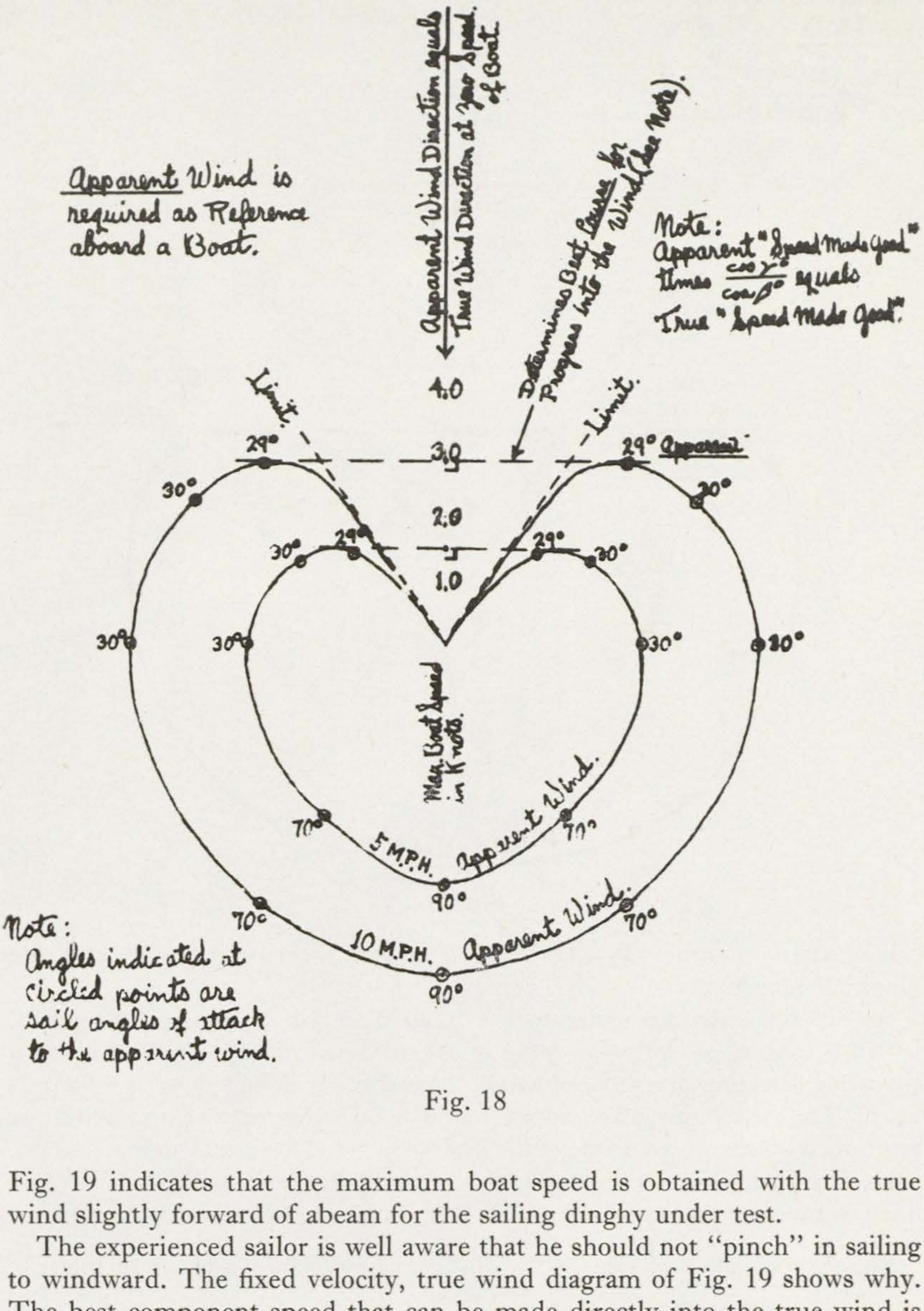


Fig. 18

Fig. 19 indicates that the maximum boat speed is obtained with the true wind slightly forward of abeam for the sailing dinghy under test.

The experienced sailor is well aware that he should not "pinch" in sailing to windward. The fixed velocity, true wind diagram of Fig. 19 shows why. The best component speed that can be made directly into the true wind is shown by the perpendicular intercept to the wind direction which is tangent to the polar curve of speed.

An observer aboard a boat does not want to be handicapped with the awkwardness of converting all data to refer to a true wind and interpolating between curves to achieve fixed true wind velocities. The question naturally arises as to whether the more convenient apparent wind plot of Fig. 18

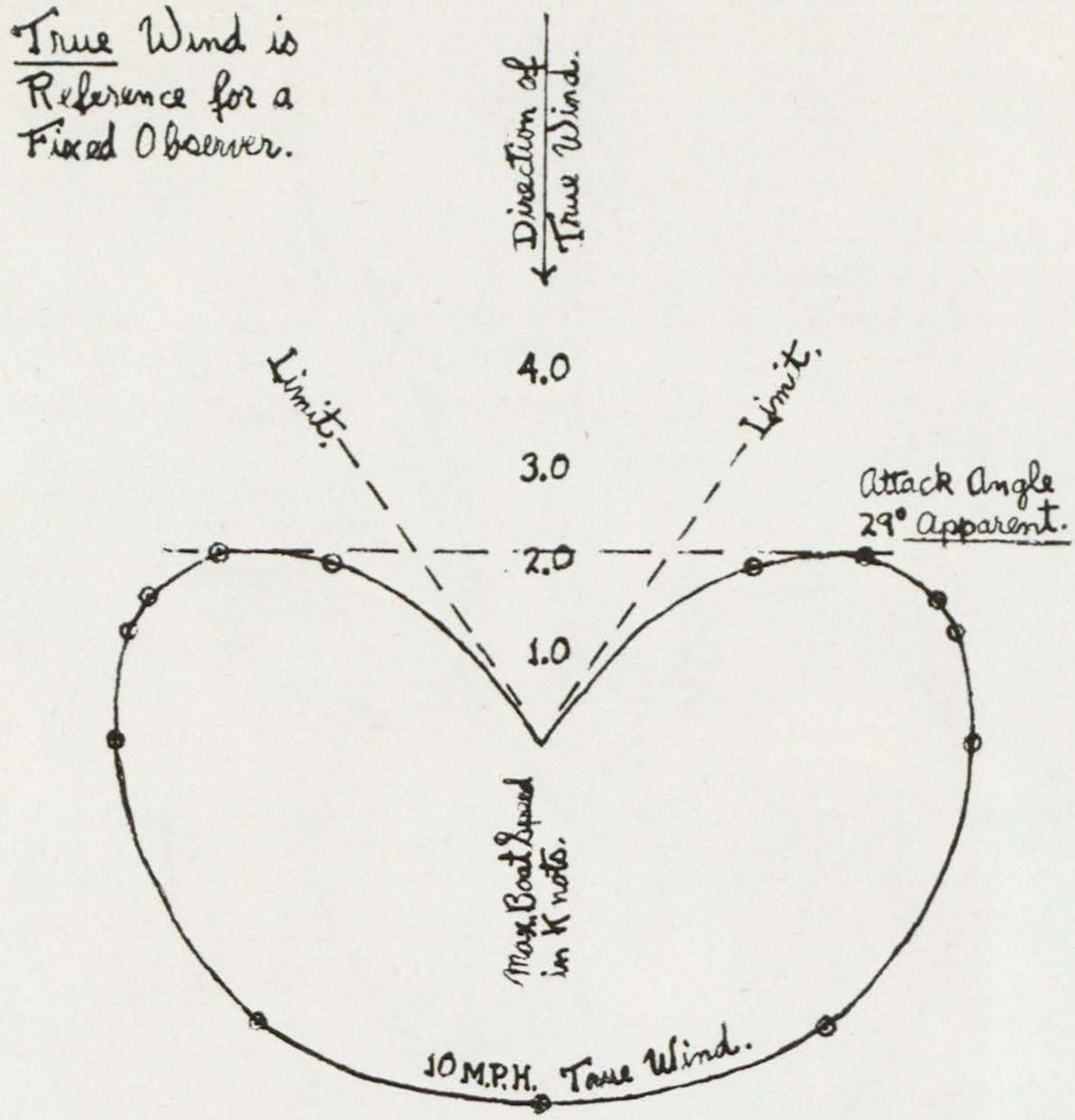


Fig. 19

can be used in some way. The answer is yes, within the accuracy of the graphical tangency.

As before, a perpendicular to the wind direction is drawn, in Fig. 18, which is tangent to the polar curve of speed. The intercept of this line with the wind direction gives the *apparent* "speed made good" directly to windward. To obtain the *true* "speed made good" this apparent quantity is multiplied by $\cos\gamma^\circ/\cos\beta^\circ$ to get the desired value. This can be demonstrated, using Fig. 1, by resolving components of the boat speed on to the direction lines of the true and apparent winds and comparing the results.

Should the rate of change of $\dfrac{\cos\gamma^\circ}{\cos\beta^\circ}$ be appreciable, a check of the true speeds made good for points each side of tangency is desirable, since this can affect the optimum slightly.

Concluding Remarks

To the sailing craft racing man who is serious about winning races, this writing should point a way by thoroughly "knowing the boat". The following is a series of suggestions:

Do not use the simple types of wind "tell-tales". Construct one or more having an azimuth circle for giving the apparent wind angle in degrees to the centre-line of the boat. Simple mechanical types suffice and can be read easily if mounted in the lower region of the mast side-stays, one on each side. If a mast-head indicator is desired, it might be of the electrical, remote meter reading type.

Mark on the azimuth circle the angle which represents the highest pointing of which the boat and sail are capable. This can be a check and warning should the boat or its adjustments get "out of tune".

Place other marks on the azimuth circle which indicate the best windward sailing angles to the apparent wind at one or more wind strengths. By all means use these marks.

For each indicated apparent wind angle, there exists, as shown by this writing, a best boom position. Put marks along the rail to show this proper boom position. Write the corresponding apparent wind angle adjacent to this mark and again use it on all courses.

Finally, place marks along the centreboard adjusting means which gives perfect balance with the other adjustments. Adjacent to these marks, again write the corresponding wind angle.

After rounding a mark of the racing course, *immediately* adjust boom and centreboard to the positions indicated by the wind vane angle. Other boats may be wasting time with the usual "cut-and-try" methods while you are sailing away from the pack. This procedure has been proven to be effective indeed.

CHAPTER II

IMPROVING SAILING CRAFT PERFORMANCE

Reprinted from AYRS 37, Oct. 1961

by Edmond Bruce

In the past, several contributors to the AYRS have indicated their belief that more can be accomplished in improving sailing-craft performance by concentrating on sails rather than hulls. I am writing to show how hull and sail efficiency, as indicated by their Lift to Drag ratios, are inter-related with the angle of the course from the apparent wind, thus giving a true picture of the situation.

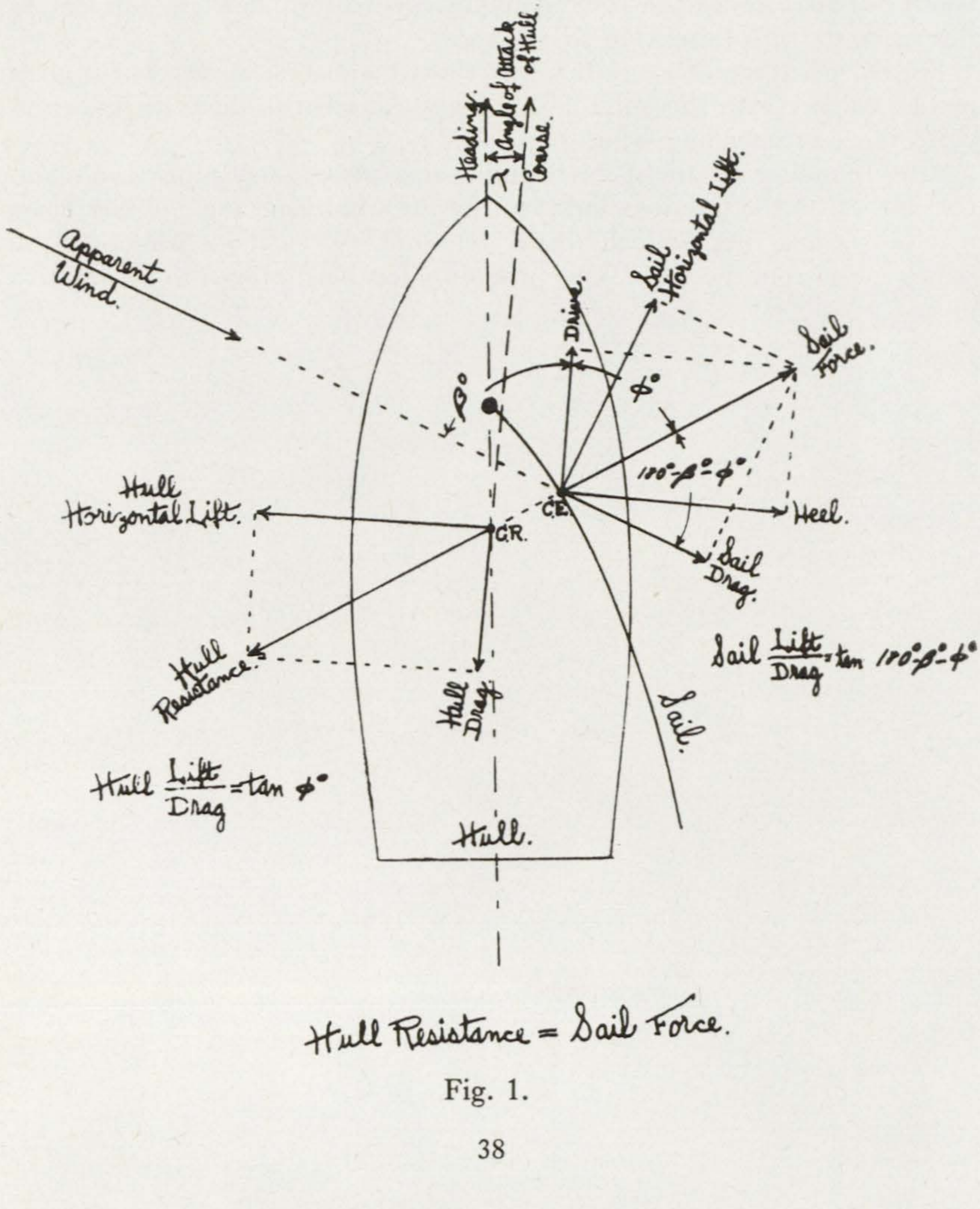


Fig. 1.

Fig. 1 is the conventional windward diagram of horizontally balanced forces for sail versus hull. A cat-rigged sailing craft is drawn for simplicity. After acceleration has ceased, the total hull resistance must equal the total sail force in magnitude and must oppose it in direction as drawn. The usual horizontal Lift and Drag component forces for sail and hull are indicated. The total sail force is also resolved into the components which indicate the useful drive along the achieved course and the heeling component hori-

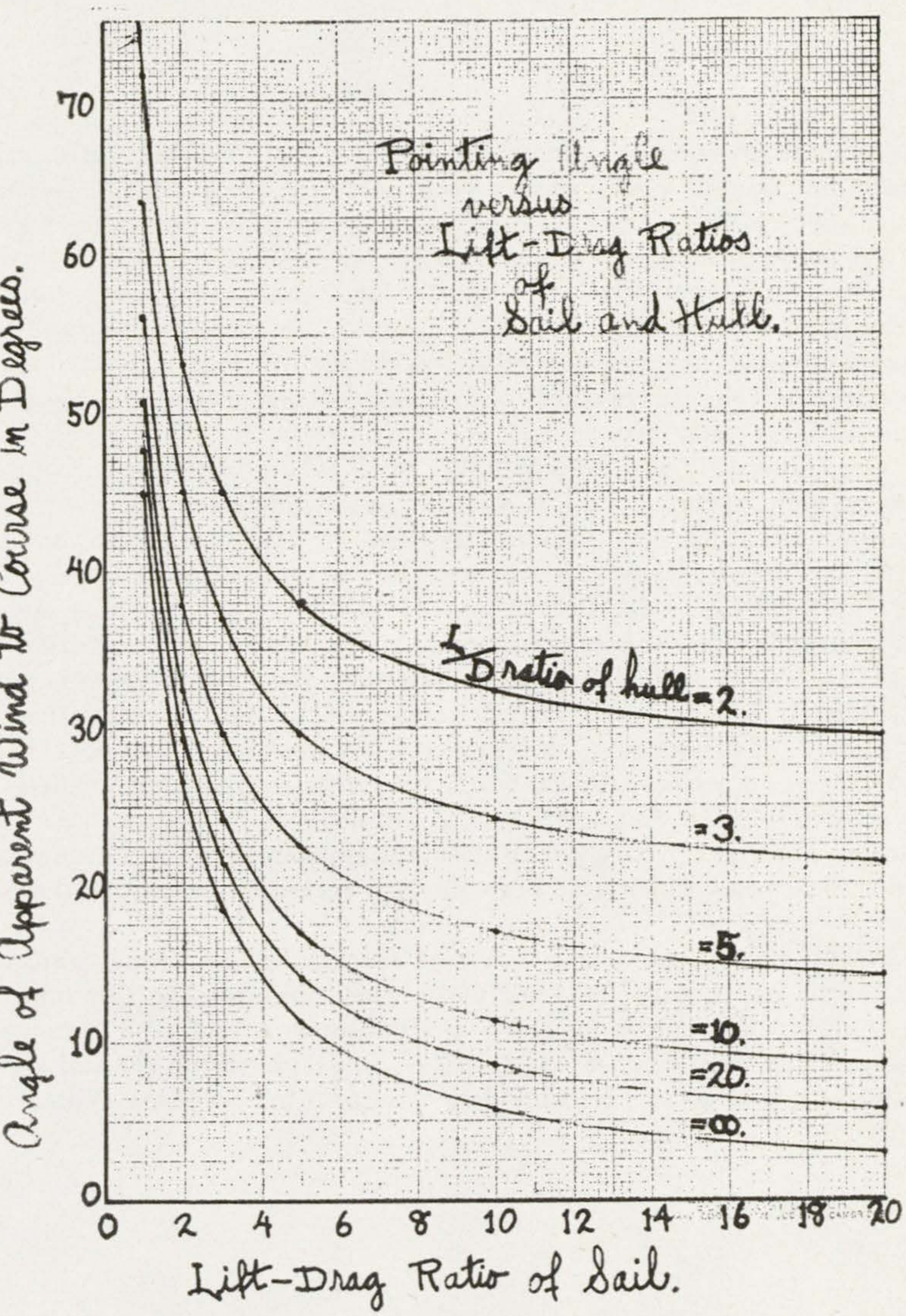


Fig. 2.

zontally perpendicular to that course. These components must equal and oppose the mentioned hull components.

β, in Fig. 1, represents the angle between the apparent wind and the achieved course. ϕ is the angle between that course and the total sail force. The hull will seek a speed and angle of attack which will create balance with the demands of the sail. Thus, simultaneous equations can be written as:

$$\text{(a) Hull } \frac{\text{Lift}}{\text{Drag}} = \tan \phi \qquad \text{(A)}$$

$$\text{(b) Sail } \frac{\text{Lift}}{\text{Drag}} = \tan (180^\circ - \beta - \phi) \qquad \text{(B)}$$

Using these equations, for every value of hull lift-drag ratio (sample maximum values: 3 for cruising yacht, 4 for a catamaran, 20 for an ice yacht), we can find a value for ϕ. From equation (B) we can now get a series of values for each value of ϕ which relates sail lift-drag with the angle of the apparent wind from the achieved course. Fig. 2 is a plot of these results.

Each curve of Fig. 2 is for a different value of hull lift-drag ratio and shows how the course angle becomes greater as the sail lift-drag ratio gets less. The disposition of the curves shows how the course angle becomes greater as the hull lift-drag ratio gets less.

The curves of Fig. 2 are applicable to all sailing craft and all courses in respect to the apparent wind. Note that they are independent of wind velocity and boat speed provided the lift-drag ratios are known for these conditions.

As an example, suppose a cruising boat, at some windward speed, has a maximum possible hull lift-drag ratio of 3. It has a sail which, at optimum adjustment for the course, produces a lift-drag ratio of 5. The curves show that the limiting angle β that can be sailed into the apparent wind is not less than 30°. If the boat speed were 35 per cent of the apparent wind, the calculated angle of the course to the true wind will not be less than 45°.

Other examples are: An ice-boat with a chassis, measured lift-drag ratio of about 20, in a towing test, and a sail of about 8, in a tethered test, fitted the curve of Fig. 2 precisely at 10° from the apparent wind in pointing ability. All the sail boats which have been similarly measured have fitted the curves also.

Finally let us examine the curves to see whether we should concentrate on sail or hull improvement for most benefit. We can see that improving the hull lift-drag ratio from 3 to 5 at a sail lift-drag ratio of 8 improves the course angle from $25\frac{1}{2}°$ to $18\frac{1}{2}°$, i.e., 7°, while improving the sail lift-drag ratio from 6 to 10 at a hull lift-drag ratio of 5 improves the course angle from $20\frac{1}{2}°$ to 17°, i.e., $3\frac{1}{2}°$.

CHAPTER III

THE COURSE THEOREM

(The Components of the Apparent Wind Angle)

Reprinted from AYRS 41, Oct. 1962

by John Morwood

In AYRS No. 37 *Aerodynamics I* (the previous chapter) Edmond Bruce very cleverly showed the relationship between the three factors; (1) the angle of the apparent wind to the course in degrees, (2) the lift to drag ratio of the hull to the course and (3) the lift to drag ratio of the sails and hull to the apparent wind. It is felt that the matter can be more simply stated as follows:

"On any heading, the angle between the apparent wind direction and the course made good is equal to the sum of (1) the 'drag angle' of the hull force to the water flow and (2) the 'drag angle' of the aerodynamic force produced by the sails and hull to the wind flow". This statement may be called the "Course Theorem".

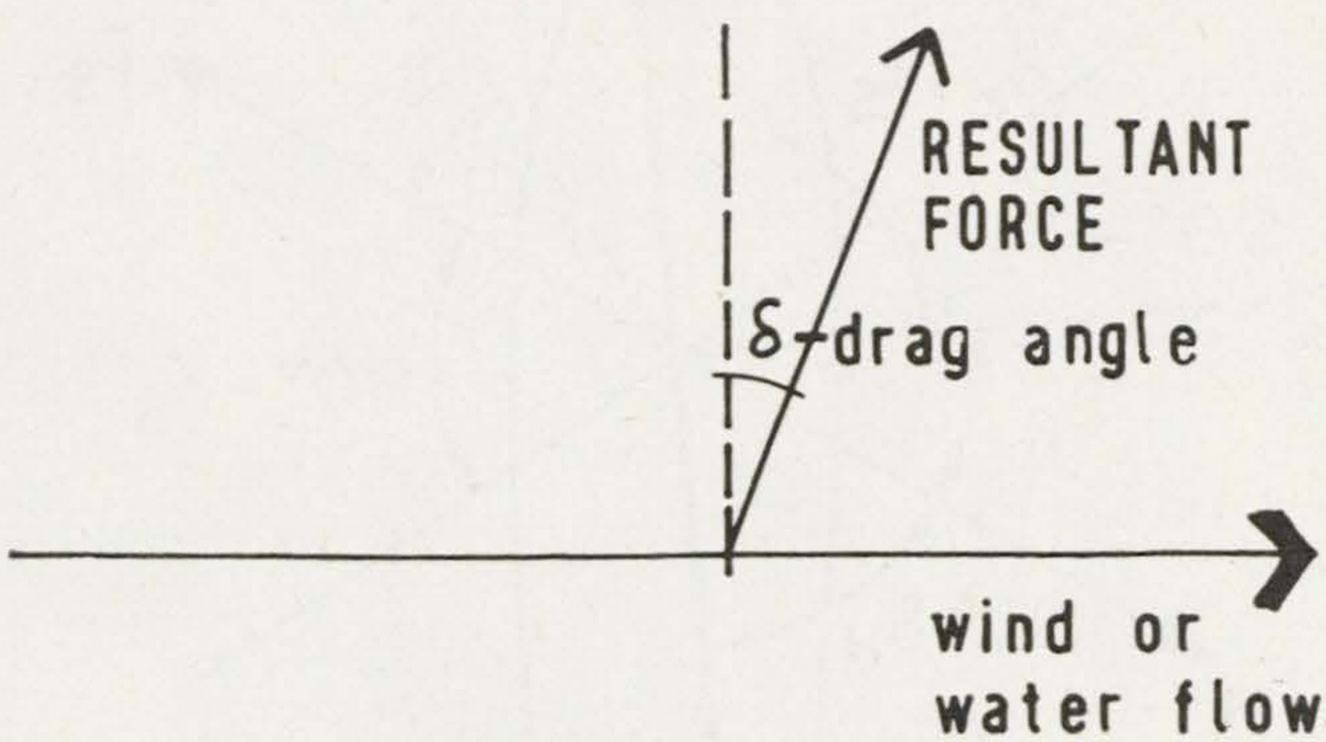


Fig. 1.

Fig. 1 shows what is meant by the "drag angle". This angle is the angle aft of a right angle to a wind or water flow at which the force produced by an aerofoil or hydrofoil acts. This angle would be zero if there were no drag.

The proof. The diagram of Fig. 2 shows the two main forces acting on a sailing boat with the direction of the apparent wind and the course made good marked. The apparent wind AL blows on the sailing boat, both hull and sails, and creates a force F_S making a drag angle δ_S. Since the dotted line is at right angles to AL, the angle F_SOL is $90° - \delta_S$.

The boat sails along the course SC making an angle of leeway which creates a force F_H which is equal in size and opposite in direction to F_S.

This force acts at a drag angle δ_H. Again since the dotted line here is at right angles to CS, the angle F_HOS is $90° - \delta_H$.

Now the angle F_HOA is equal to the angle F_SOL and hence equal to $90° - \delta_S$, as marked.

Then, since COS is a straight line, $180° = \beta + 90° - \delta_S + 90° - \delta_H$ and $\beta = \delta_S + \delta_H$ as the Course Theorem states. Thus it is proved.

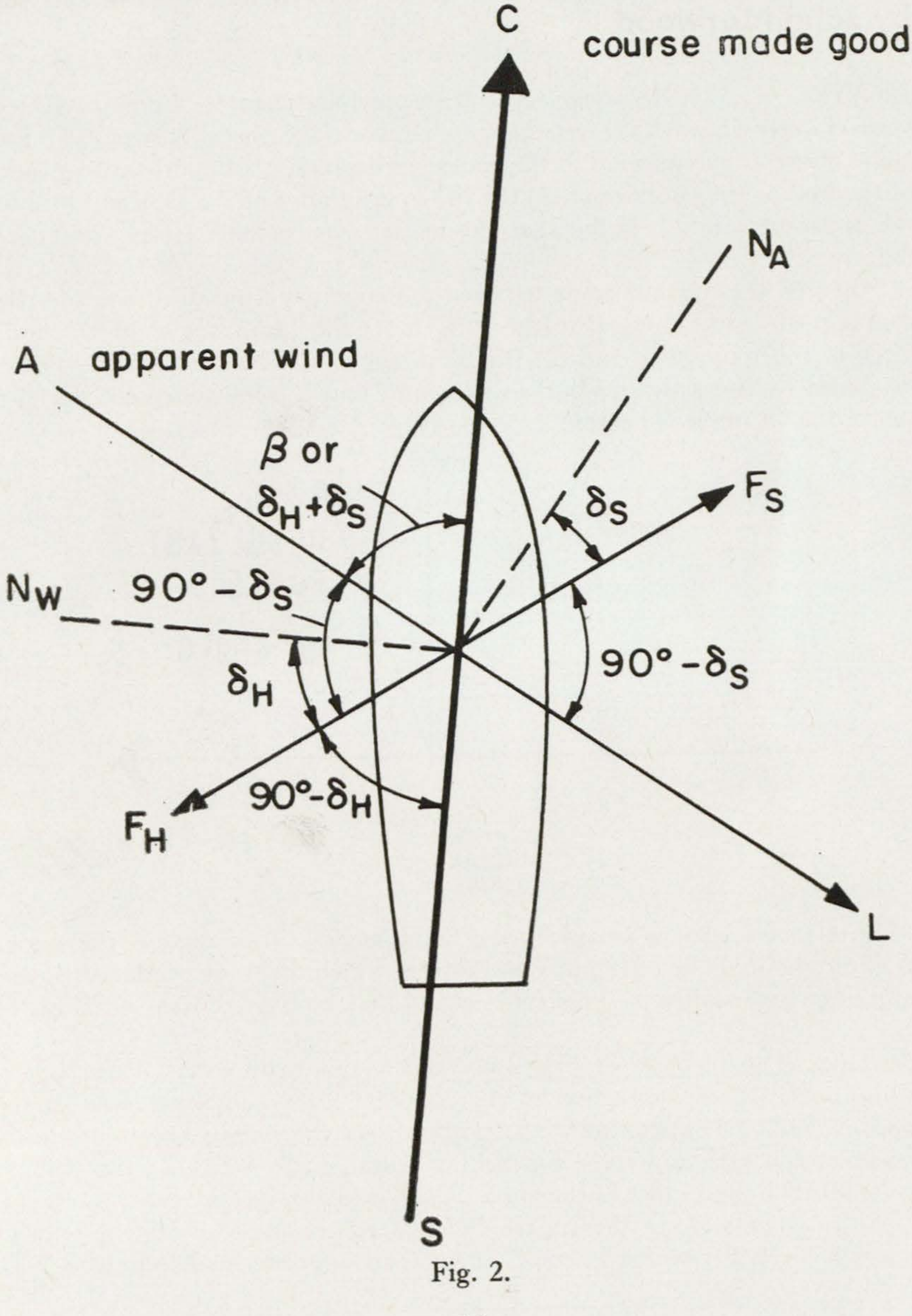


Fig. 2.

Inference. This theorem shows that if either the drag angle of the aerodynamic force produced by the sails and hull, or the drag angle produced by the hull in the water can be reduced by any amount, the minimum pointing of the yacht to windward can be reduced by that amount.

CHAPTER IV

DESIGNING FOR SPEED TO WINDWARD

Reprinted from AYRS 61, July 1967

by Edmond Bruce

Situation

Is the reader one of those sailors who feels quite satisfied when his leeway angle, or sideways drift, is very small, even when sailing hard on the wind? It is the writer's contention that this small leeway may be an indication of a poor hull design. It suggests too much lateral plane and therefore too much wetted surface.

Several syndicates, involved with "America Cup" contenders, have worried about the conflicting facts that:

a At full size, only about one to one and one-half degrees of leeway is experienced to windward.

b Towing tank data, on a precision model of the boat, had shown leeway angles of four to five degrees, on high-pointing, windward courses.

These people tend to blame these discrepancies on the towing tank and to an assumed inaccuracy in scaling a model to full size.

The writer does not believe that the towing tank proper or scaling is at fault. The difficulty may lie jointly in the test methods decided upon and in the magnitude and angle of sail force represented by the so-called "Gimcrack Coefficients".

This writing will try to delve into this situation and present the author's viewpoint. A better understanding will help all sailing. If faults do exist, some cures are suggested.

Significance of Leeway Angle

Our concern for the value of the full size hull's leeway angle can be explained by the following sequence of related logical statements:

a The leeway angle of a hull is identical with the angle of attack of a symmetrical foil, as used in studies of fluid dynamics.

b There exists an angle of attack which produces an optimum lift-drag ratio for a foil or hull.

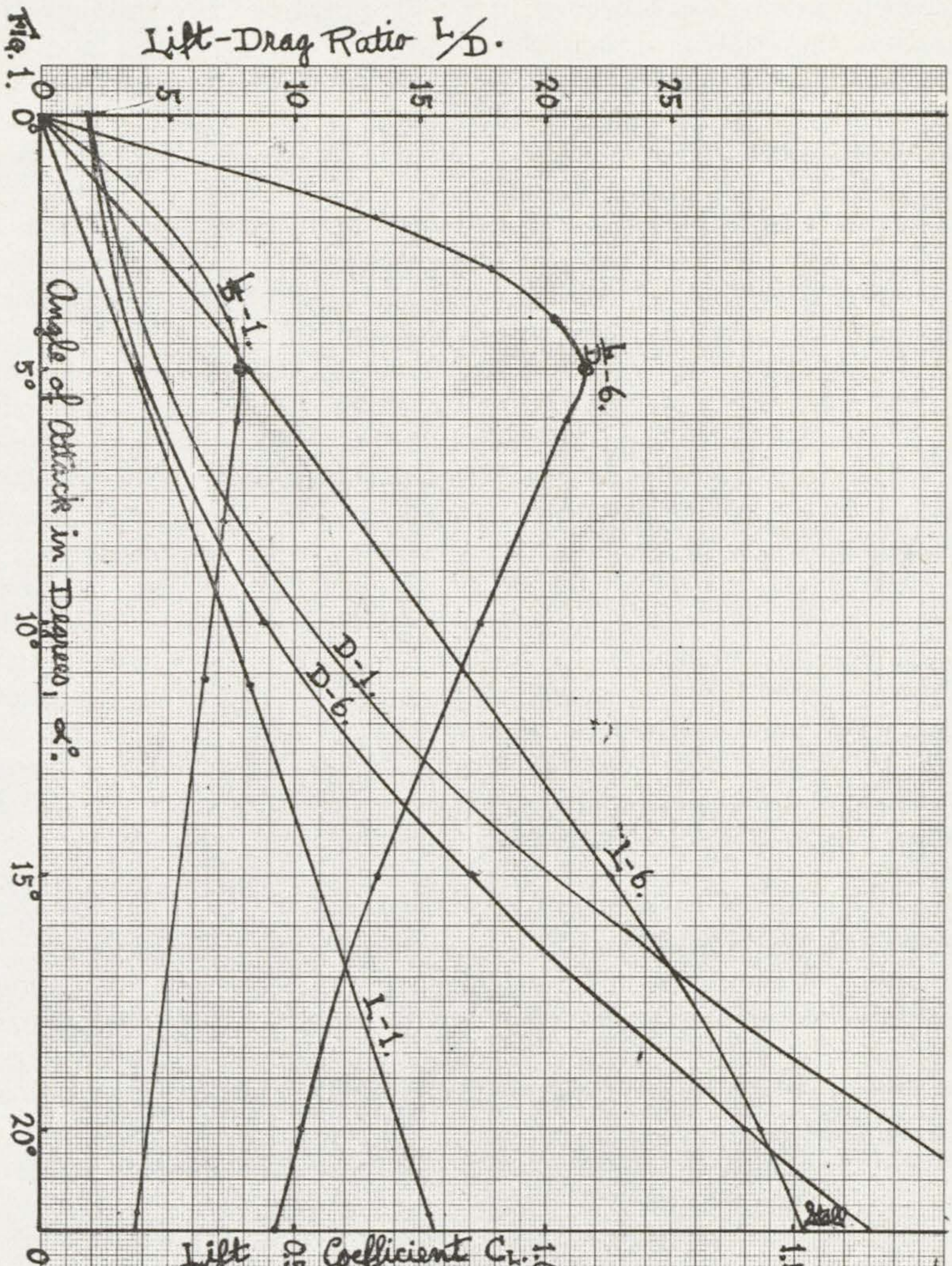
c A highest lift-drag ratio corresponds to a smallest drag angle in the "Course Theorem". (See Chapters II and III.)

d The smallest drag angles, for hull and sail, result in the smallest course angle to the apparent wind since the latter is always their sum.

e Therefore, a hull leeway angle exists which will produce the highest pointing of the hull's course in respect to the direction from which the apparent wind is blowing.

One must comment on the above, also on the "Course Theorem", and say that all of these pertain to angles alone and do not include force or velocity magnitudes. These absent magnitudes will be provided from empirical data, on sail and hull, later on in this writing.

If speed is the primary objective, a competent designer should adjust the size of his chosen under-water body so that a maximum, lateral, lift-drag ratio, at the hull's speed, is achieved to counteract the sail force that is expected. The latter is limited by stability considerations. If the water



resistance were square law with speed, as is the case for the sail, also in aeronautics, the best lateral area and angle of attack would be constant at all speeds. Since this is not entirely true for a hull, due to wave-making, a fixed keel must be a compromise. This gives the adjustable area of a centreboard some advantage when properly used. When the area of a keel is constant, a small change in leeway angle must be expected with changing speed or with a change in course.

It has been the writer's towing-tank and full size experience that, for every hull in which the lateral area has been adjusted to achieve the optimum lift-drag ratio to windward, the leeway angle has never been less than 4 degrees or greater than 6 degrees. It would appear that any hull outside of these limits probably is of improper design.

Many keel boats have areas which are too large. Quite a few multi-hulls have boards that are too small with excessive leeway as the result. Let us examine the literature of aeronautics and see if we can confirm the conclusions as to the best angular range.

The fixed keel, of say a 12-meter, is subject to the same physical laws as a foil in aerodynamics after a proper allowance for fluid density is made. However, a strict requirement is that the keel must be deep enough not to contribute appreciably to surface wave-making.

In Fig. 1, examine the curves of the lift and drag coefficients versus angle of attack for two NACA No. 0012 foils of aspect ratios 6 and 1. The latter corresponds broadly to many keels in sailing craft. These are further handicapped in lift-drag ratio due to the drag of the hull proper. In this foil-shape designation, the first 00 indicates a symmetrical foil. The final 12 means a thickness which is 12 per cent of the cross-sectional chord length. This thickness is among the best for airplane symmetrical foils, at least at the high Reynolds' Numbers used. At the low Reynolds' Numbers, encountered in sailing, further investigation is badly needed, due to "separation".

Also plotted in Fig. 1 is the ratio of lift to drag for each of these two foils, which differ only in aspect ratio, as stated. It is seen, in each case, that optimum lift-drag is achieved at an angle of attack of about 5 degrees. Even though the low aspect ratio foil is much poorer, its angle of attack for highest L/D is substantially the same. Thus one might conclude that aspect ratio does not appreciably affect the optimum angle of attack for a given cross-sectional shape of a foil.

As to varying thicknesses of foils, Table I indicates the angle of attack at which the stated optimum L/D was achieved, in NACA reports, for symmetrical foils. All optimum angles are within the cited range of 4 to 6 degrees. Also note the remarkable fact that, at the fixed aspect ratio but regardless of maximum lift, the coefficient of lift is always 0·40 at the angle where maximum lift-drag ratio is achieved.

Returning again to Fig. 1, it teaches that, at the angle of attack of 22 degrees which produces a maximum lift coefficient of 1·52 for the aspect ratio of 6, the resulting lift-drag ratio is only 9 as compared to 21·6 at an angle of 5 degrees. It follows that for highest pointing, one does not necessarily select a shape that gives the maximum lift. The thinner foil NACA No.

TABLE I

Aspect Ratio = 6 in all cases. At high Reynolds' Numbers

Foil	Maximum L/D	Angle of attack degrees	C_L	Maximum C_L	Angle of attack degrees
Flat Plate NACA	6·7	5	0·40	0·78	15
No. 0006	23·5	4	0·40	0·88	16
No. 0009	22·5	5	0·40	1·27	18
*No. 0012	21·6	5	0·40	1·52	22
No. 0015	21·0	5	0·40	1·53	22
No. 0018	19·8	6	0·40	1·50	23
No. 0021	18·5	6	0·40	1·38	23
No. 0025	16·5	6	0·40	1·20	23

*Best overall for airplanes due to high lift and high L/D.

0006 of Table I would seem slightly better at $L/D = 23{\cdot}5$ and $C_L = 0{\cdot}40$ than No. 0012 even though its maximum C_L is much smaller.

High lift devices, such as airplane take-off flaps, are of little value in a keel, except for steering, because of the high resulting drag. The author disagrees with those that advocate a slight weather helm rather than a centred helm with a balanced sail position. The keel curvature achieved with the angled rudder is too far aft. It resembles a flap. A sail balance that achieves some degree of weather helm is one of the factors which cause a reduction in leeway angle, possibly one degree or more. A centred helm, on a properly balanced boat, still has some side pressure due to the keel's angle of attack.

The writer undertook a simplified mathematical analysis so as to try to understand why an optimum angle of attack in the range of 4 to 6 degrees is so persistent. I do not wish to burden this writing with mathematical details that would be of interest to so few readers.** However, for those who may want to investigate for themselves, the final result is stated in the following:

For a flat plate, if C_P is the normal pressure force coefficient and C_F is the tangential frictional force coefficient, also if α is the angle of attack, L/D maximum works out to occur when:

$$\frac{C_P}{C_F} = \frac{1}{\tan^2 \alpha}$$

Now if $C_P = 1{\cdot}25$ (a reasonable value for both sides combined) and $C_F = 0{\cdot}006$ (twice the Schoenherr coefficient since both sides are involved), the calculated optimum angle of attack turns out to be about 4 degrees which is quite independent of size and shape. The ratio of $\dfrac{C_P}{C_F}$ would have to change by more than 50 per cent to alter this optimum angle of attack only by 1 degree.

One might conclude that the range of 4 to 6 degrees, as the optimum angle

**See Appendix B for details.

of attack, is so persistent because only the fundamental ratio of forces, with a flow normal to or tangential to an elementary surface, is involved. These may be quite rigidly fixed quantities in nature. Using the overall performance measuring instruments, which the writer described in AYRS No. 56 (Chapter XI of this book), it was found on a 38-ft keel-centreboard ocean racer that even on a reach, the centreboard area had to be reduced, for best performance, so that the leeway angle was again between 4 and 5 degrees. This is reasonable since one always wishes to provide the required lateral lift with the least possible drag. In other words, the best possible lift-drag ratio is still required even though the total amount of lateral lift desired was reduced by providing a smaller area. In a boat having a fixed keel area, the leeway on a reach is bound to be less than when hard on the wind. This means that an excess of drag is unavoidable.

From all the above, it is seen that there is a substantial case for being suspicious of a hull design where the leeway angle is out of the range of from 4 to 6 degrees. Some people apparently considered the writer very irreverent when he stated, in print, that in his opinion, the "America Cup" contest was being conducted in "house-boats". The 12-meter class members seem to have copied each other's mistakes in lateral plane. I would like to predict that, if a proper leeway angle is included in an otherwise good design, a winner will be produced, if properly handled.

I will now attempt to show that one villain in the situation may be the magnitude of the "Gimcrack Coefficients". Too large a coefficient used in towing tank tests would result in too small a leeway angle at full size, as we will see later. I believe that the lateral plane areas, often used in 12-meter boats, should be reduced at least one-third. This correction together with a reduction in weather helm could provide a leeway angle of some 4 degrees.

Gimcrack Coefficients

At some towing tanks, sailing hulls are tested for windward performance using assumed component magnitudes and their determining direction for the sail forces. These sail forces are represented by coefficients obtained from tests which were made while sailing the approximately 6-meter yacht *Gimcrack* on the wind with the main-sail luff just "full and by". Since these coefficients are independent of sail area (or apparent wind strength) this area can be adjusted to suit the stability of the hull being tested or to some restricting sail area measurement rule.

A danger that must not be overlooked is that, if by chance the Gimcrack coefficients were too large and the hull's lateral plane area was adjusted to accommodate them, real sails on the final full size boat, with a rule-prescribed sail area, would be teamed with a hull lateral plane size that is too large to achieve an optimum lift-drag ratio.

Let us look into the history of the Gimcrack Coefficients and come to some conclusions as to their accuracy. Thirty-six years ago, there appeared some suggestions which made possible a considerable advance, for that day, in the technical understanding of sailing. Among other things, there were proposed the so-called Gimcrack Coefficients. These permitted the extension of towing tank sailing hull work, beyond merely running courses, to include those of windward sailing.

For steady state equilibrium, a sailing hull always automatically adjusts its three component angular attitudes and speed so that the water-caused resistance exactly opposes the direction of the sail force but equals its magnitude. From the time of the Gimcrack proposal to the present, it has been the usual practice of some commercial towing tanks, when dealing with simulated windward sailing, to assume that the hull is driven by a Gimcrack type of sail plan. By using only one standard sail plan, it was felt that the merits of various hull designs could be more accurately compared.

In the original publication, Stevens ETT No. 10, its author revealed some weaknesses in the Gimcrack full size tests. The anemometer was reported as hand-held by a man on deck, not at the higher centre of effort of the sails. Due to the velocity gradient of the wind with height above water, such readings were undoubtedly lower than those at the height of the centre of effort of the combined sail plan. The total coefficient of the lift and drag component coefficients, that were used, times the sail area times the *square* of the correct apparent wind velocity must equal and oppose a fixed equivalent water force, as was determined from the displacement's righting moment for the angle of heel and the forward resistance of the hull when towed. For a given force, too large a coefficient would result from a wind velocity that was too small, especially since the wind velocity must be squared.

If the original total coefficient, which included the fluid density, were converted to the familiar aeronautical type of coefficient, which expresses density separately, its magnitude would have been 2·34, a ridiculously high value compared with known foils. The author was aware of this discrepancy and worried about it. He compared his value with those obtained by E. P. Warner who used 18-in by 3-in rectangular, rigid, curved metal plates in wind-tunnel tests. Warner's maximum total coefficient was reported at 1·85.

In Stevens report ETT No. 16, the author arbitrarily reduced the total coefficient to 1·835 based on a published wind velocity gradient with height, as was mentioned previously. This was no more than an educated guess since the hull's effect was not considered. The writer feels that this value is still too high. A rigid curved plate, having an aspect ratio of 6, would have a big advantage over soft cloth sails which were subject to luffing, subject to the presence of parasitic windage and having lower aspect ratios.

The coefficients employed should have been still further reduced. When sailing hard on the wind, one should trim sails for a maximum lift-drag ratio. The coefficient for this adjustment is smaller than the maximum coefficient. For example, Table I indicates that Foil No. 0012 at an aspect ratio of 6 and having maximum C_L at 1·52 should use C_L at only 0·40 for a maximum lift-drag ratio of 21·6. Later, in Table II, it will be seen that a single cloth sail on a dinghy, in the presence of parasitic windage, employs C_S at 1·39 compared with a maximum of 1·61 to obtain a maximum lift-drag of only 3·27 or a drag angle of 17 degrees.

Thus the better the sail or foil, the smaller is C_S to achieve an optimum lift-drag ratio. The poorer sail has to use higher values to overcome excess drag. The writer would be better satisfied if C_S maximum for the Gimcrack Coefficients were about 1·6. Also the C_S, used for highest pointing or maximum L/D, might be about 0·9 when used for towing tank work to windward. These were values measured by the writer using tethered tests on 600 square feet of mainsail and jib. A leeway angle of 4 degrees was achieved with these sails on a 38-ft craft when the keel's centreboard was carefully adjusted.

There are further treatments of the Gimcrack Coefficients in Stevens ETT No. 17 and No. 22, but the non-heeled value of the total coefficient for windward sailing was not changed from the 1·835 value to my knowledge.

The writer has some additional complaints about the determination of the Gimcrack Coefficients:

a The course to the apparent wind was never actually measured. This is a sensitive parameter when on the wind.

b No consideration was given to the harmful windage on the hull and rigging which certainly would affect the coefficients.

c The stated average angle of attack for the sails of 2 degrees seems extremely low. This is hardly possible without luffing.

d There is no proof whatever that the fixed sail coefficients, as reported, achieved the *best* speed made good to windward. Only a single course was employed.

In view of the costs in time and money of the many tank tests that have taken place, more accurate coefficients are certainly warranted. I have little quarrel with the excellent running tests that the towing tanks have produced. However, I have understandable doubts in the "speed made good" reports that are based on the Gimcrack Coefficients. Many boats can improve their speed directly into the wind by sailing freer. This is especially true of multihulls which might fare badly under the Gimcrack procedure's predictions.

I am glad to report that various people recognise the need for more accurate coefficients and are taking steps to produce them. The writer has a number of suggestions which are described in the section that follows.

Suggested Replacement for the Gimcrack Coefficients

Any new effort to determine sail force coefficients should be improved in method and made more encompassing than the Gimcrack Coefficients. For example, all courses should be included, not just one hard on the wind. The optimum angle of attack for the sails should be specified for any course. This would include the highest pointing course of which a hull is capable or, in other words, the hull's smallest possible drag angle without "stalling". For highest pointing, no one sail adjustment suffices for all hulls. The same holds true for the best "speed made good" to windward and the course it requires.

In all that follows, we must thoroughly understand the "Course Theorem", as previously mentioned, and what is meant by a sail or a hull drag angle. It is this new theorem that has made possible a better and simpler understanding of technical sailing. A hull drag angle, geometrically, is the angle between the direction of the total sail force or the hull resistance and an abeam perpendicular to the hull's course, not to the heading. A sail drag angle is the angle between the same total sail force and a perpendicular to the direction of the apparent wind. The course angle to the apparent wind can be proved to be the sum of the sail and hull drag angles as will be seen later in Fig. 2. This produces the exact angular opposition required between the sail force and hull resistance.

Sails can be compared, at any sail drag angle, based on only their own coefficients. These sail coefficients can be obtained, for all sail drag angles and quite independent of wind speed, from wind-tunnel tests or from full-size tethered tests which the sailing amateur can perform. For accuracy, a procedure must be provided which takes account of the parasitic windage on hull and rigging. The full-size tethered type of sail tests produces such results without extra effort.

The Gimcrack Coefficients compare hulls, on one windward course only, by assuming that they use one standard type of sail plan and adjustment. Various hulls can be compared more simply by examining only their own coefficients, for all given hull drag angles and hull speeds but independent of a sail's drag angle. Data then would be available for a hull on all courses and any sail plan, not simply running and hard on the wind with a Gimcrack type of sail, as at present.

The towing tank should be equipped for hull total force measurements versus any hull drag angle and speed within range. The towing force, at a known angle to the course, should be applied through a point equivalent to the sail's centre of effort. The model hull should have no angular attitude restraints whatever. This is particularly true in waves or when any degree of "snaking" is present due to the stern vortices which so often occur. The hull will self-adjust its own angular attitudes of heel, pitch and yaw.

A method should be available for combining both the sail and the hull coefficients to predict overall performances on any course, over a range of wind strengths. The speed data could be plotted in polar diagrams of course in respect to both the true and the apparent winds.

A simple graphical method for obtaining the *optimum* speed made good to windward is possible, not merely a speed made good on a single course as in the Gimcrack method. This best speed made good to windward requires an optimum adjustment of sail angle and hull course as will be described later.

All of the above recommendations are accomplished in the following suggested procedure:

Fig. 2 shows the aeronautical type of equation and plotted sail data obtained from tethered tests on a full-size International 12-ft Dinghy. This is a polar curve of the sail total coefficient C_S versus the angle between its force direction, O-C_S, and the direction of the apparent wind source, O-A. Note that this angle is always greater than 90 degrees. The sail's angles of attack are marked along the curve.

Also shown is the corresponding drag angle for the sail, δ_S. It is the angle between the force direction O-C_S and O-Y, a perpendicular to the apparent wind direction. By definition, the tangent of this angle equals the sail coefficient drag component C_{SD} over the sail coefficient lift component C_{SL} or D_S/L_S.

C_S is an aeronautical type of coefficient to enable comparison with known aircraft data. Also, the above mentioned tethered type of sail testing was described in Chapter I. Improved directional stability can be obtained with a Y-shaped bridle attached to bow, stern and mooring.

Fig. 2 shows a graphical method for the determination of optimum sail values, C_S, C_{SD}, C_{SL}, δ_S and α for any given course of the hull in respect to the apparent wind. As an example, there is drawn a boat's course assumed as being 45 degrees from the apparent wind.

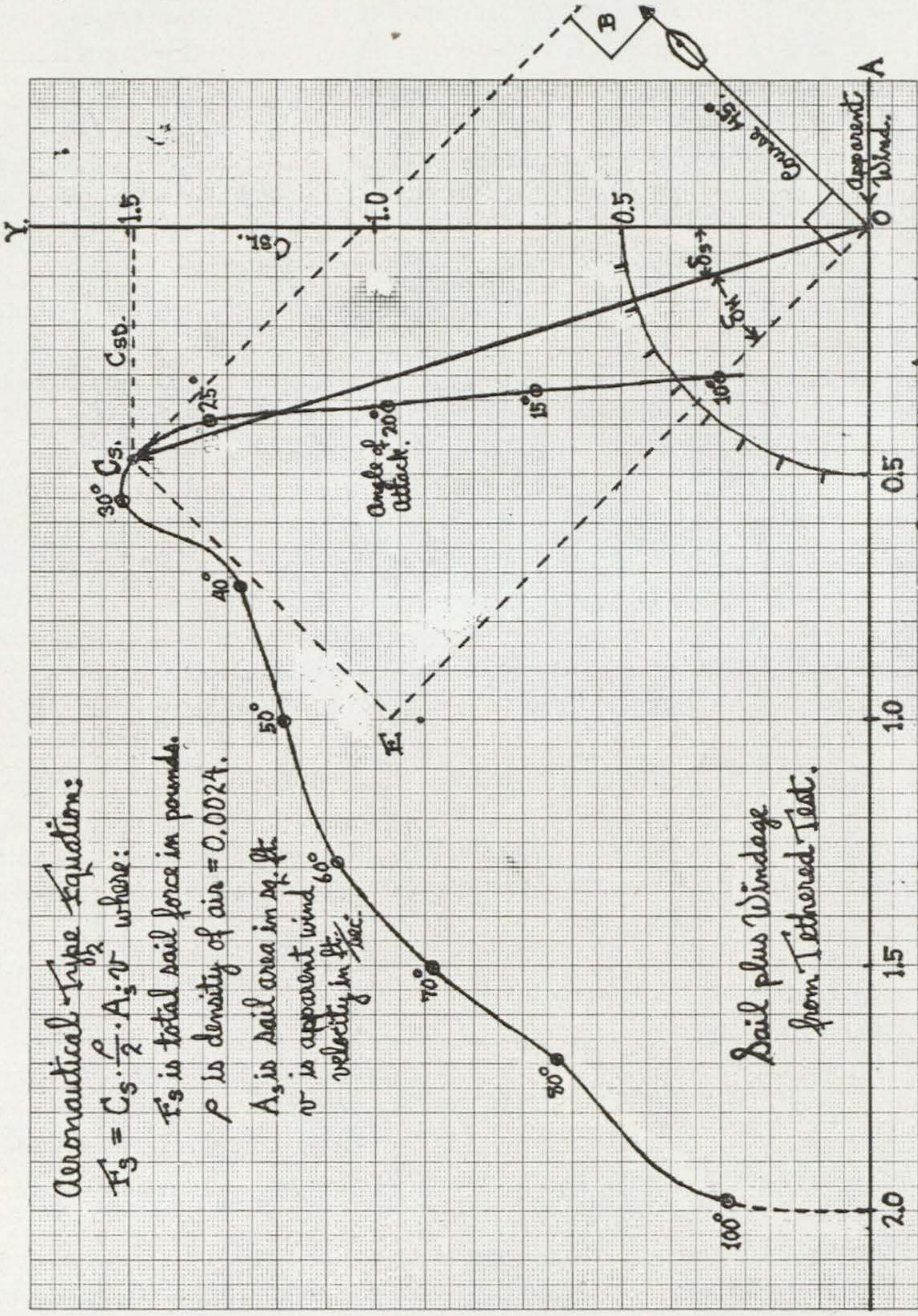


FIG. 2. Polar Plot of Total Sail Coefficient C_S for International 12-ft. Dinghy.

The best values of C_S and angle of attack of the sail, for any course, are those which produce the largest component of sail force in the direction of the hull's travel. This optimum driving component O-B can be obtained graphically by means of the dotted line, B-C_S which is simultaneously perpendicular to the course and tangent to the curve of coefficients. The point of tangency, C_S, determines the magnitude of all the above desired values.

From the "Course Theorem", we know that the course angle must equal $\delta_S + \delta_H$. From a graphical construction, the sail drag angle δ_S has been determined. Obviously, the required drag angle for the hull, δ_H, can be obtained by subtraction. It can be represented also by a graphical construction as follows:

In Fig. 2, the dotted line O-E is drawn perpendicular to the boat's course O-B. As previously described, the angle δ_H, between this line and the sail force direction O-C_S, is the required hull drag angle.

Adding the indicated drag angles δ_S and δ_H, in Fig. 2, gives a graph angle equal to the drawn course angle to the apparent wind. This can be proved by the fact that the enclosing lines of these summed adjacent angles are respectively perpendicular to the apparent wind line and the boat's course line, therefore their included angles are equal. Thus the "Course Theorem" is proved.

Precisely as was done for the course angle of 45 degrees, in Fig. 2, the procedure was repeated for a range of all possible course angles from 36 to 180 degrees. The results are listed in Table II together with certain comments. There is added, in that table, the sail's best adjustment if it were on an ice-boat, rather than on a water-craft. This demonstrates that a sail must be adjusted depending on the hull for highest pointing. A fixed adjustment, as used in the Gimcrack procedure, seems in error.

The contents of Table II are plotted in Fig. 3. Here are expressed all of the sail's optimum parameters and the drag angle that is required of the hull for any course.

In the design of a towing tank, the writer prefers towing the model with a cord and falling weight rather than by an overhead carriage on rails. A falling weight provides a constant force whereas the carriage achieves a constant speed. Constant force permits studies of acceleration and other non-steady-state phenomena such as hull "snaking" and motion in waves.

A falling weight system can easily produce a towing force through a location equivalent to the centre of effort of the sails. Important is the fact that the force can be at any horizontal angle to the hull's course. The hull seeks its required attitudes of heel, pitch and yaw automatically. There is no tiresome "fooling around". Possibly a carriage system can be modified to do many of these things also.

Fig. 4 shows the hull coefficient K_H versus towing angle δ_H plotted for two chosen speed-length ratios. Note that changes are not great with varying speed. There would be no appreciable difference if it were not for wave-making. As the towing angle is measured from a horizontal perpendicular to the course, it becomes equal to the hull drag angle, δ_H. The required

TABLE II
International 12-ft Dinghy *Sail* including Hull Windage

Comments	Course to apparent wind $\delta_S + \delta_H°$.	Sail drag angle $\delta_S°$.	Required hull drag angle $\delta_H°$.	Sail angle of attack $\alpha°$.	Equivalent aero-nautical total sail coefficient C_S.
An ice-boat adjustment	17° smallest possible	17° smallest possible	0°	25°	1·39
Highest course and best speed made good to windward	36°	18°	18° smallest possible	28°	1·51
	45°	19°	26°	29°	1·56
	60°	21°	39°	30°	1·61
	90°	21°	69°	30°	1·61
	120°	21°	99°	30°	1·61
Sail stalled	150°	75°	75°	85°	1·90
Sail stalled	180°	90°	90°	90°	2·00 (windage adds)

Above plotted on Fig. 3.

hull drag angle for each course, for the dinghy being measured, is obtained from a curve shown in Fig. 3.

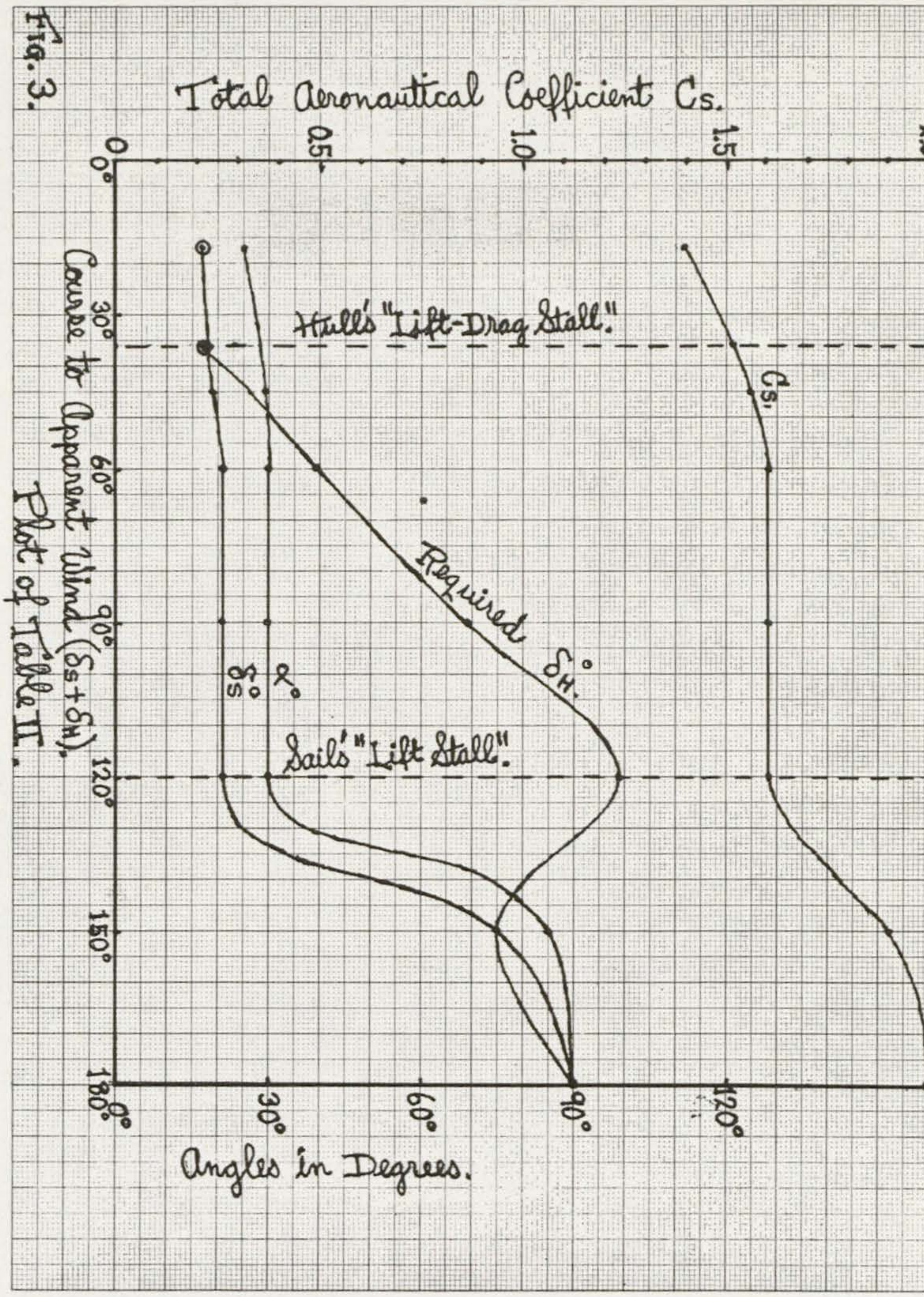
Whereas an aeronautical type of coefficient C_S was used for the sail, to enable comparison with aeronautical data, a hull coefficient of this type would be more complicated than need be. It is difficult to accurately measure wetted surface area due to wave-making which varies with each speed. For this reason, a simpler type of hull coefficient is used. It is in terms of the hull weight W in pounds rather than wetted area. Also, the total resistance R_T is in pounds and the boat velocity V_B is in knots. This new coefficient will be called K_H rather than C_H because of these differences. It has been derived in other writings (Chapter XXI) as being:

$$\frac{R_T}{W}\ \% = K_H \cdot \frac{V_B^2}{W^{1/3}}$$

$$\text{Thus, } K_H = \frac{100 \cdot R_T}{W^{2/3} \cdot V_B^2} \text{ where } R_T = F_S$$

Also for sails in air and an apparent wind V_A in knots,

$$C_S = \frac{293 \cdot F_S}{A_S \cdot V_A^2}.$$

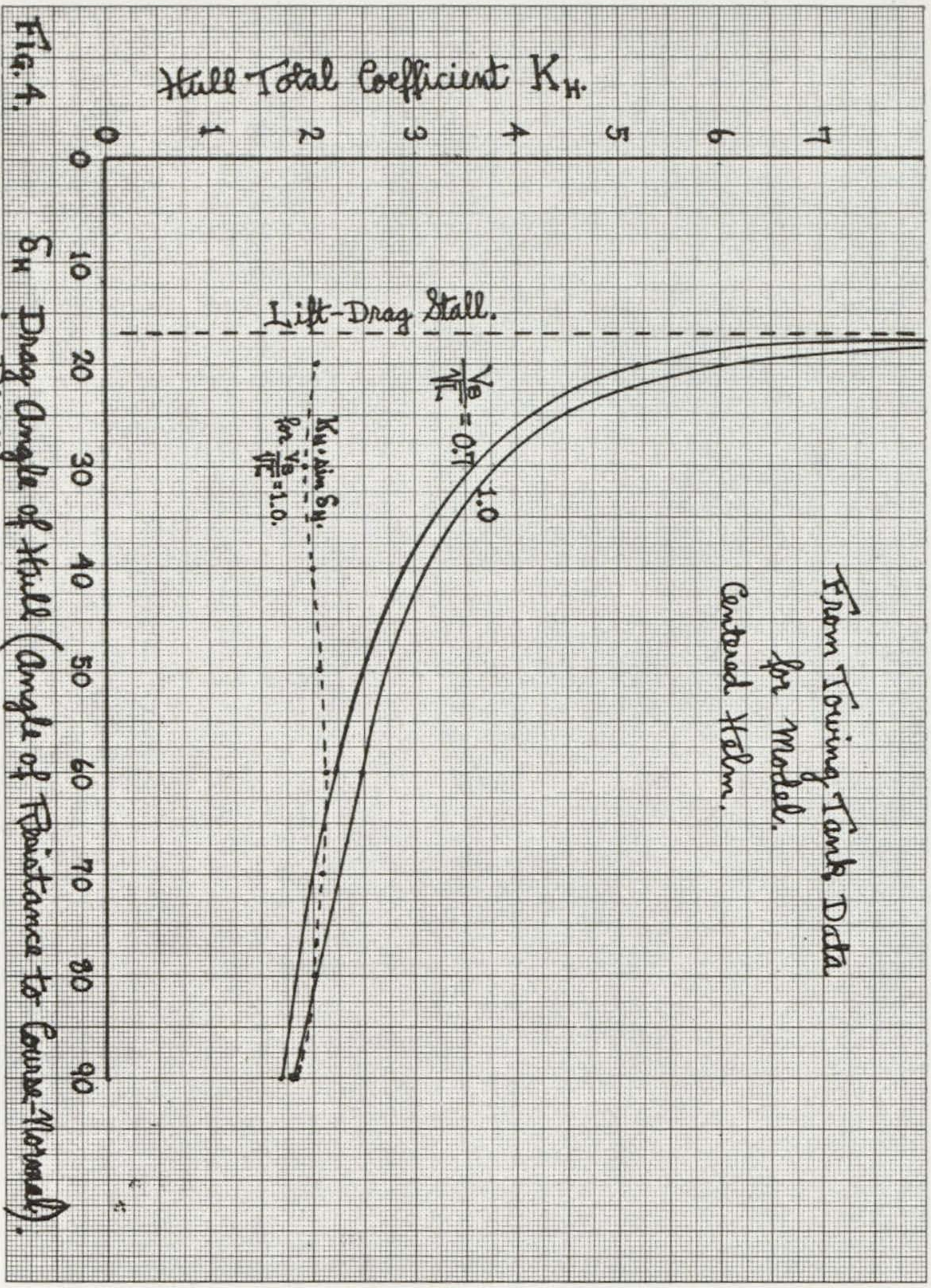


Combining and reducing,

$$\frac{V_B}{V_A} = 0{\cdot}585 \ \frac{\sqrt[2]{A_S}}{\sqrt[3]{W}} \cdot \sqrt{\frac{C_S}{K_H}} \qquad \text{(A)}$$

for any given $\dfrac{V_B}{\sqrt{L}}$ and course.

Equation (A) is highly important since it predicts a sailing craft's overall performance in terms of the ratio of boat speed to apparent wind speed on any



course. One must know only the sail coefficient and the hull coefficient at a given $\frac{V_B}{\sqrt{L}}$, also the sail area and craft weight.

Using equation (A), Table II, Fig. 4, together with a sail area of 80 sq ft and a weight with crew of two totalling 507 lbs, permits calculating the overall performance for all courses. A polar curve of the results constitutes the right-hand apparent wind portion of Fig. 5. The left-hand, true wind portion of Fig. 5 was obtained from the following two conversion formulas:

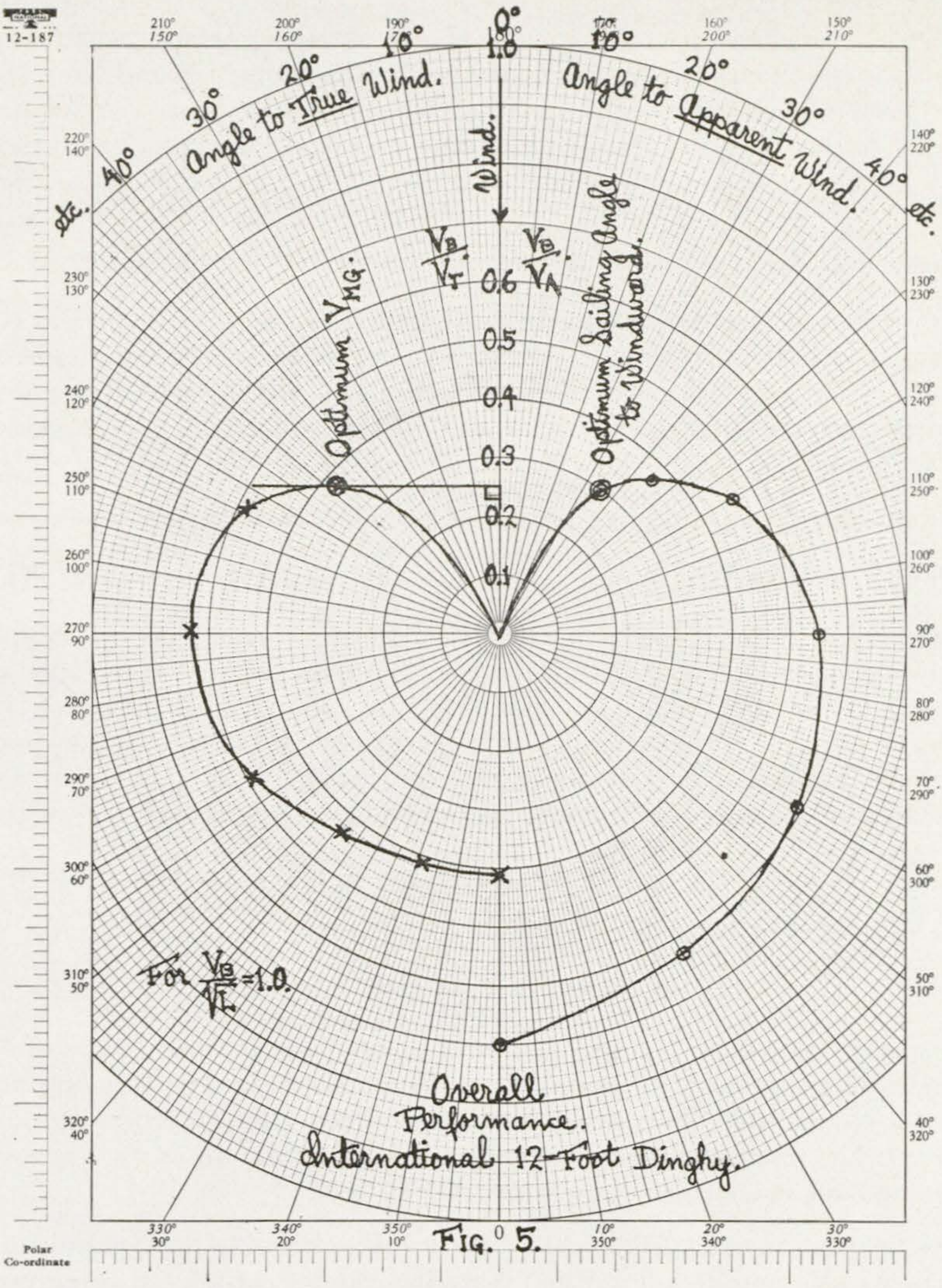


FIG. 5.

$$\frac{V_B}{V_T} = \frac{V_B \big/ V_A}{\sqrt{1 + \left(\frac{V_B}{V_A}\right)^2 - 2\,\frac{V_B}{V_A}\cos\left(\delta_S + \delta_H\right)}}. \tag{B}$$

Where the true wind to course angle is γ°,

$$\tan\gamma = \frac{\sin\left(\delta_S + \delta_H\right)}{\cos\left(\delta_S + \delta_H\right) - \frac{V_B}{V_A}}. \tag{C}$$

On the left-hand true wind curve of Fig. 5, is a graphical construction which is simultaneously perpendicular to the wind direction and tangent to the performance curve. The point of tangency determines the required course to the true wind and its speed ratio to produce the best "speed made good" directly into the true wind. The latter value, in terms of $\frac{V_B}{V_T}$, equals 0·25 for $\frac{V_B}{\sqrt{L}} = 1$, read at the intersection of the perpendicular with the wind direction. Converting this course, by means of equation (C), to the apparent wind reference, the course to steer is 35 degrees to the apparent wind, as marked on the right. Any attempt to achieve this result with a fixed course and sail adjustment, as in the Gimcrack method, seems subject to serious error.

Returning to equation (A), giving the overall performance, it is seen that the ratio of the fixed values $\frac{\sqrt[2]{A_S}}{\sqrt[3]{W}}$ is vital to the performance. When the coefficients for a hull and sail are unknown, a good "rule of thumb" criterion of its potential performance is this ratio, where W includes the weight of the crew. Being dimensionless, this ratio is independent of size. This is not true of the ratio of weight per square foot of sail used by some authors. The writer uses the stated ratio for cataloguing all sailing craft. It is remarkably consistent with known performance comparisons.

The ratio of total coefficients $\frac{C_S}{K_H}$, in equation A, is identical with the ratio of their drive and resistance components $\frac{C_S \,.\, \sin \delta_H}{K_H \,.\, \sin \delta_H}$. K_H sin δ_H for $\frac{V_B}{L} = 1{\cdot}0$ is plotted with dotted lines in Fig. 4. Since this resistance component is nearly constant, especially over small ranges of δ_H, maximizing only the drive component by graphical means to obtain optimum speed, is warranted. This is within the accuracies of the empirical measurements. The resistance component is not precisely constant as its drag angle is varied due to a change in the water flow-pattern.

A further use of equation (A) is that it makes possible the determination of hull coefficients at full size and quite independent of the sail being used. Full size towing is not necessary. $\frac{V_B}{V_A}$ for the course and speed is determined from full size performance tests, as described in Chapter XIV. C_S for the course is determined by full size tethered sail tests as described in Chapter I. By substituting all of these values, for the course, into equation (A), one can solve for the unknown value of K_H for any course.

Such coefficients could be compared with those of competitive hulls. Also the accuracy of hull coefficient determinations, by corresponding models tested in a towing tank, can be assessed. This is seldom done in current practice.

Final Remarks

It seems quite proper that all of us might use the best technical procedures available even if faults are known to exist. The results could be more useful than none at all. The Gimcrack Coefficients possibly have been in this category all these years.

If my criticisms were to be merely destructive, this article never would have been written. As reasonable and supposedly improved methods are now proposed, I hope that my criticisms of the Gimcrack methods will be considered constructive.

CHAPTER V

SPEED MADE GOOD TO WINDWARD

Reprinted from AYRS 70, Nov. 1969

by Edmond Bruce

The following discussion may startle many sailors. Theoretically, a sailing-craft may be too fast for achieving any worthwhile "speed made good" to windward! One had better slow it down by reducing the sail area! An optimum sail area exists, for windward work, even when heeling is not the sail limitation. This discussion also will provide the magnitudes that are missing from the "course theorem" which is only angular in content.

For understanding, one must be familiar with the well-known sailing vector triangle. It is shown in Fig. 1 with all of its components labelled. $\beta°$ is any course angle to the apparent wind, for the boat. This, in turn, is the sum of the drag angles of the sail and the hull, according to the "course theorem". $\gamma°$ is the course angle to the true wind. V_B is the vectorial boat speed, showing magnitude and direction. V_A is the vector speed of the apparent wind while V_T is, likewise, the speed and direction of the true wind. V_{MG} is the desired "speed made good" directly into the true wind.

Knowing the sum $\beta°$ of the minimum possible drag angles, also the specified boat speed V_B and the true wind V_T, the entire triangle can be completely determined. This is true providing that there is the proper amount of sail area to drive the boat at the speed specified. Any greater sail area would cause hull stalling. Thus there is an optimum sail area.

As an example, suppose that we have a very fast, non-heeling multi-hull having a large, but variable, sail area and light-weight hulls. Assume, for example, that the minimum drag angles for the sail and for the hull are each 15°. Then the minimum possible course angle $\beta°$ to the apparent wind becomes 30°.

A lesser angle would encounter either a hull or a sail stalling condition. These are quite practical angles, not exceptionally low values.

Due to a sufficiently large sail area and the light hull weight, assume, as shown in Fig. 2A, that the resulting speed ratio $V_B/V_T = 1{\cdot}73$. This was chosen so as to have a convenient 30°–60° right triangle. Because it is a right triangle, as shown, the "speed made good" to windward is zero on its highest pointing course!

Suppose the sail area is reduced somewhat so that the speed ratio becomes $V_B/V_T = 1{\cdot}50$, in the same true wind V_T, as shown in Fig. 2B. The class 'D' Catamaran *Wild-Wind* and several Class 'Cs' are supposed to have achieved this ratio. Thus all this is not fantasy. We are discussing today's developments. For similar shaped sails, there is no reason to believe that less sail area changes the sail's minimum drag angle, therefore the minimum course angle, $\beta° = 30°$, is as before. As a result, the "made good" ratio now is increased to $V_{MG}/V_T = 0{\cdot}28$ from the previous zero.

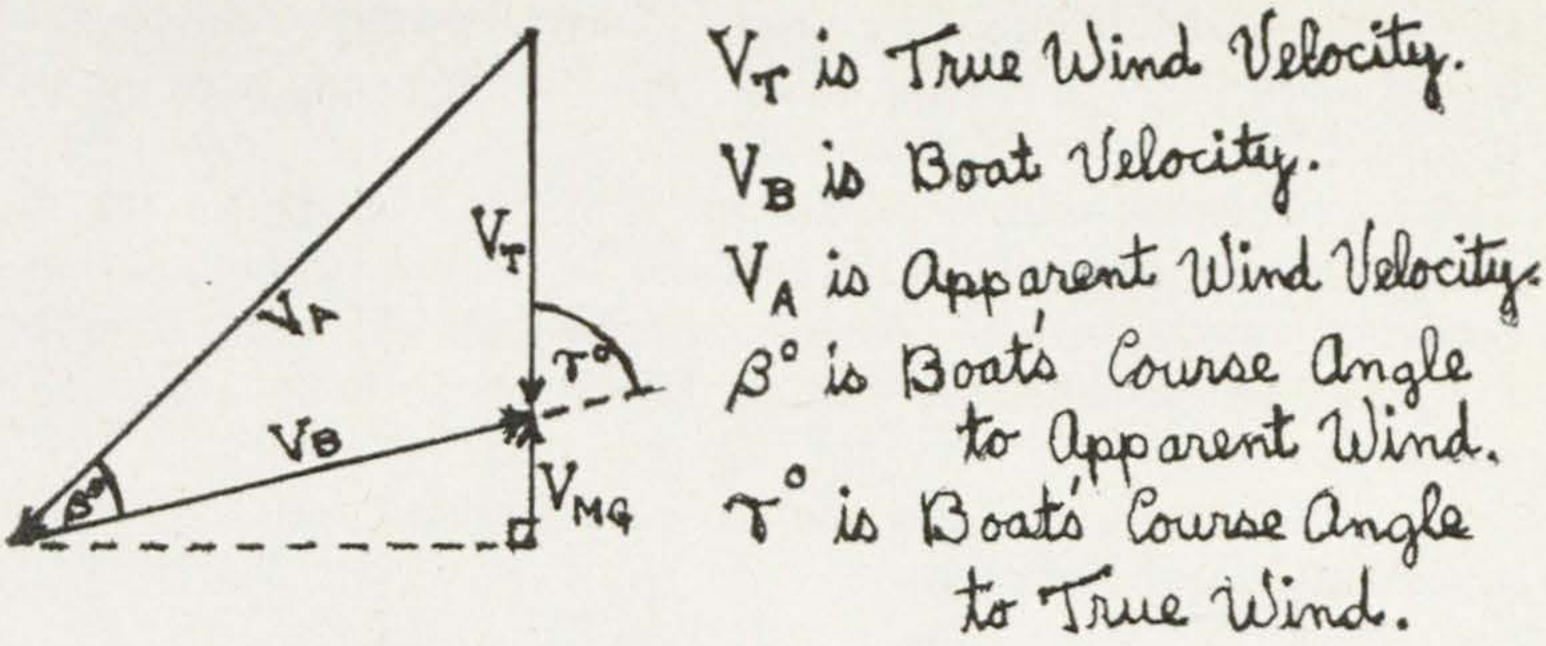


Fig. 1

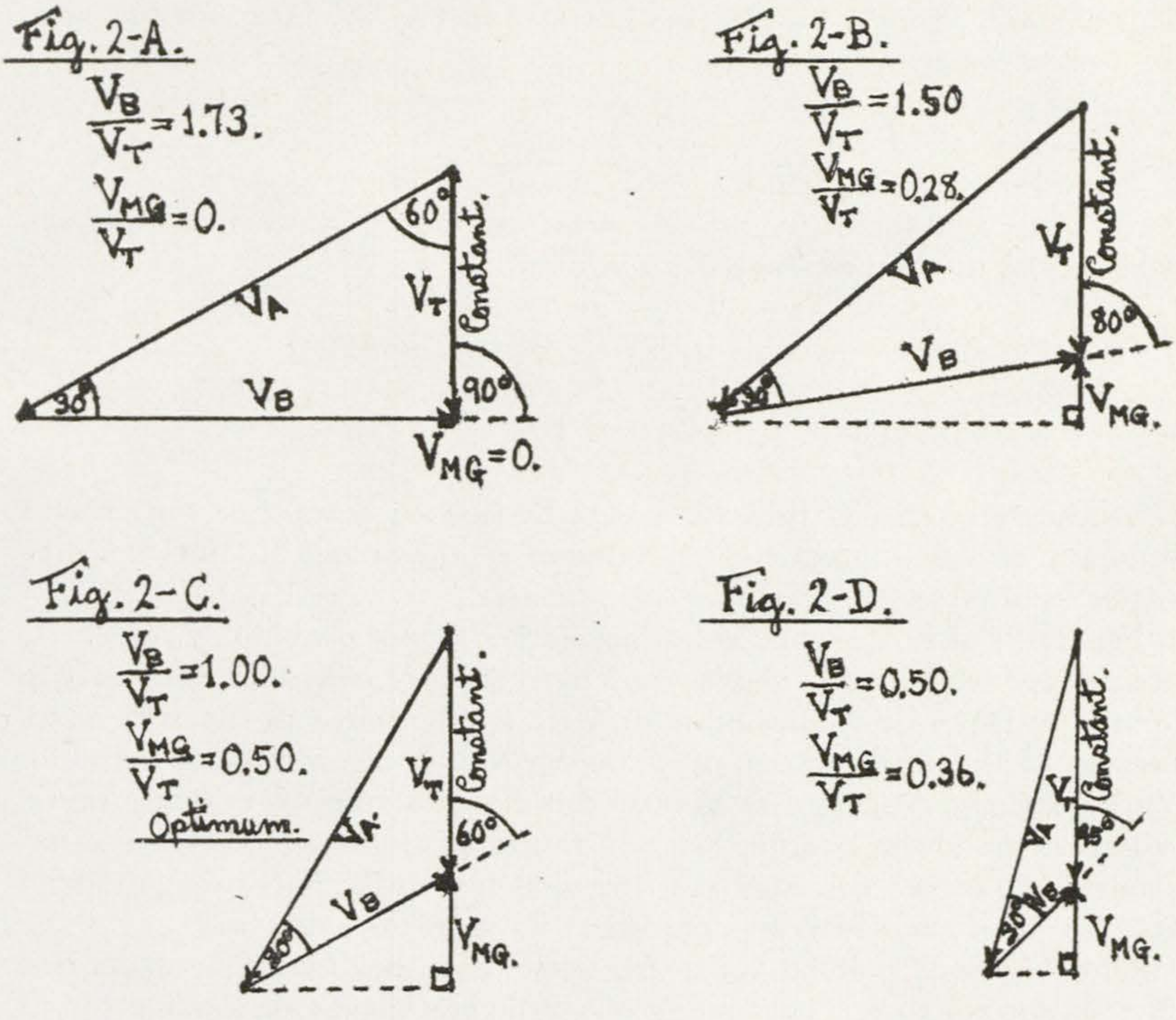


Fig. 2

In Fig. 2C, the speed is further reduced to $V_B/V_T = 1{\cdot}00$ by a still smaller sail area. Now $V_{MG}/V_T = 0{\cdot}50$, a substantial increase. In Fig. 2D, a further sail reduction causes $V_B/V_T = 0{\cdot}50$. Now one obtains only $V_{MG}/V_T = 0{\cdot}36$, therefore the sail reduction has been carried too far. The case where $V_B/V_T = 1{\cdot}00$ and $V_{MG}/V_T = 0{\cdot}50$, as shown in Fig. 2C, can be proved to be the optimum situation for $\beta° = 30°$.

We have not been aware of the advantages of variable sail area, in practical sailing, because our sails have been, generally, on the skimpy side. This was forced upon us by a heeling limit. Non-heeling configurations will change this.

A mathematical analysis of all this is at hand but seems too involved to interest the majority of AYRS readers. It requires differentiation of transcendental functions, etc. One can simply scale the vectors and angles, of Fig. 2, for an easy check, if desired. However, the final results can be stated mathematically.

For any minimum course angle $\beta°$, the largest "speed made good", that is possible, can be written:

$$\frac{V_{MG}}{V_T} = \tfrac{1}{2}\left(\frac{1}{\sin\beta°} - 1\right).$$

This equals 0·50 for $\beta° = 30°$, as illustrated in Fig. 2C. Also, for this case, the boat speed is:

$$\frac{V_B}{V_T} = \tfrac{1}{2}\left(\frac{1}{\sin\beta°} - 1\right)\frac{1}{\cos\gamma°} = \frac{V_{MG}}{V_T}\cdot\frac{1}{\cos\gamma°}.$$

This equals 1·00 for $\beta° = 30°$, as shown. As for $\gamma°$, in previous equation, when achieving the best "speed made good":

$$\tan\gamma° = \frac{1}{\tan\beta°\left(\dfrac{1}{\sin\beta°} - 1\right)} \text{ or } \gamma° = 45° + \frac{\beta°}{2}.$$

It can never be smaller than 45° except by slowing down. See Fig. 3 for a summary of V_{MG} curves for any value of $\beta°$. Lowering $\beta°$, thus the drag angles, is always beneficial.

Fig. 2D is of further interest in that, rather than showing only the effects of a sail reduction, it also shows, for a fixed sail area, why it does not pay to "pinch" when sailing to windward. It is sailing closer to the true wind, because of the smaller value of $\gamma°$ for V_B/V_T. It has a reduced value for V_B/V_T and also V_{MG}/V_T as compared to the optimum. Note that it is still sailing at the lowest possible sail and hull drag angles, since they are unchanged. $\beta° = 30°$ as before. It is the reduction in the boat's magnitude of speed V_B that altered the apparent wind V_A so as to enable this.

John Morwood pointed out to me that a boat may be sailing at its best drag angles whether it is pointing on its highest course or striving for its best V_{MG} by sailing slightly freer. It was only after the above calculations that I realised that this was possible.

This statement is important. On *any* course, the sail area should be increased until the minimum possible apparent course angle $\beta°$ is reached, for highest speed. This establishes the optimum sail area when non-heeling foils are employed. The actual sail area must be obtained from empirical curves of sail and hull as in the writer's article in the previous chapter. Such curves also reveal the drag angles.

The vector triangles, of Fig. 2, can be found to illustrate why a slower

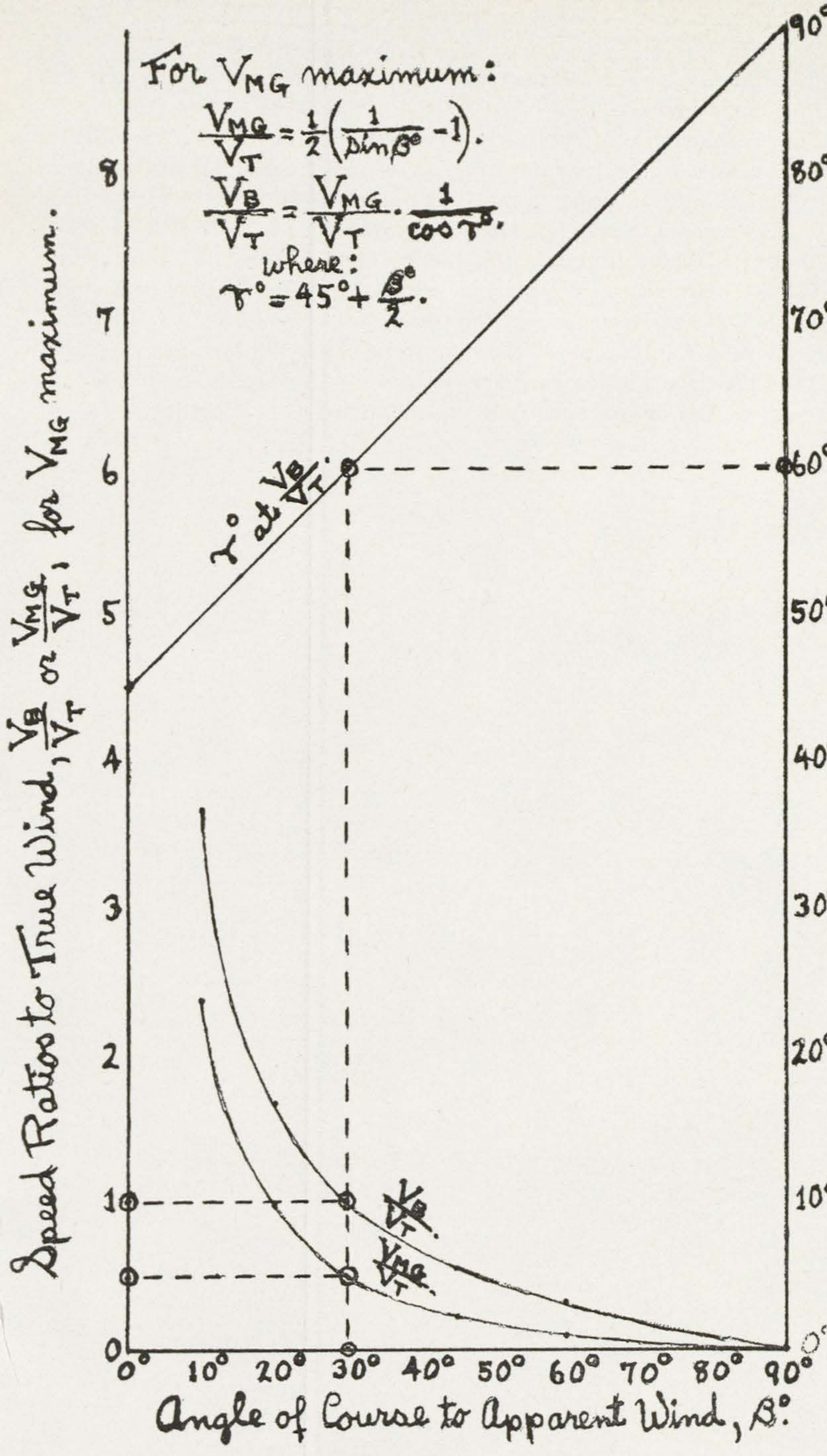

For V_{MG} maximum:
$\frac{V_{MG}}{V_T} = \frac{1}{2}\left(\frac{1}{\sin\beta^\circ} - 1\right)$.
$\frac{V_B}{V_T} = \frac{V_{MG}}{V_T} \cdot \frac{1}{\cos\gamma^\circ}$.
where:
$\gamma^\circ = 45^\circ + \frac{\beta^\circ}{2}$.
γ° at $\frac{V_B}{V_T}$.
$\frac{V_B}{V_T}$.
$\frac{V_{MG}}{V_T}$.
Speed Ratios to True Wind, $\frac{V_B}{V_T}$ or $\frac{V_{MG}}{V_T}$, for V_{MG} maximum.
Angle of Course to True Wind, γ°, for V_{MG} maximum.
Angle of Course to Apparent Wind, β°.
0
1
2
3
4
5
6
7
8
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°

Fig. 3

boat often can point higher, to the true wind or a mark, than a faster boat but the former loses in V_{MG}.

Mr. Bert Goldstone, of Sudbury, Massachusetts, U.S.A., a member of AYRS, has been working, for some time, on related analyses. He has obtained, among other things, an upper limiting speed along any course for an ideal boat. It gives a goal to strive for. He also pointed out the truth that the locus of the apex of $\beta°$ is always a circle if $\beta°$ and V_T are held constant. This greatly simplifies the mathematics required by employing the geometry of a circle. Possibly we will hear from him in the future.

Does the reader still insist on claiming to be expert on how to best sail to windward? We have a lot to learn yet. This is what makes sailing technology so interesting. Any discovery or new understanding is exhilarating.

CHAPTER VI

OPTIMUM SIZES OF CENTREBOARDS

Reprinted from AYRS 41, Oct. 1962

by Edmond Bruce

During September 1961, the writer observed, from his cruiser, two of the International Catamaran Races on Long Island Sound, U.S.A. These races were between the British *Hell-Cat* and the American *Wild-Cat.*

There followed a lot of spoken and written discussion saying that *Hell-Cat* was superior to windward because of a higher aspect ratio sail rig. Personally, I do not believe there was a marked advantage in either sail rig. From my towing tank experience, I feel it was those large wooden centreboards on *Hell-Cat*, compared to its rival's smaller boards, which provided the difference in windward performance.

As to the sails, the actual areas were the same for both boats. Also the foot of both mainsails appeared to be about the same length. Merely transferring a small narrow strip of cloth from the head of *Hell-Cat's* mainsail to the roach, as in *Wild-Cat*, should make a negligible difference in sailing to windward.

As to centreboards or centreplates, many catamarans need larger boards than conventional hulls since, when shallow, rounded hull sections are used, they have lost their lateral grip on the water. Tank tests show that then their maximum lateral lift-drag ratio is less than 2·2, without their centreboards lowered. Hulls designed to favour running resistance differ in shape from those where the design gives preference to windward performance.

There is no reason why a rounded section catamaran cannot be designed to point as high or higher than conventional sailing craft provided two things are done:

First, the hull windage should be reduced by "turtle-back" bows and "tumble-home" elsewhere above the water-line. Over-hanging sitting platforms must be abandoned.

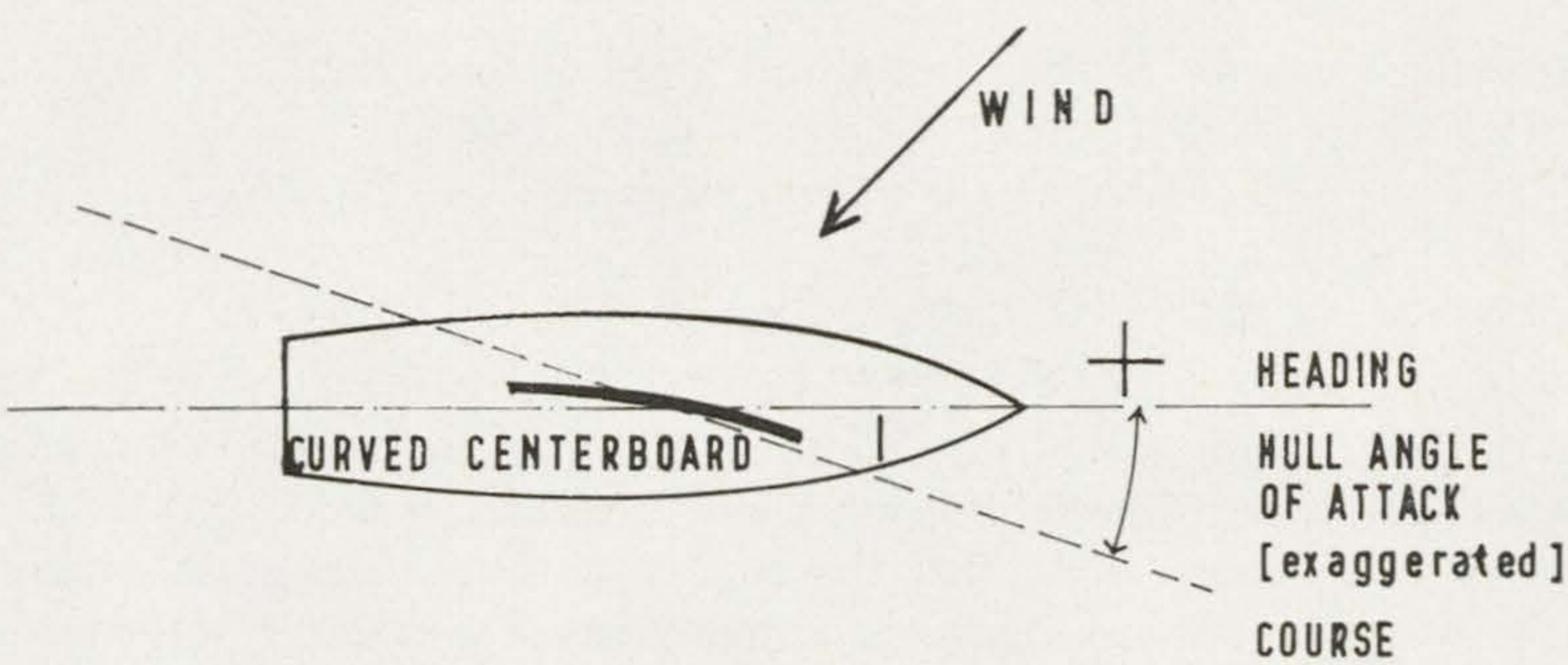


Fig. 1

C

Second, a greater than optimum size, adjustable centreboard should be fitted to complement the lift-drag characteristics of the hull. The board should be well-formed, well-located and adjusted to a proper angle of attack. Strange as it may seem, this optimum angle with the boat's centreline is often negative rather than positive when curved plates or foils are used rather than flat plates. The failure of some attempts at angled boards has been due to this discrepancy. Negative angles result when the optimum angle of attack of a centreboard is less than the angle of attack of the hull. See Fig. 1.

In the belief that the average reader prefers graphical explanations rather than mathematical, the writer has devised the graphical method shown in Fig. 2. It will be advantageous to use combined lifts of hull and centreboard in the presence of their least combined drags. By plotting the centreboard lift and drag components in the upper right hand quadrant and those of the hull in the lower left hand quadrant, we have a graphical layout that automatically adds the separate lifts and drags and also shows the respective optimum angles of attack for each. It also indicates the optimum area of the centreboard for the fixed speed as stated. In general, larger centreboards are desirable at greater speeds due to the rapidly rising resistance of the hull.

Fig. 2 was drawn for the hull speed of three knots through the water simply as an example of the method. The scales of lift and drag, as drawn, are not the same. This is to permit a less crowded diagram. At a higher hull speed, the centreboard curve would have its shape unchanged if the coordinate labels were increased by the square of the speed ratio. However, the drag of the hull curve would increase at a greater rate, due to wave-making. This would require a different hull curve.

Assume that a rectangular flat plate is to be used as a centreboard. Its depth is to be three times its fore and aft dimension. Due to the presence of the hull, preventing an end-effect, the aspect ratio is 6, by the theory of images. Examining NACA Reports for such a foil, the coefficients of lift C_L and drag C_D, for various angles of attack α°, are extracted as follows:

Angle α°	0°	2°	4°	6°	8°	10°	12°
C_L	0·00	0·14	0·26	0·39	0·52	0·64	0·73
C_D	0·035	0·037	0·042	0·059	0·085	0·123	0·161
L/D	0·0	3·8	6·2	6·6	6·1	5·2	4·5

Now for either lift or drag and a hull speed of three knots (5·1 ft/sec),

$$\text{Pounds} = C \times (\text{Density}/2) \times \text{area sq ft} \times (\text{ft/sec})^2$$

where area is for one side only.

or

$$\text{Pounds} = 25{\cdot}8 \times C \times \text{area sq ft}$$

for three knots in sea-water.

In the upper right part of Fig. 2, the lift and drag, in pounds versus angles of attack, have been plotted for centreboard areas of 3, 6 and 9 sq ft for a hull speed of three knots. Note that the curves of the several areas intersect. This proves that optimum centreboard area exists. For example, if the centreboard alone is asked to develop 50 lbs of lift to counteract sail forces, it can

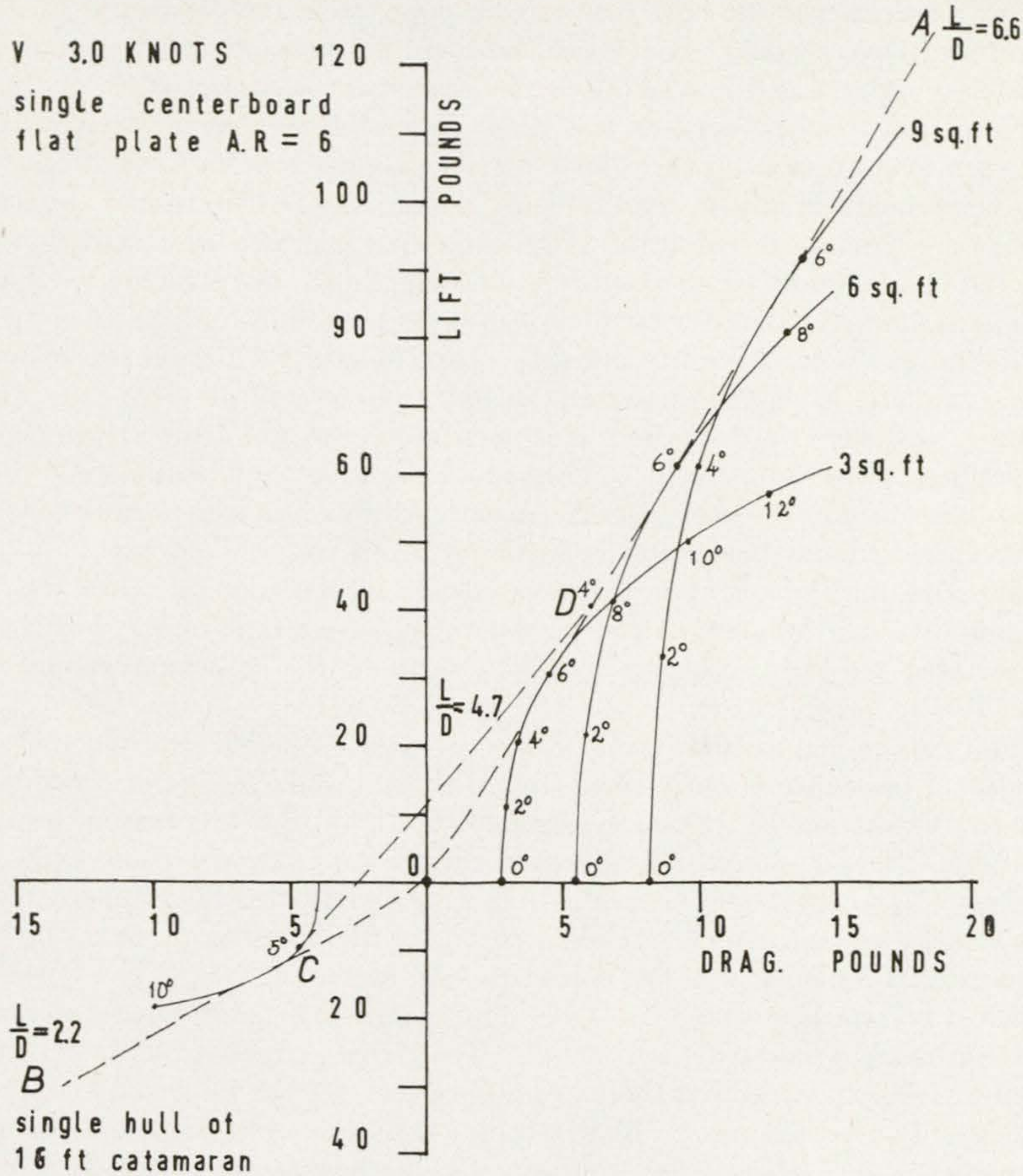


Fig. 2

do this with less drag when 6 sq ft of area is used rather than either 3 or 9 sq ft.

Notice that dotted line O-A represents the highest possible ratio of lift/drag = 6·6 for these centreboards. Also, the optimum angle of attack for all areas, beside those drawn, is 6 degrees, the point of tangency of the dotted line O-A with the curves. Dotted line O-B, in the lower left of the sketch, is the maximum lift/drag = 2·2 for one of twin hulls having shallow, rounded sections. The catamaran hull curve was extracted from towing tank model data of a typical form of such a hull 16 ft long, L/B = 8 and a prismatic coefficient of 0·54.

Of course, for the complete boat, the optimum lift-drag ratio of the centreboard alone will be degraded by the drag of the hull. However, an amount of lift from the hull can be used advantageously so that, for a 50 lbs overall lift, the least possible overall drag is encountered. The dotted line C-D is the writer's estimate of the best that can be done, with the 50 pound lift, in minimising overall drag. The overall hull and centreboard lift-drag ratio of line C-D appears as 4·7, which is better than many catamarans.

Note that the best area of the single centreboard now is intermediate between 3 and 6 sq ft for the 3 knot speed. Also, the best angle of attack for the centreboard is still 6 degrees while that of the hull is near 5 degrees. These are so close to being the same angle that a centreline installation of the flat board should be satisfactory. Since Fig. 2 is drawn for only one hull, this area should be doubled to about 9 sq ft for twin hulls.

If the reader plots the lift and drag characteristics of a good foil instead of a flat plate, using the same hull, an improved overall lift-drag ratio may result. However, the increased sensitiveness of the foil's correct angle of attack may cause adjustment trouble and a negative angle to the centreline may be required for optimum performance. All this has been seen in towing tank measurements before this confirming theory was worked out.

Whereas the above graphical analysis produced a prediction of 4·7 for the overall lift-drag ratio, a tank test on the model gave a ratio of 4·3. For those who insist on high accuracy in the calculation, the following should be noted:

Foil data in aeronautical text books is for high Reynolds' Numbers where frictional resistance is quite small. At sail boat speeds, Reynolds' Numbers are low and therefore frictional resistances are high. For this reason, greater accuracy can be obtained if the aeronautical foil frictional resistances are calculated and subtracted from the drag values. Then the boat foil frictional resistances are calculated and reinserted into these values of drag. In the interest of simplicity, this has not been done in Fig. 2.

Most present day catamarans have centreboards which are much too small for optimum windward performance. The driving force of a model of a well-known catamaran was increased 20 per cent, for the same sail force, and the speed increased nearly 10 per cent, on a course 40 degrees from the apparent wind, when larger, improved centreboards were installed. Full size hull speed was originally 5 knots, in this case.

Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 66A, Oct. 1968
Modified Feb. and Oct. 1973

July 8, 1968

Dear John,

I am completely in agreement with your interest in low aspect ratio keels and centreboards, provided that it is not over-done. Over the years, I have varied many times the aspect ratio of keels and centreboards, as well as their area, on models in the towing tank. Always I have obtained the same answer. When an optimum area and angle of attack are employed, the best aspect ratio is approximately 1·0.

The above aspect ratio is not at all in accord with the teachings of subsonic aerodynamics. I believe that I know why. An air-foil or sail is deeply immersed with oceans of air above. There is no appreciable difference in static pressure between their top edge or bottom edge even when in a vertical position. Thus the top edge has nearly 100 per cent of the static pressure of the bottom edge.

For a surface-piercing vertical hydrofoil or rudder, the static hydraulic pressure of the top edge is 0 per cent of that of the bottom edge. Thus, the pressure distribution for air-foils and shallow water-foils is entirely different. Therefore their theories are *not* equivalent. Of course, dynamic pressures add to or subtract from these static pressures to get the total pressure differences between the two sides of a foil. The water surface-level adjusts accordingly.

If the depth to the top of a board is enough to assure ample hydrostatic pressure, centreboard size is easily calculated by equating the sail side-force to the board sideways lift, when hard on the wind. This assumes that the hull does not contribute appreciably to the side resistance. The result is the formula:

$$\frac{\text{Sail area}}{\text{Board area}} = 257 \left(\frac{V_B}{V_A}\right)^2$$

where V_B is the boat speed
V_A is the apparent wind speed.

The formula is based on a board lift coefficient of 0·40 at maximum L/D as discussed in connection with Table I of Chapter VI. The sail side-force component coefficient used was 1·30.

As an example, if the boat speed to apparent wind speed ratio is 1/3, when hard on the wind, the sail area to board area ratio calculates to be 28·6. This agrees reasonably well with Harrison Butler's value of 25 to 35.

Note that a slow boat requires a larger board area than a fast boat. Also, if the hull contributes to the side-force, a somewhat smaller board can be employed. When a 45° canted board is used for non-heeling, it should be $\sqrt{2}$ or 1·41 times the size of a vertical board.

The above does not suffice for surface-piercing foils and others not deep enough to provide sufficient hydrostatic pressure.

Tank tests on surface-piercing foils have revealed a new method of calculating the required submerged area for foils. It may well prove to be the simplest and most accurate method to date.

No portion of a foil can support a normal pressure which exceeds the hydrostatic pressure at that point resulting from the depth. If it encounters a greater positive pressure, a wave will pop out of the water surface, thus injuring the effectiveness. A corresponding negative pressure on the weather side will "suck" the water level downward leaving only air in contact. This ventilation is even more harmful.

Tests have shown that, as a factor of safety, one should not attempt more than 70 per cent of the above critical pressure, if adequate foil action is expected. This gives us the basis for a good and simple calculation for the minimum area of a foil.

For example, suppose that a rectangular surface-piercing foil has an immersed depth of 2 ft. Its average depth will be 1 ft. Since salt water weighs 64 lbs/cu ft, the average hydrostatic pressure on the foil will be 64 lbs/sq ft of area of its vertical projection for one face. Using the above factor of safety of 70 per cent, one gets nearly 45 lbs/sq ft for the maximum pressure that can be supported. Thus if, for example, the side force of a sail is 200 lbs, $200/45 = 4{\cdot}44$ sq ft of projected vertical plane area is needed for an effective foil. Thus the foil should be at least $4{\cdot}44/2$ ft wide, or 2·22 ft.

In the future, I intend to employ this method since tank experiments fully support this theory.

Sincerely,
EDMOND BRUCE

CHAPTER VII

HANDICAPPING SAILING RACES

Reprinted from AYRS 66A, Oct. 1968

by Edmond Bruce

Purpose

For a long time, the writer has been distressed by the lack of a solid mathematical foundation in any present sailing handicap system with which he is familiar. Many of us have witnessed how small boats often defeat large boats in light wind handicap races. In strong winds, the reverse is usually true. This is the subject of this article.

Among existing rules, the so-called "Time on Distance" is a poor method, in my opinion. It gives a time allowance per mile. This has little mathematical foundation as it is correct only for one speed. A *ratio* system for speed or elapsed time, such as the "Portsmouth Yardstick", is much to be preferred. Also, the length of the course becomes immaterial if only elapsed time is involved. Even this system needs improvement to more nearly agree with natural laws.

Racing in strong winds

Consider only displacement boats of the usual length-beam ratios. This excludes most narrow multi-hulls which avoid the so-called "hull speed limit" caused by its generated water-wave pattern. It also excludes planing boats for the same reason.

Let us compare two similar shaped boats that differ only in size. Assume that they are in a wind which is strong enough to drive both boats at their "hull speed limit". Numbering the smaller boat 1 and the larger boat 2, their speeds V versus length L are:

$$V_1 = 1{\cdot}34\ \sqrt{L_1}.$$
$$V_2 = 1{\cdot}34\ \sqrt{L_2}.$$

Thus, $\dfrac{V_2}{V_1} = \sqrt{\dfrac{L_2}{L_1}}$ is the desired speed ratio for specified lengths.

If Boat 2 has twice the length of Boat 1, as an example,

$$\frac{V_2}{V_1} = \sqrt{\frac{2L_1}{L_1}} = \sqrt{2} = 1{\cdot}414.$$

In terms of the elapsed time T,

$$\frac{V_2}{V_1} = \frac{T_1}{T_2} = 1{\cdot}414.$$

Thus, $T_2 = \dfrac{T_1}{1{\cdot}414}$

Regardless of the length of the course, Boat 1 should be allowed to divide its elapsed time by 1·414 under a fair handicapping system *when the winds are strong*.

Racing in light winds

In light winds, a "hull speed" ratio has no meaning whatever. The above reasoning no longer applies. Wave-making is so low that frictional resistance dominates the situation. This resistance is approximately proportional to V^n where n may be between 1·8 and 2·0. The exact value of n does not matter as we shall see.

Compare the two boats, as discussed above, when both are in the same light wind. The larger Boat 2 would have 4 times the sail area of the smaller but similar shaped Boat 1 since it has twice the length. This means that Boat 2 has 4 times the driving Force F and therefore 4 times the hull resistance R. It also has 4 times the wetted area and 4 times the hull cross-sectional area of Boat 1. Writing all this in the form of equations and assuming n as the exponent of V,

For Boat 2, $F_2 = R_2 = kA_2V_2^n$ where A is any hull area and k is a proportionality.

But $F_2 = 4F_1$ and $R_2 = 4R_1$.

Substituting $4R_1 = k4A_1V_2^n$ and $R_1 = kA_1V_2^n$.

For Boat 1, $F_1 = R_1 = kA_1V_1^n$.

Equating, $kA_1V_2^n = kA_1V_1^n$.

Therefore, $V_2^n = V_1^n$ or $V_2 = V_1$.

Thus the value of the exponent n does not matter. We discover that similar shaped boats travel *at the same speed* in the same light wind regardless of size.

The above demonstrates that in light winds, when $\dfrac{V}{\sqrt{L}} <$ about 0·4 for both boats, the larger boat should *not be handicapped*. Any fair rule should reflect this situation.

Summary

The writer's principal objections to existing handicap sailing rules have been outlined. No rule will ever be closely accurate unless, in some way, a variable factor is provided which is a function of the average strength of the wind, encountered over the course, in relation to the boat's size. This can be determined in a relative manner by calculating the average achieved $V/\sqrt{L}$ for each boat. Of course, if this is used, the course distance must be known.

The writer has devised one handicapping method for the above accomplishments. It will be withheld for the present. It is suggested AYRS readers let the Editor know how they would solve this problem. A collective judgment is necessary since acceptability, as well as simplicity, is most important to its success. In final form, it might be called 'The AYRS Handicapping System'.

PART TWO

SPEEDS AND FORCES

CHAPTER VIII

ANGLES AND SPEEDS

February 1973

by Henry A. Morss, Jr.

A. *The Sailing Triangle.* "Sailing triangle" is the simplest among several titles which have been applied to the geometrical expression of the fundamental relationship between boat speed, true wind speed, apparent wind speed, speed made good to windward, and the angles and symbols, as shown in Fig. 1.

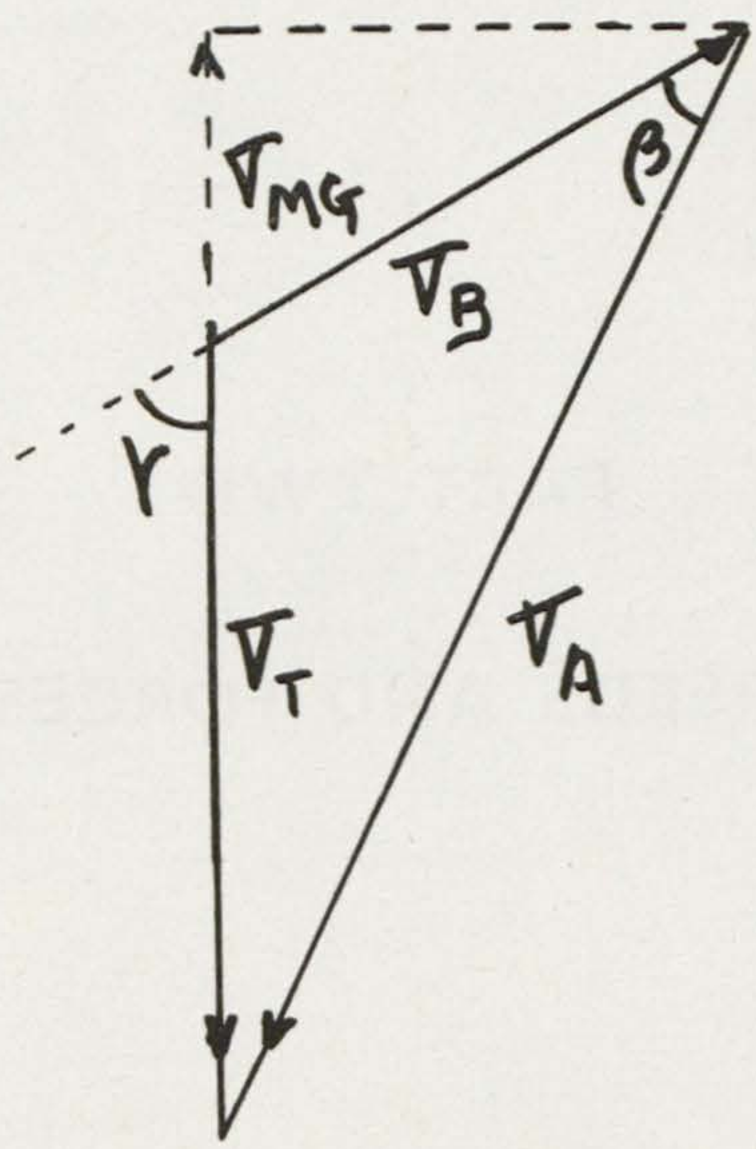


Fig. 1. The Sailing Triangle

The trigonometrical formulae which describe this are

$$\frac{V_A}{\sin \gamma} = \frac{V_B}{\sin(\gamma - \beta)} = \frac{V_T}{\sin \beta} \qquad \text{(A)}$$

$$V_T^2 = V_A^2 + V_B^2 - 2\, V_A\, V_B \cos \beta \qquad \text{(B)}$$

$$V_{MG} = V_B \cos \gamma \qquad \text{(C)}$$

This triangle, suitably drawn for a case in point, can be used for all sailing situations—boats sailing on water, on ice, or on the land at any angle to the wind.

Several other forms of these relationships, derivable directly from them (see appendix A), are useful for different purposes. We note some of them here for reference.

$$\frac{V_B}{V_T} = \frac{\sin\gamma}{\tan\beta} - \cos\gamma = \frac{\sin(\gamma - \beta)}{\sin\beta} \tag{D}$$

$$\frac{V_B}{V_A} = \cos\beta - \frac{\sin\beta}{\tan\gamma} = \frac{\sin(\gamma - \beta)}{\sin\gamma} \tag{E}$$

This one, (E), is useful in planning instruments for "on-board" measurements of performance. V_B, V_A, and β can be measured, enough to determine the sailing triangle. (A triangle is determined by any three of its sides and angles if at least one of these is a side.) With those three known, this formula can be solved for γ. Then V_T can be figured by means of (A) and V_{MG} by (C).

If one is willing to settle for the ratios V_B/V_A and V_B/V_T and the substantial data which can be derived from them, then a much simpler, less expensive, and less burdensome scheme of observations on board may be adequate, as Edmond Bruce points out in Chapter XVI.

Fig. 2 is a pair of plots, one for each of these ratios versus gamma for selected values of beta. They can be used separately to find either ratio if the angles are known. They can be used together when one of the ratios and one of the angles are known as a means for finding the other ratio and angle.

$$\frac{V_{MG}}{V_T} = \frac{V_A V_B \cos\beta - V_B^2}{V_A^2 + V_B^2 - 2 V_A V_B \cos\beta} \tag{F}$$

This is a formula which expresses V_{MG}/V_T in terms of quantities which can be measured on board a boat while sailing. It can be used in setting up an analog computer which will give a continuous reading of that ratio as the boat moves along. This is a part of the new, more sophisticated instrumentation which is being developed. (See Chapter XVIII.)

Before proceeding into further detail, let us notice qualitatively here a point which will be covered shortly in full quantitative fashion. As sailors have often observed, when a craft sailing at a fixed angle to the true wind picks up speed she "brings the apparent wind forward" or reduces beta. This appears in Fig. 3. What many have failed to realise is that there is a limit to this process, reached when beta comes down to the lowest value at which the boat can sail effectively. Beyond that, she must sail wider of the true wind, or increase gamma. Even that has its limit, as we shall see.

B. *Circles of Constant Beta.* (a) *The Circle.* If we draw a circle through the three apices of the sailing triangle, we have what may be called a "circle of

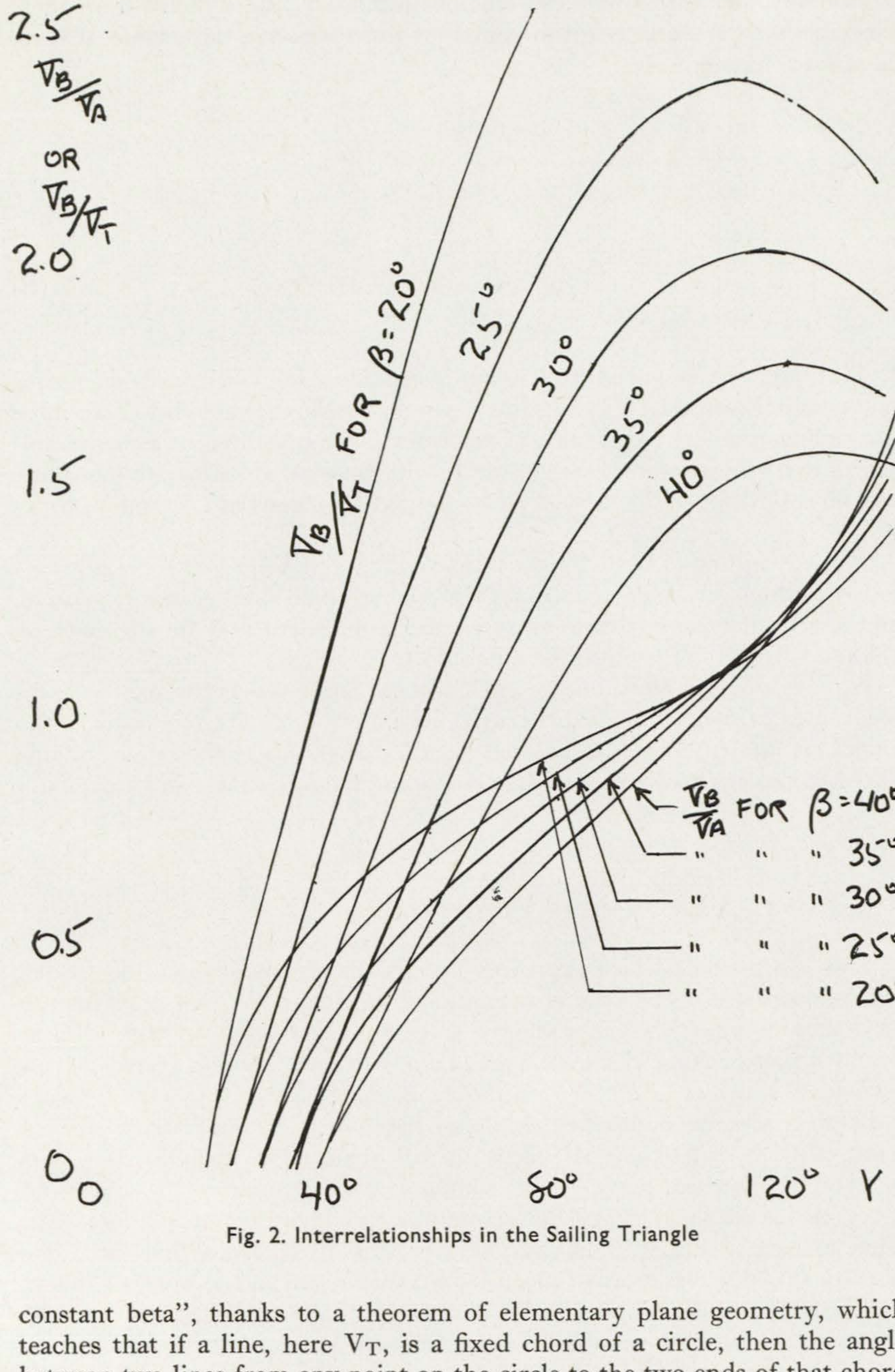


Fig. 2. Interrelationships in the Sailing Triangle

constant beta", thanks to a theorem of elementary plane geometry, which teaches that if a line, here V_T, is a fixed chord of a circle, then the angle between two lines from any point on the circle to the two ends of that chord is the same for all points on the circle on the same side of the chord. Thus in Fig. 4, $\beta_2 = \beta_1$ wherever these two points A and B are located on the circle

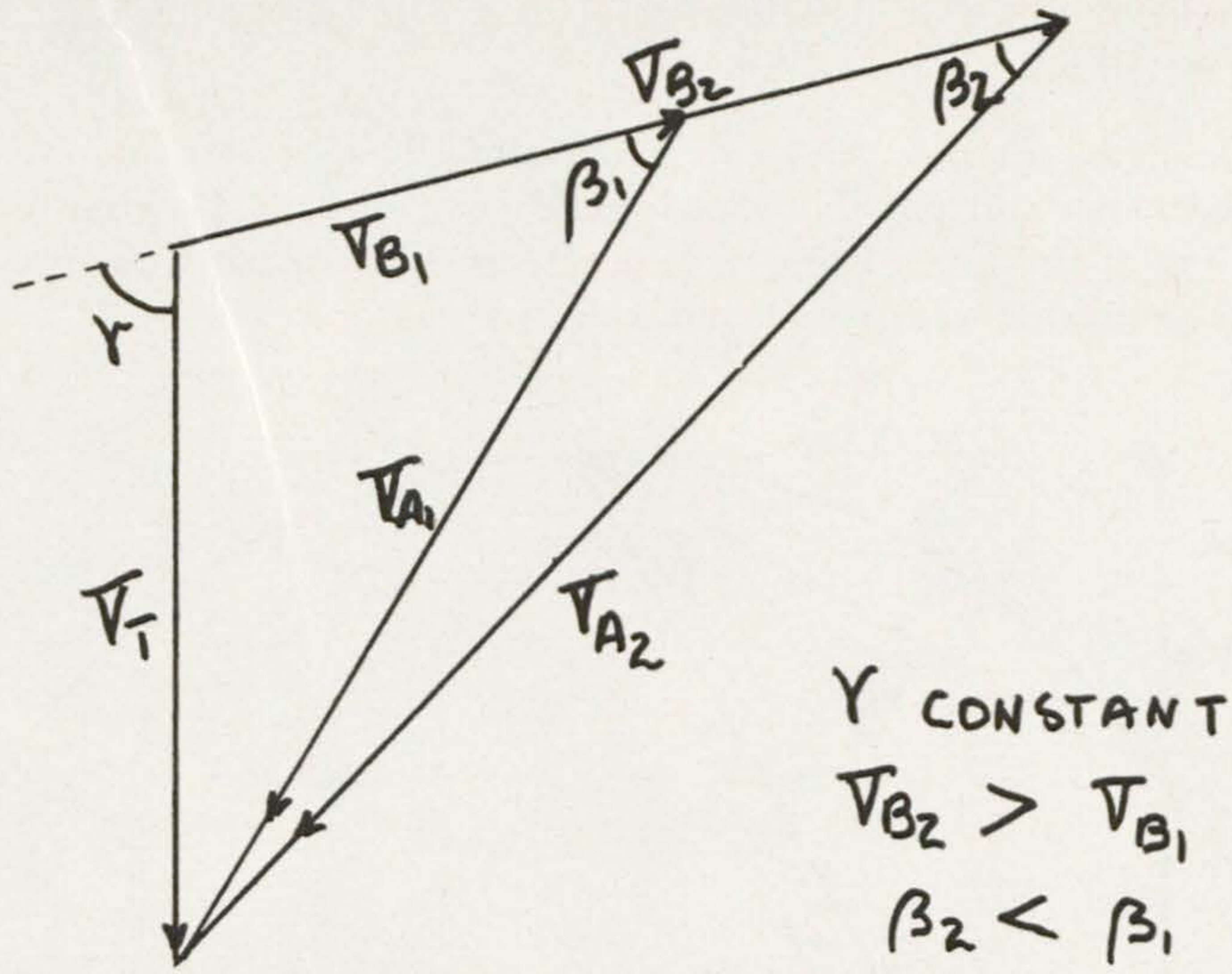


Fig. 3. Wind comes forward (beta declines) as speed increases on fixed course to true wind, gamma

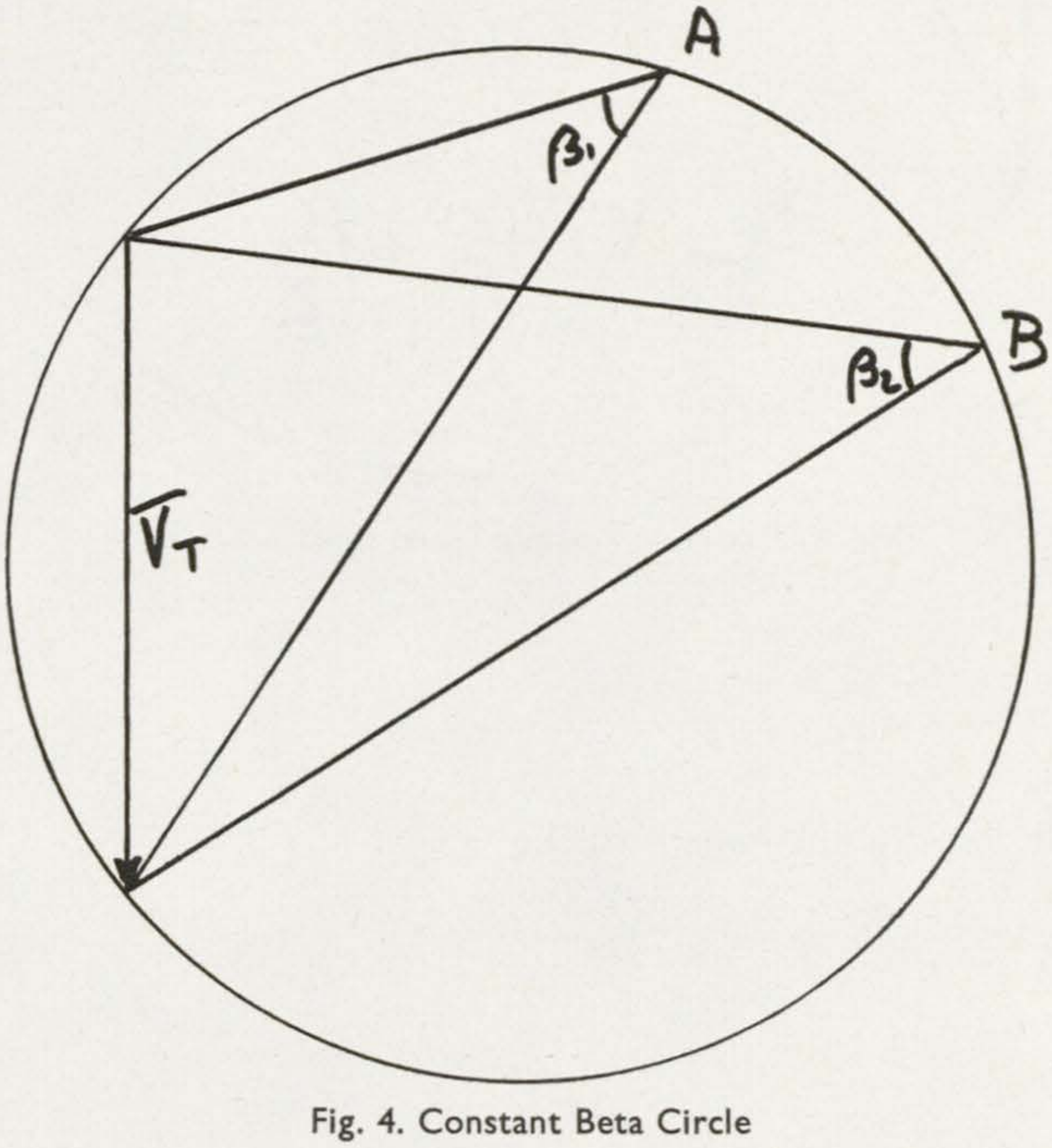


Fig. 4. Constant Beta Circle

to the right of the chord. Sailing triangles drawn in various ways in such circles can tell a lot about sailing.

(b) *Maximum Possible Speed to Windward.* The construction of Fig. 5 shows the maximum possible speed made good directly to windward by a craft sailing at the given value of beta. It can be shown that a boat sailing thus will be making a course off the true wind

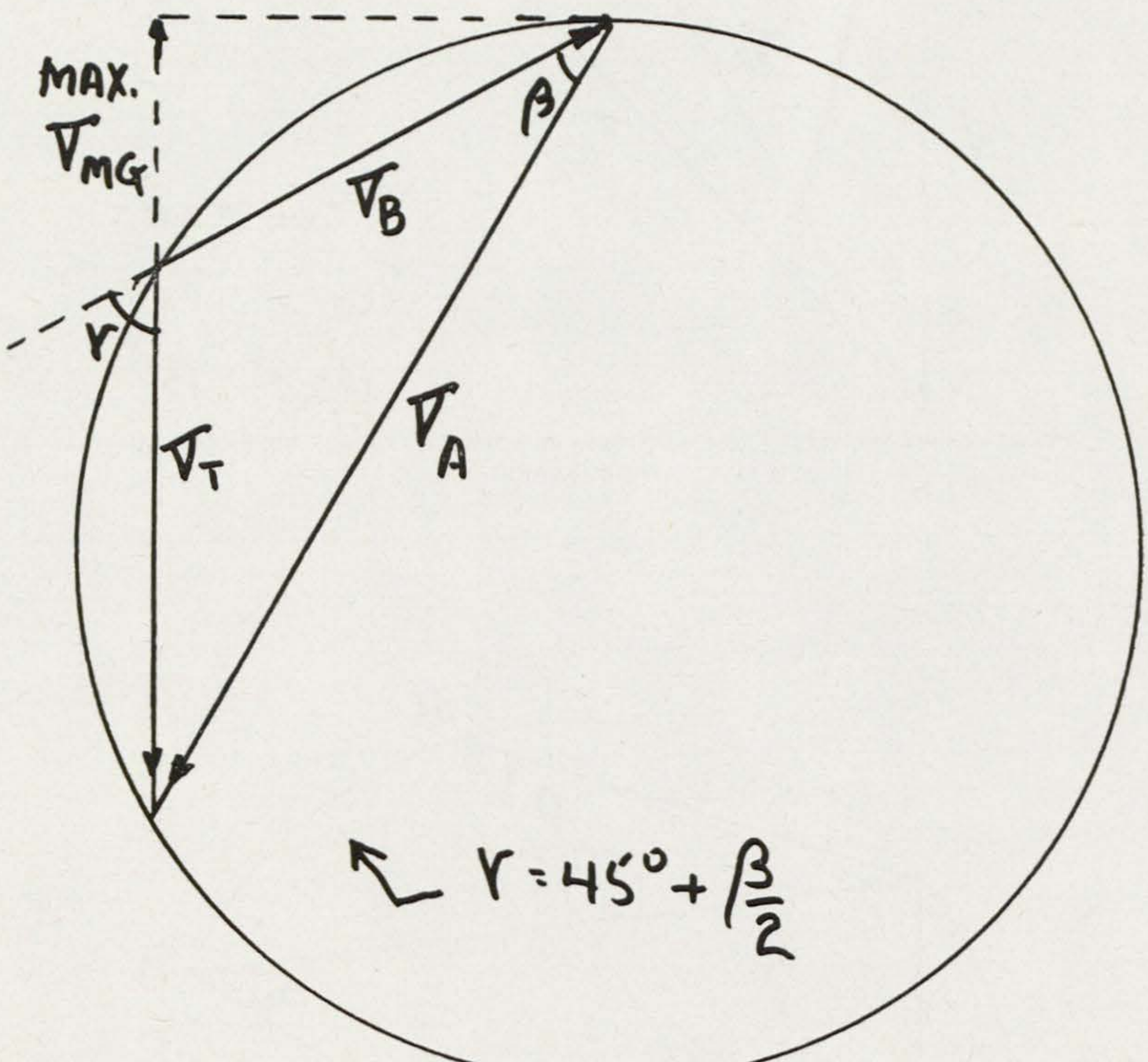


Fig. 5. Maximum Possible Speed to Windward

$$\gamma \text{ for max. } V_{MG} = 45° + \frac{\beta}{2} \tag{G}$$

Her speed through the water will be

$$\frac{V_B}{V_T} \text{ for max. } V_{MG} = \frac{\sin\left(45° - \frac{\beta}{2}\right)}{\sin \beta} = \frac{\cos\left(45° + \frac{\beta}{2}\right)}{\sin \beta} \tag{H}$$

$$\text{or} \quad \frac{V_B}{V_A} \text{ for max. } V_{MG} = \frac{\cos\left(45° + \frac{\beta}{2}\right)}{\sin\left(45° + \frac{\beta}{2}\right)} \tag{I}$$

and her speed made good to windward will be

$$\text{Max.} \frac{V_{MG}}{V_T} = \frac{\cos^2\left(45° + \frac{\beta}{2}\right)}{\sin\beta} = \frac{1}{2}\left(\frac{1}{\sin\beta} - 1\right) \tag{J}$$

It may be noticed that as beta becomes smaller, the numerator in each of these expressions gets larger and the denominator smaller. Thus, as the value of beta gets smaller, V_B and V_{MG} for maximum V_{MG} grow larger.

These are geometrical limits on what is possible for a boat sailing at a constant value of beta when she is doing her best to windward. These limits are very high, as appears in Fig. 6. With non-planing monohulls, they may never have been reached, except possibly at rather high beta. They may never have been achieved with planing monohulls. They have been reached with ice boats and probably have been reached by some of the fastest racing catamarans.

Most monohulls reach their best V_{MG} for a given beta (and indeed for any value of beta at which they can sail well) closer to the true wind than is called for in this limiting situation, that is, for gamma less than $45° + \frac{\beta}{2}$. If they are sailed wider of the true wind, they can not increase speed enough to hold beta constant. Instead, beta increases.

As an illustration, Fig. 7 shows what is probably about the situation for today's racing 12-meter class boats in a moderate breeze. They do their best to windward with beta at about 22° and gamma at about 37° or 38°. In a 10-knot wind they might be sailing through the water at a speed of about seven knots and making good to windward about 5·6 knots, far below the theoretical maxima, but fast sailing nevertheless. To match the geometrical limit for $\beta = 22°$, they would have to sail at almost 15 knots at gamma equal to $45° + \frac{22°}{2}$ or 56° and would then make good to windward V_{MG} of about 8 knots.

The reader may wish to figure other possible examples—a sailing dinghy, a modern planing sailboat, or a 'C'-class racing catamaran—if he can measure or guess at likely values of minimum beta.

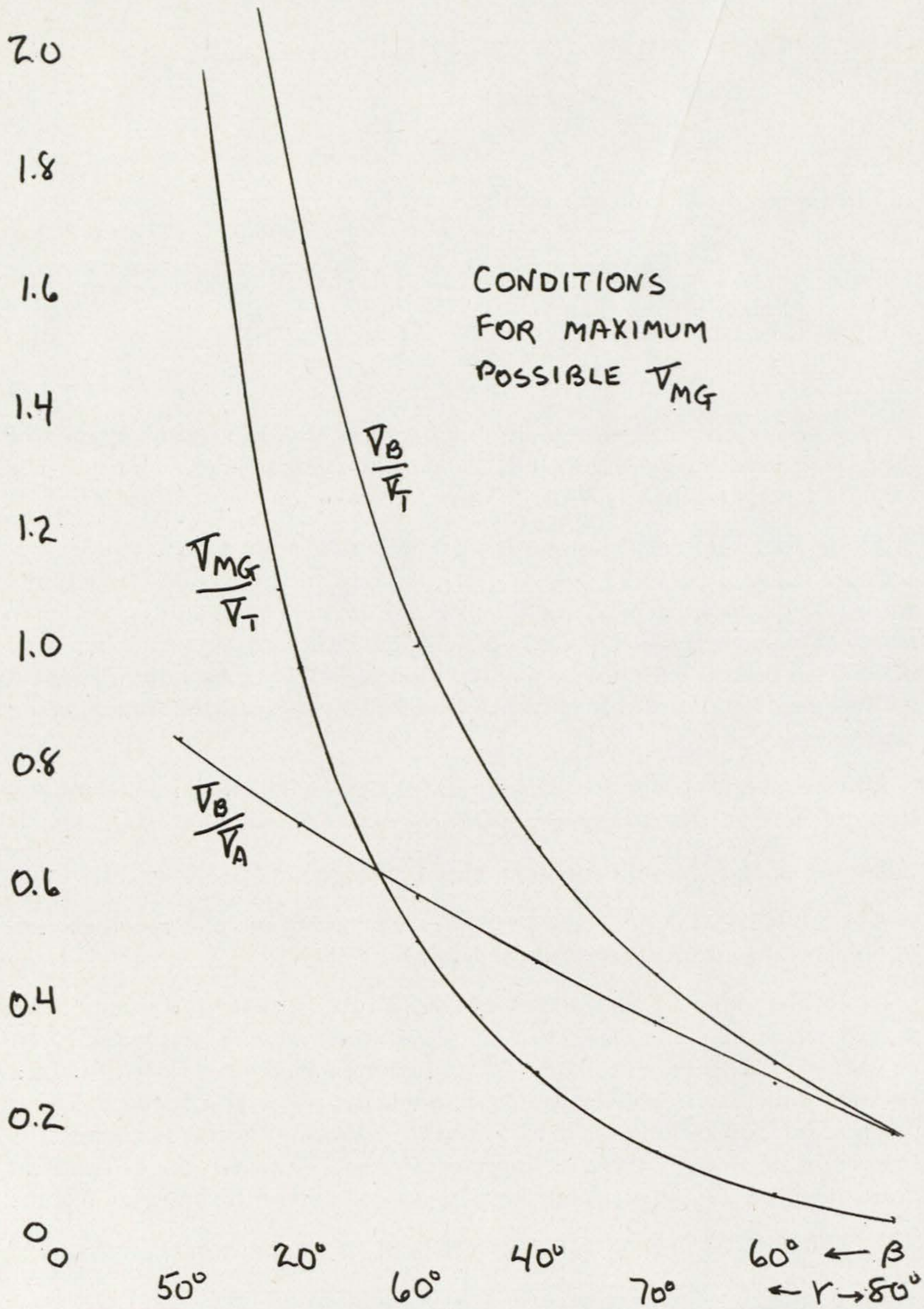


Fig. 6. Values at Maximum Speed to Windward

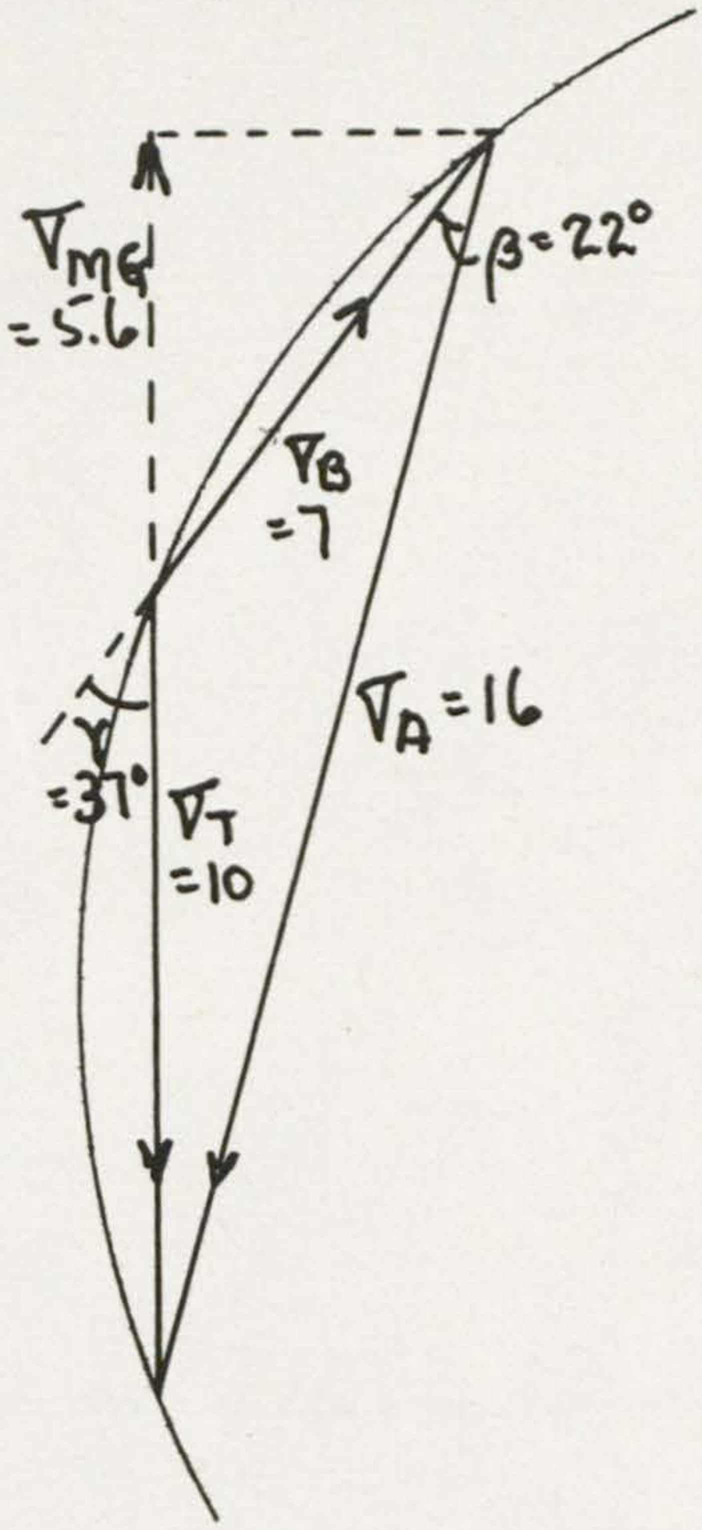


Fig. 7. Sailing Triangle for 12-meter in 10-knot wind

If nothing else, this study reveals that design for best performance to windward means design for maximum speed at minimum beta with the appropriate amount of sail area and stability.

From the diagram it is evident that if a boat can go fast enough to hold beta constant when she is sailing at values of gamma above $45° + \frac{\beta}{2}$, then her problem for best V_{MG} is different. She must *slow down* while holding beta constant until she brings gamma down to $45° + \frac{\beta}{2}$. This problem has shown up with ice boats. Smaller ones have been faster to windward than larger ones, for just this reason, as Edmond Bruce was the first to point out.

As more people sail boats which have this capability, they will explore the best means of slowing down as needed. Will they be able to do it with something like pinching? Will the best solution be to reduce sail area?

(c) *True Wind Abeam.* Fig. 8 shows the sailing triangle in the circle of constant beta for sailing with the true wind abeam (gamma equal to 90°). In this situation,

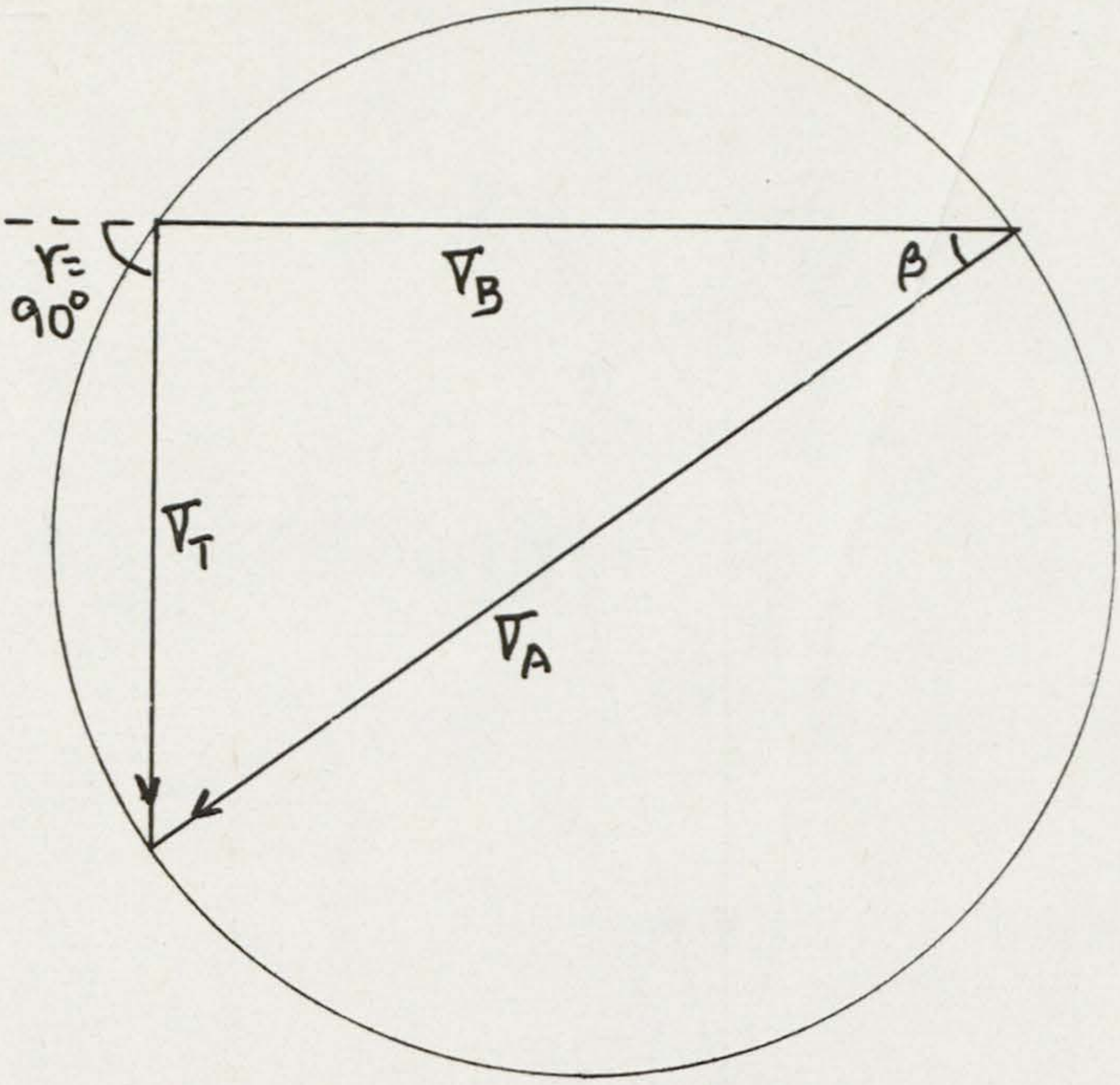


Fig. 8. Maximum Speed with True Wind Abeam

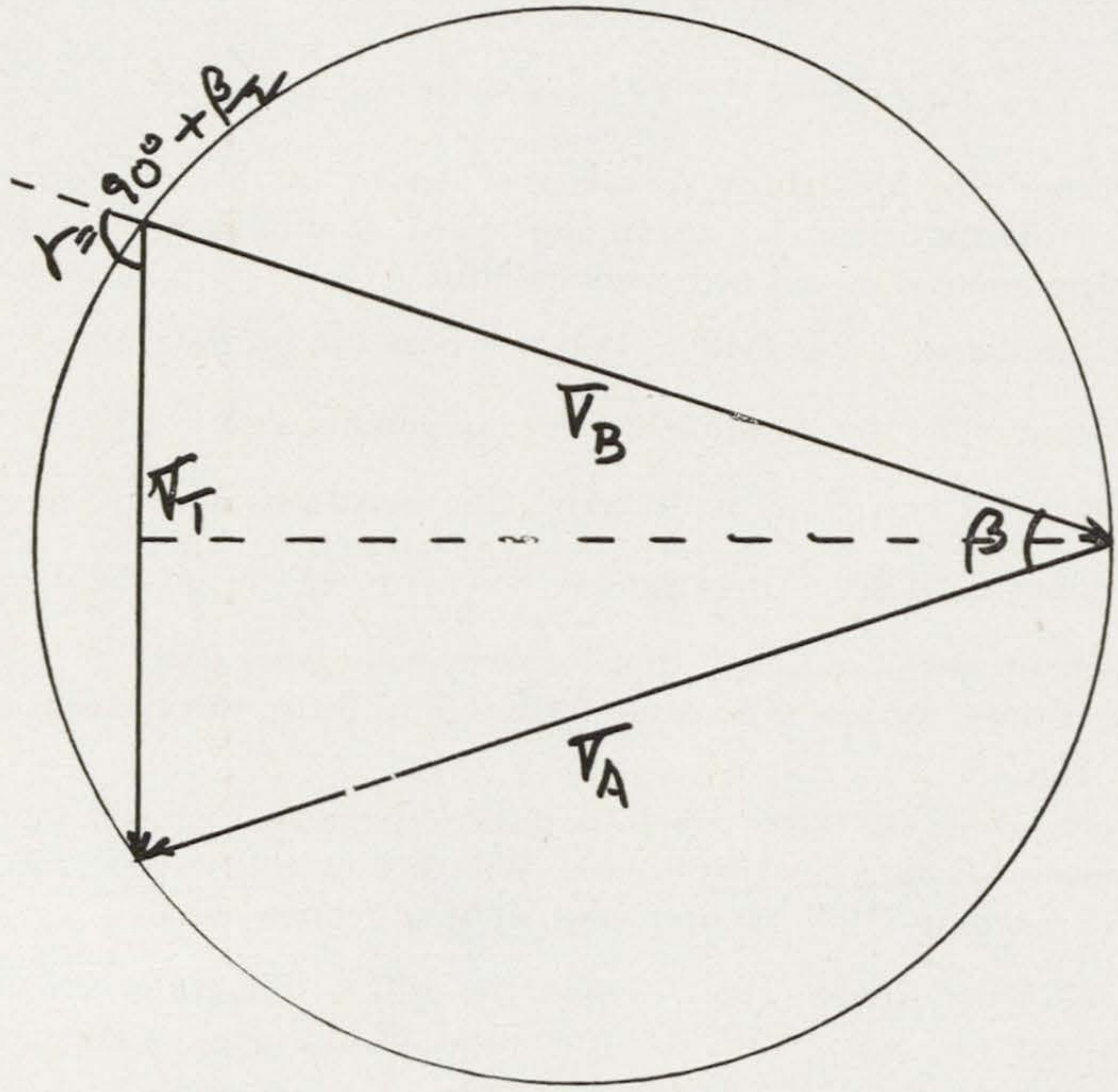


Fig. 9. Maximum Speed with Boat Speed equal to Apparent Wind Speed

$$\gamma = 90^\circ \tag{K}$$

$$\frac{V_B}{V_T} = \frac{1}{\tan \beta} \tag{L}$$

$$\frac{V_B}{V_A} = \cos \beta \tag{M}$$

This is fast sailing. For beta of 35°, the boat speed is about one and four tenths times true wind speed and for beta of 30°, one and seven tenths. The fastest multihulls have surely reached the lower of these. A few may have reached and exceeded the higher.

(d) *Boat Speed Equal to Apparent Wind Speed.* Every now and then the condition $V_A = V_B$ or $V_A/V_B = 1$ is of interest. This happens when V_T is the foot of an isosceles triangle. This triangle in the constant beta circle is drawn in Fig. 9. Values of V_B in relation to V_T are slightly higher than for wind abeam as given in the previous paragraph. For this case,

$$\gamma = 90^\circ + \frac{\beta}{2} \tag{N}$$

$$\frac{V_B}{V_T} = \frac{1}{2 \sin \frac{\beta}{2}} \tag{O}$$

$$\frac{V_B}{V_A} = 1 \tag{P}$$

(e) *Maximum Possible Speed.* In Fig. 10 we find the condition within the circle of constant beta for the maximum possible sailing speed. It occurs, obviously, when V_B is a diameter of the circle. In this case the apparent wind V_A is perpendicular to the true wind V_T. Here

$$\gamma \text{ for max. } V_B = 90^\circ + \beta \tag{Q}$$

$$\frac{V_B}{V_T} \text{ max.} = 1/\sin \beta \tag{R}$$

$$\frac{V_B}{V_A} = 1/\cos \beta \tag{S}$$

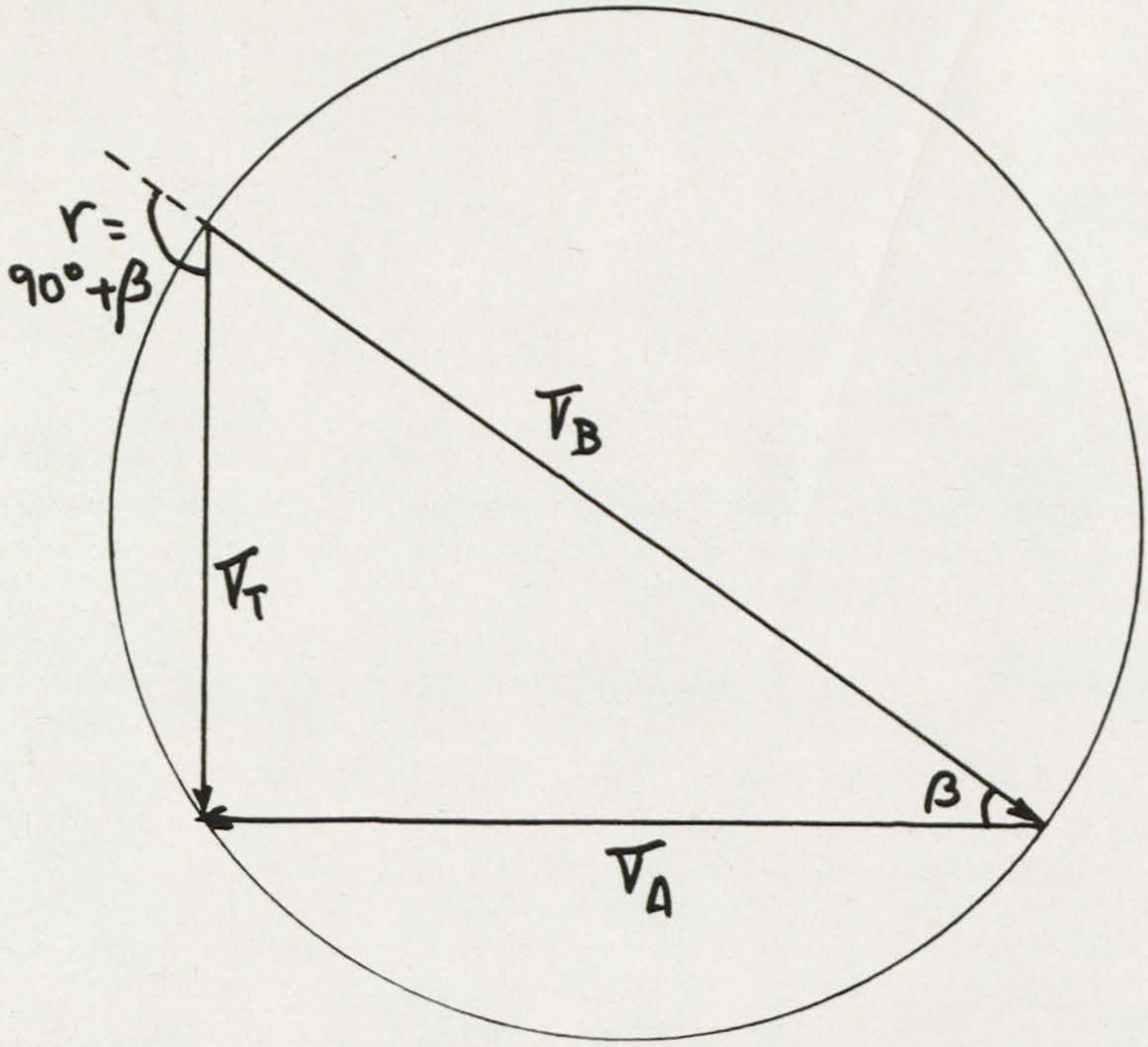


Fig. 10. Maximum Possible Boat Speed

This is an absolute limit on boat speed in a true wind V_T for sailing at a given value of beta. We see impressively that high boat speed can be achieved only at relatively low values of beta. Here are some values:

β	Max. possible V_B/V_T
35°	1·7
30°	2·0
25°	2·4
20°	2·9
15°	3·9
10°	5·8

These figures have been carried to the very low values of beta to cover most ice boats as well as boats that sail on the water. It is reliably reported that an ice boat has been timed at seven times the speed of the true wind—just beyond the table and requiring that she sailed at beta just a small fraction above eight degrees. That is an *extremely* small value for most sail rigs with cloth sails. (Lift-drag ratio = 7·0.)

We can observe that the racing 12-meters are not in this league. With their very low windward beta of perhaps 22° in a 10-knot wind, they would have to sail at nearly three times their known best speed to achieve this absolute maximum.

(f) *Maximum Possible Speed to Leeward.* Any boat sailing before the wind can not match the speed of the true wind, because she would then have the apparent wind at zero and no force to drive her. The best known water speed directly before the wind is in the range of $V_B/V_T = 0{\cdot}6$.

For years there have been those who have gone to leeward faster by tacking down wind. As a glance at Fig. 11 shows, a boat which can sail fast enough to hold beta essentially constant at all sailing angles to the true wind (except before it) is a good example of one which can profit from tacking to leeward. Indeed by so doing she can realise a speed to leeward somewhat in excess of the speed of the true wind.

$$\text{For max. } V_L/V_T,\ \gamma = 135° + \frac{\beta}{2} \tag{T}$$

$$\frac{V_B}{V_T} = \sin\left(135° - \frac{\beta}{2}\right) / \sin\beta \tag{U}$$

$$\frac{V_B}{V_A} = -\,1/\tan\left(135° + \frac{\beta}{2}\right) \tag{V}$$

$$\text{and } \frac{V_L}{V_T} \text{ max.} = 1 + \text{max.} \frac{V_{MG}}{V_T} = \frac{1}{2}\left(1 + \frac{1}{\sin\beta}\right) \tag{W}$$

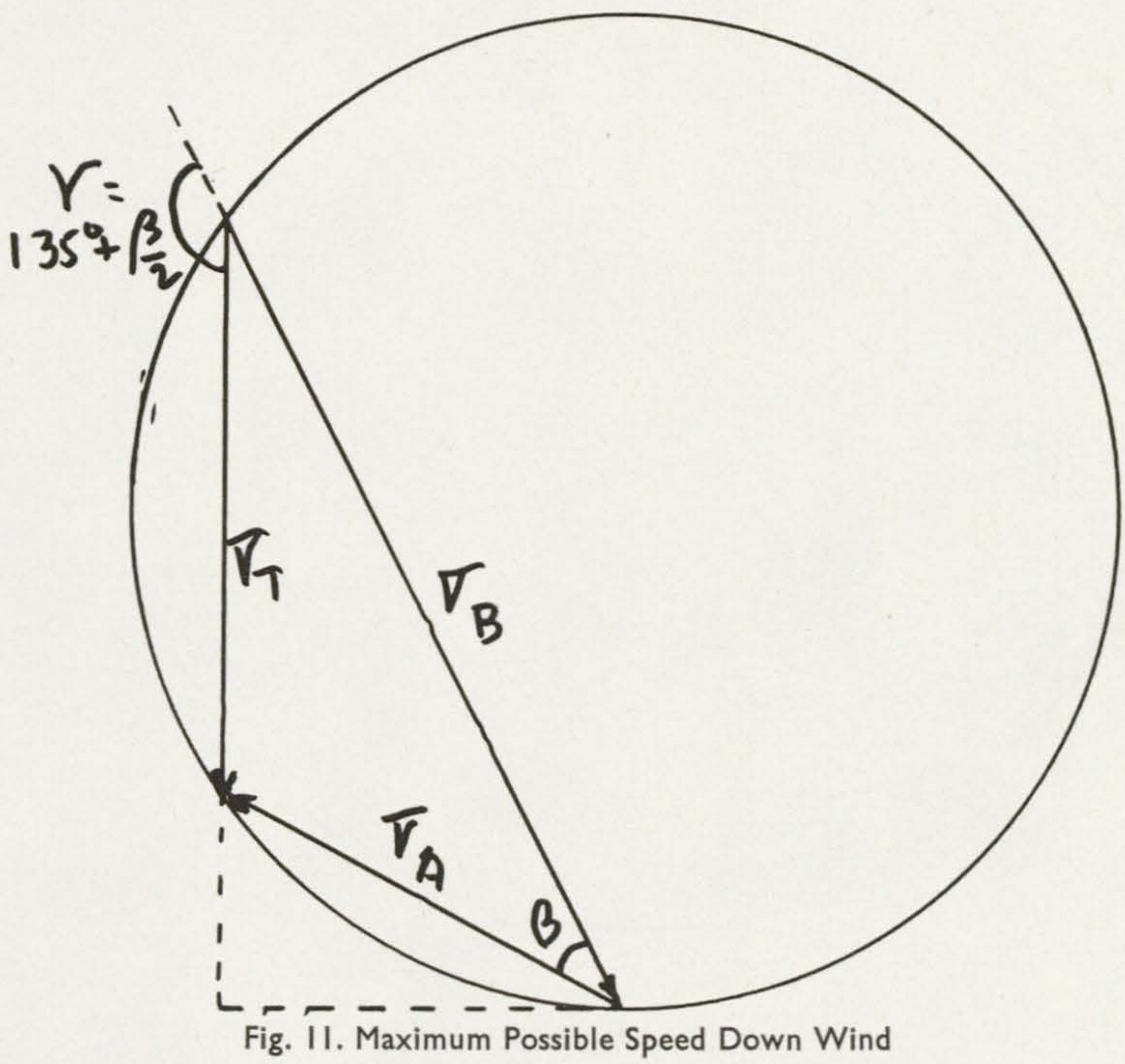


Fig. 11. Maximum Possible Speed Down Wind

Has this been accomplished? Presumably it has been, or nearly so, by ice boats. The fastest multihulls have probably fallen short of it.

This is not to say that this is the only situation in which tacking to leeward is worth while. Something like these extreme capabilities for sailing are needed if leeward speed is to exceed true wind speed. On the other hand, many boats can do better than the typical half the speed of the true wind or less reached in sailing directly before the wind by tacking down wind. This can be seen in polar curves whose "low point" is lower than the point for sailing dead before the wind.

(g) *A Set of Circles of Constant Beta.* As we have seen, a circle of constant beta is a circle in which the true wind arrow, V_T, is a chord. Lines drawn from any point on the circle to the two ends of V_T will be separated by the same angle beta whatever point on the circle is chosen, so long as it is on the same side of V_T. If on a given true wind arrow V_T we construct several of these circles, each for a suitably selected value of beta, we shall have a "set" of these circles. Fig. 12 is such a set, for beta values 30°, 35°, 40°, 45° and 50°. As beta gets smaller, the circles get bigger. That is consistent with the things we have just discussed.

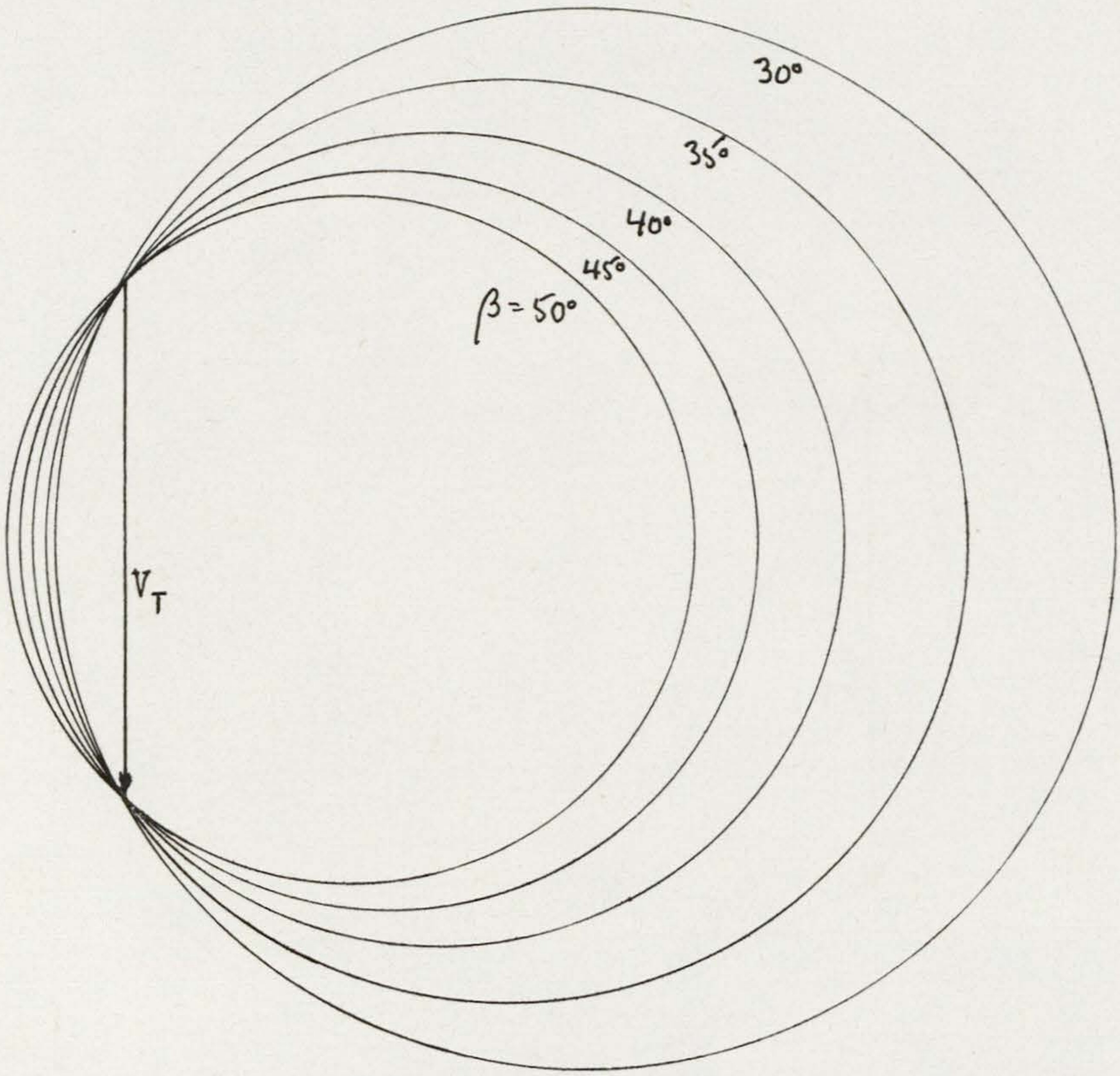


Fig. 12. Set of Constant Beta Circles

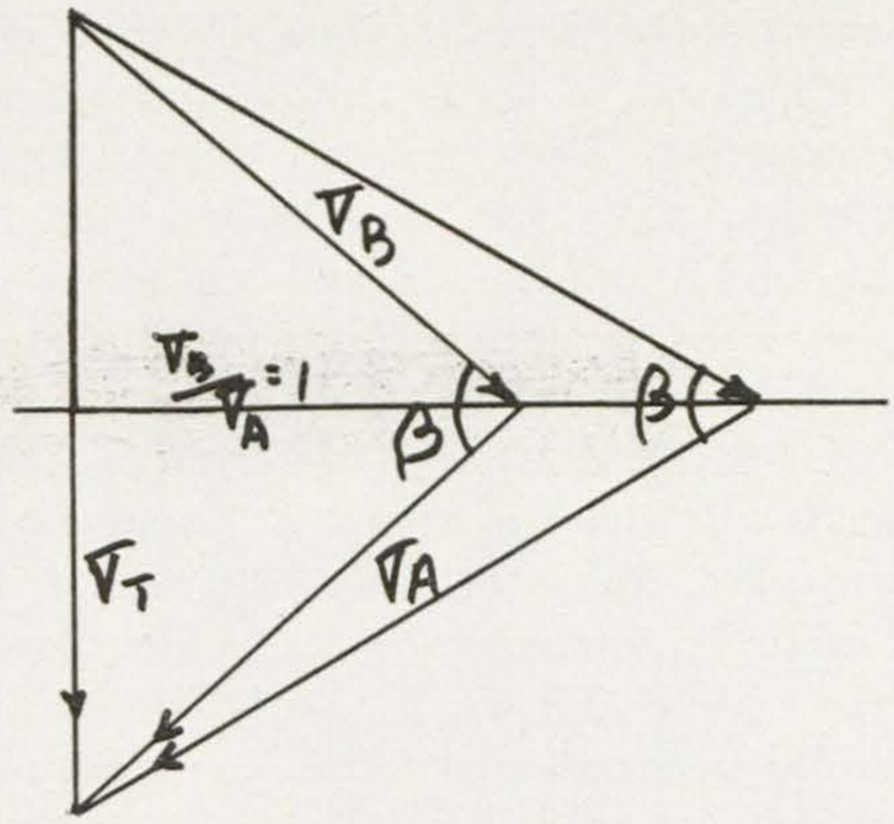


Fig. 13. "Circle" for VB/VA = 1

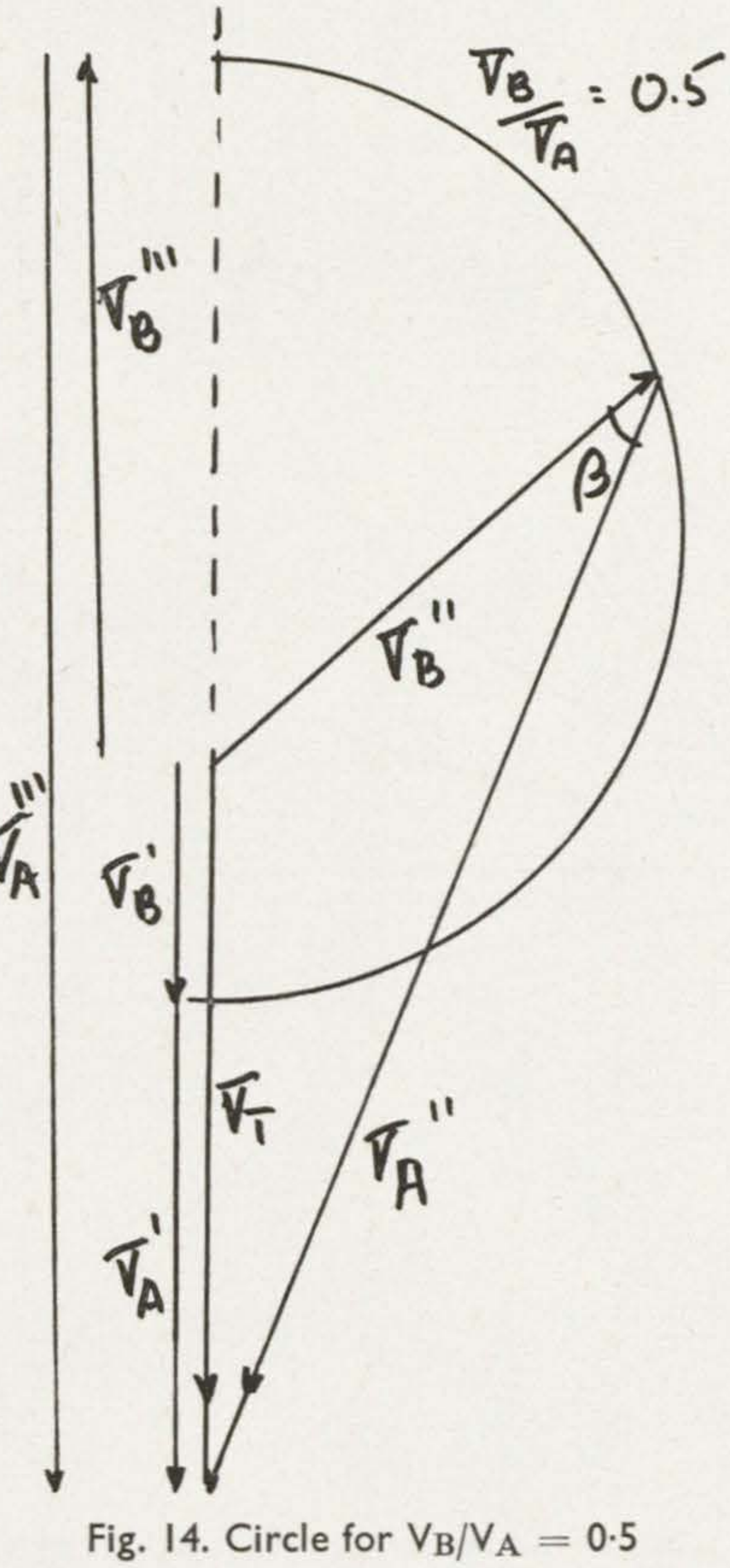


Fig. 14. Circle for VB/VA = 0·5

C. *Circles of Constant Ratio of Boat Speed to Apparent Wind Speed.* Just as the circles of constant beta can be very useful in understanding sailing and in teaching certain criteria to be kept in mind when designing for speed, so circles of constant ratio V_B/V_A can be useful, expecially because of the relationship between V_B/V_A and the sail and hull force coefficients, the sail area and the weight. This is derived, explained, and emphasised quite strongly in Chapters IV and IX of this book ("the most important formula in sailing"—Edmond Bruce).

The one of these circles which is easiest to visualise is the one we have already mentioned in part (d) of the preceding section B of this chapter. It is a special kind of circle, one with infinite radius. Itself, it is therefore a straight line. It is the "circle" for $V_B/V_A = 1$. Obviously it is the straight line which bisects and is perpendicular to the arrow for the true wind. That any point on the line is one for which $V_B/V_A = 1$ can be seen by inspection of Fig. 13.

At first sight it is less obvious that other curves for fixed values of V_B/V_A will be circles. It turns out that they are. Fig. 14 shows the one for $V_B/V_A =$

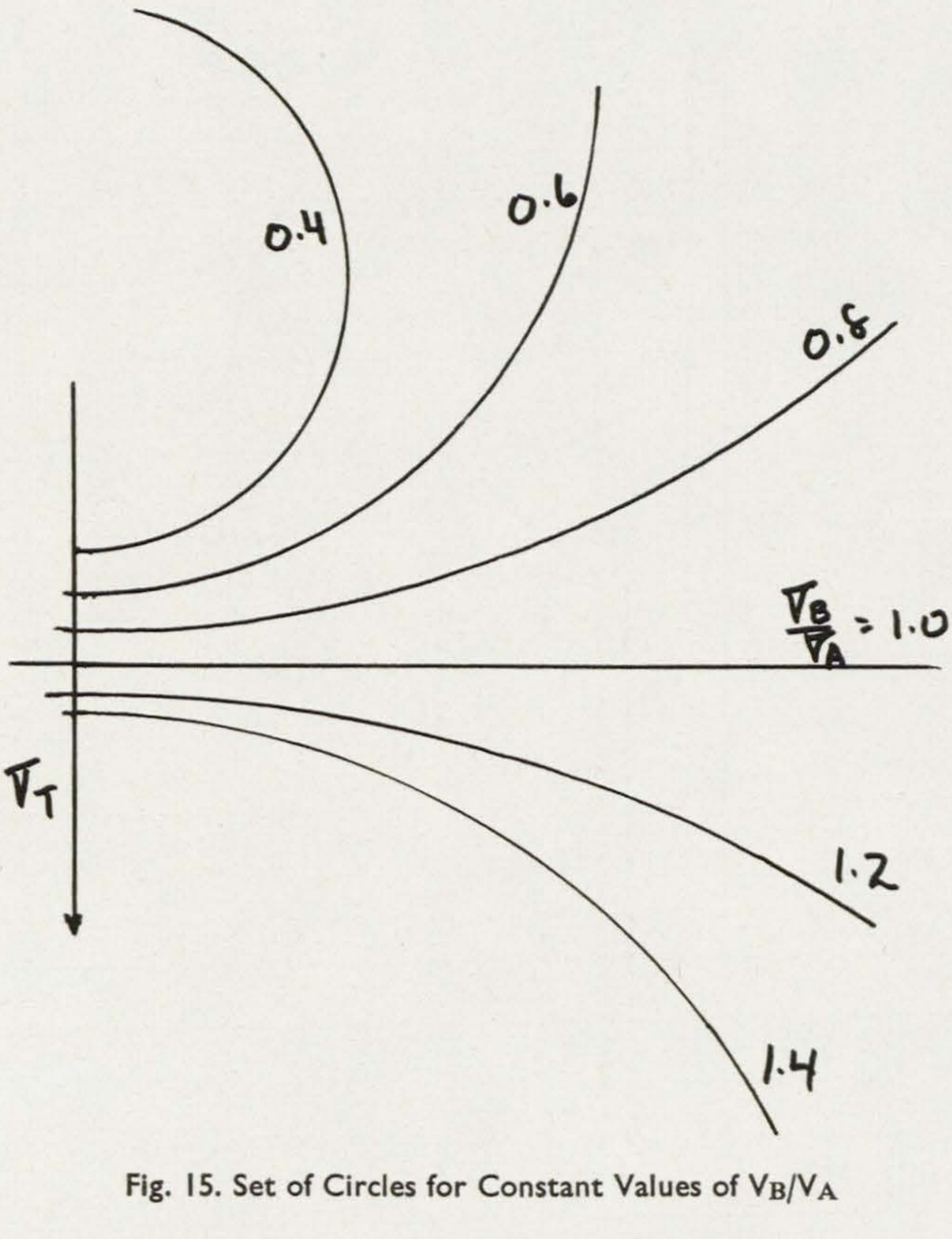


Fig. 15. Set of Circles for Constant Values of V_B/V_A

1/2. At the left of the arrow for V_T are arrows V_B' and V_A' for a dead run. V_B' has been drawn half as long as V_A' to meet the criterion. Here we see that the circle for $V_B/V_A = 1/2$ intersects the arrow for V_T one third of the way down from the top.

The arrows V_B'' and V_A'', again with the former half as long as the latter, define another point on the circle.

The highest point on the circle is obviously on the line of V_T extended, at a distance above the top of V_T equal to the length of V_T itself. This produces the necessary ratio, with V_B''' equal in length to V_T and V_A''' twice it.

By constructions of this sort, we can prepare a set of these circles. The result is shown in Fig. 15 for values of V_B/V_A equal to 1·4, 1·2, 1·0, 0·8, 0·6 and 0·4. Parts of the top and bottom of the whole graph have been left off as being beyond the range of interest.

D. *Superposition.* When these two sets of circles, the ones for constant beta and those for constant ratio V_B/V_A, are plotted together, the one superimposed upon the other, there emerges a pattern as shown in Fig. 16. At

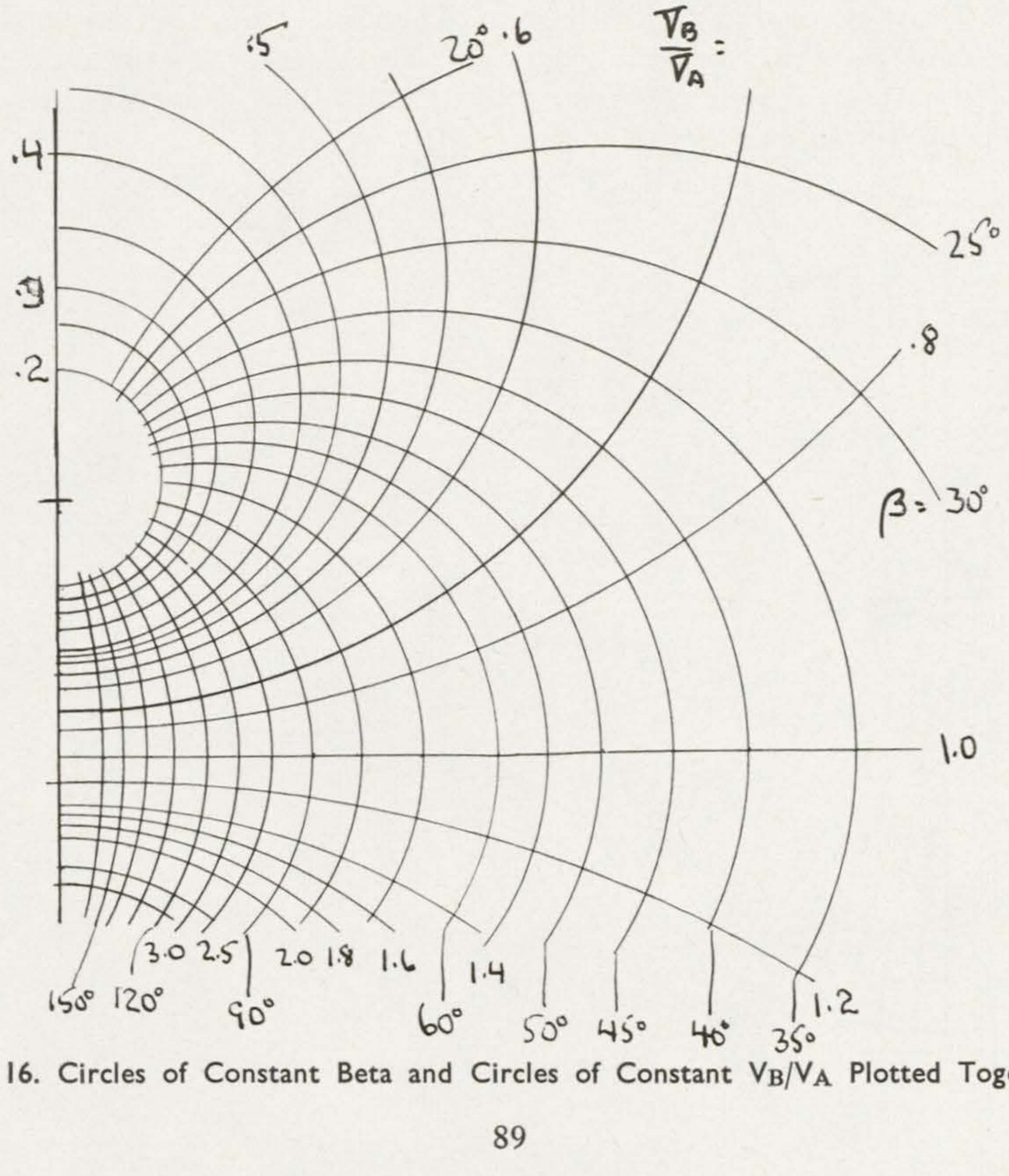


Fig. 16. Circles of Constant Beta and Circles of Constant V_B/V_A Plotted Together

every intersection the intersecting circles are at right angles to each other. For this reason, we may call them "orthogonal circles". Separately they have given real insight into some very fundamental aspects of sailing, some truths which seem to be relatively little known and understood, yet which are elementary in the sense that they are pure geometry. That these things seem to have been unknown until a few years ago is surprising indeed. They are well worth study.

It turns out that we may look upon these orthogonal circles, based as they are on the "true wind arrow", as an "apparent wind coordinate system" in the same way in which a regular system of polar coordinates (concentric circles and radial lines, as in Fig. 17) is convenient as a "true wind coordinate system" for plotting polar diagrams of sailing craft performance in relation to the true wind.

When these two entire systems are superimposed, we have a diagram with interesting properties, however complicated it may be in appearance. See Fig. 18. The value lies in the fact that any given point on the diagram has meaning in both systems of coordinates. The one point represents a single data-point of performance in relation to both the apparent wind and the true wind simultaneously. Thus, for instance, if a given point of performance is known relative to the apparent wind (by observation on board a moving craft), it may be plotted on the diagram. Then the "true wind coordinates" of the same point may be read off directly. For several years the author has found this to be a quite convenient way to make this conversion between coordinate systems.

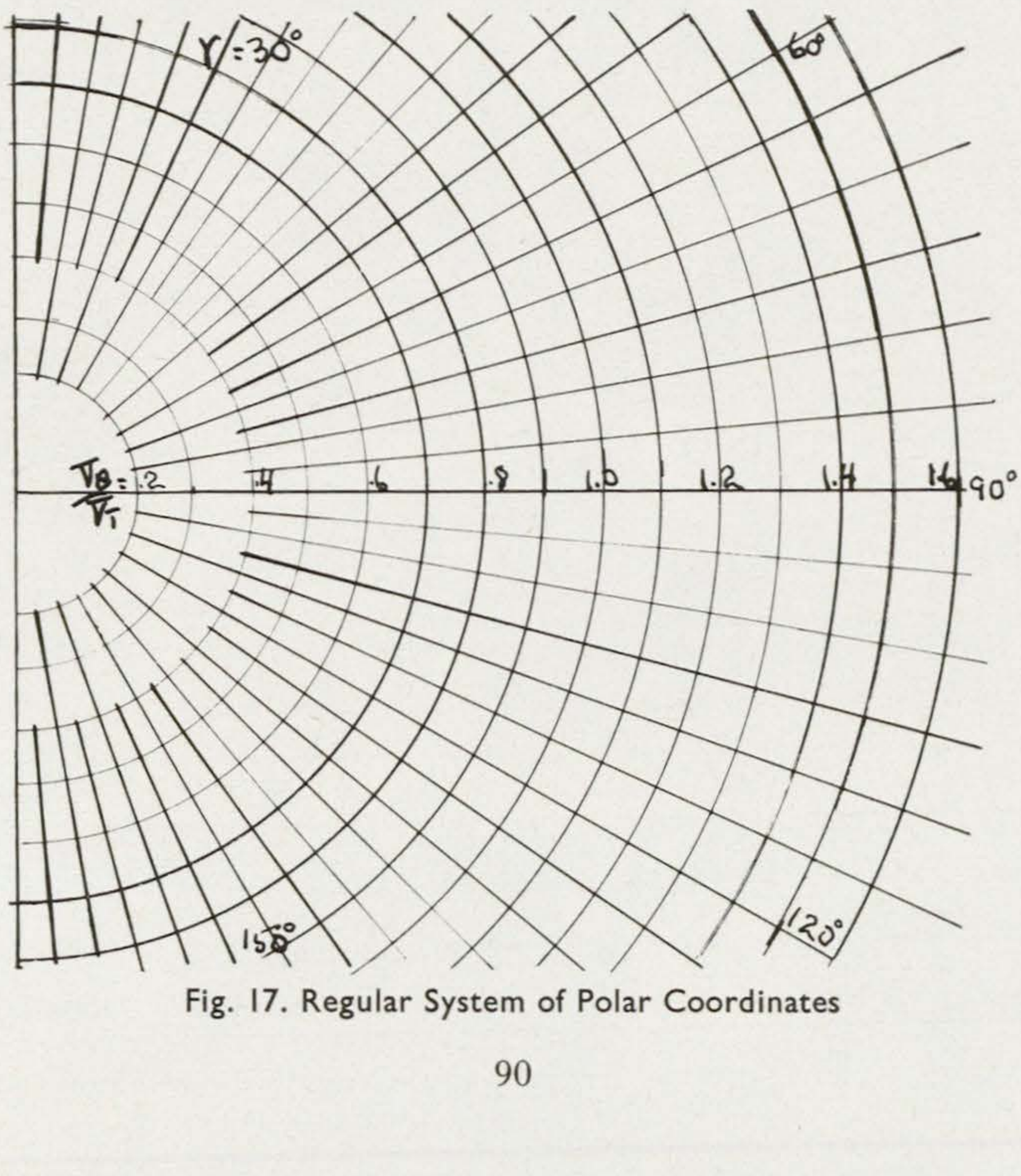


Fig. 17. Regular System of Polar Coordinates

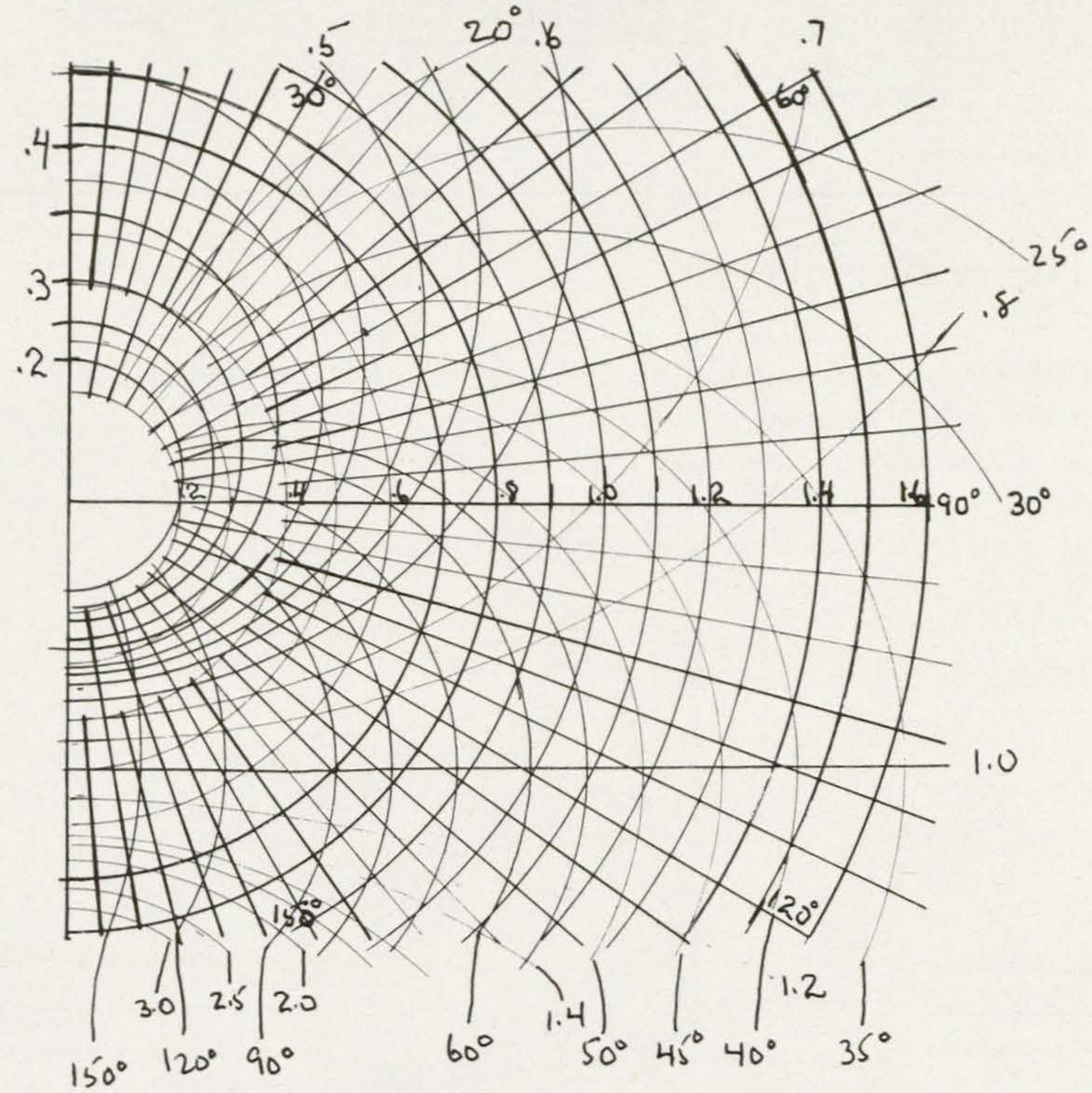


Fig. 18. Two Systems of Coordinates Plotted Together

CHAPTER IX

FORCES

February 1973

by Henry A. Morss, Jr.

A. *Directions of Forces.* Now the discussion, purely geometrical up to this point, must be extended to include forces—the directions and magnitudes of the forces which cause and limit sailing. In a thorough and definitive treatment, this would be rather complicated. We shall restrict our own review to the horizontal components of the principal forces.

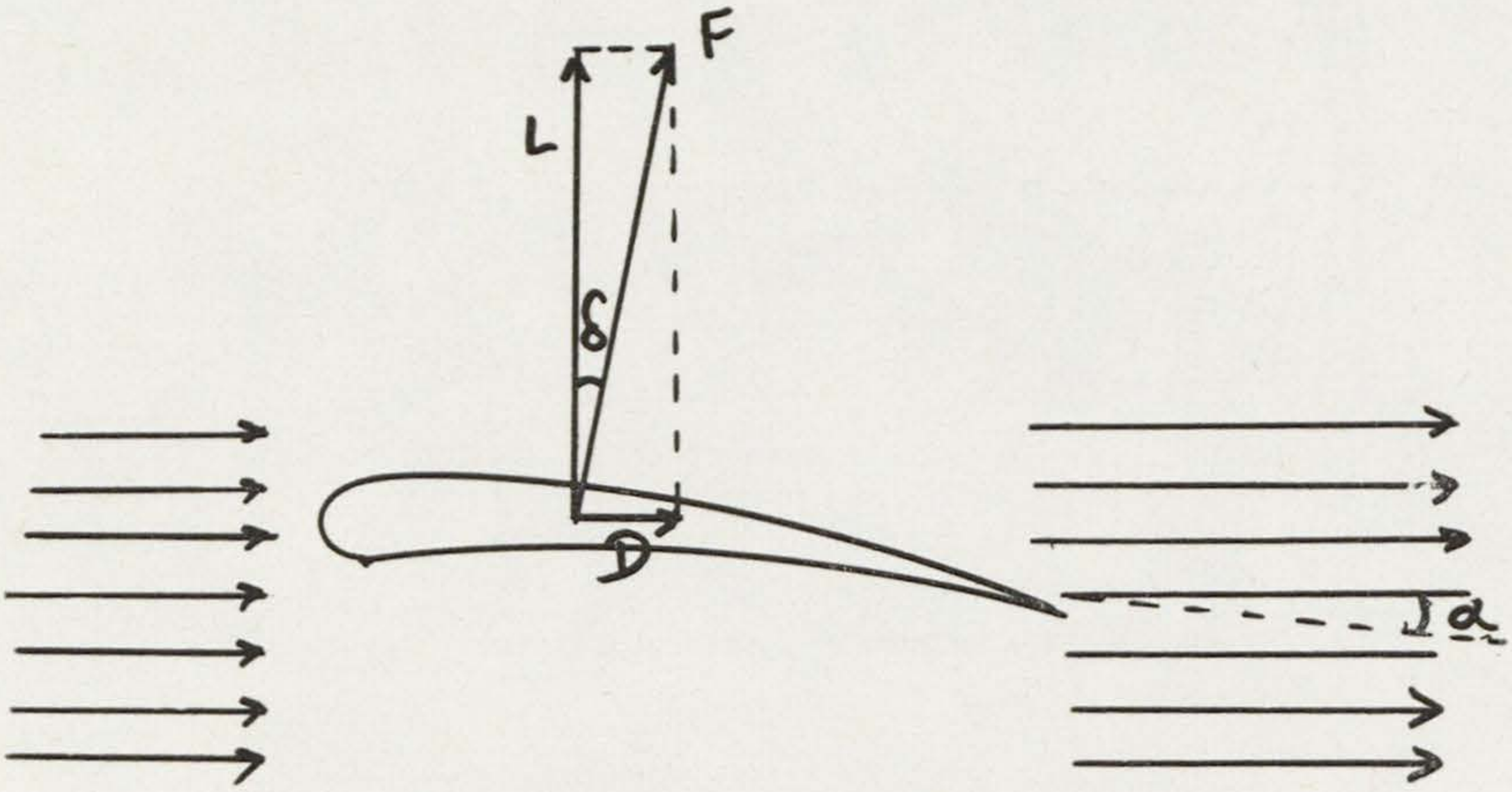


Fig. 1. Lift, drag, drag angle, and angle of attack

First, since "drag angle" proves to be a convenient concept in this kind of study, we define drag angle and related terms. For this, Fig. 1 should assist in visualising the aeronautical terminology. Think of a body in a fluid which moves past it toward the right. This motion of the fluid past the body will cause a "drag" force D in the direction of the moving fluid. Also if the body is not symmetrical about a line parallel to the motion, there will be a component of force perpendicular to that direction. This is called "lift", L. The total or resultant force produced by the motion of the fluid past the body is shown as F, the (vector) combination of L and D.

In aeronautics this set of definitions may be applied, for instance, to a wing. The lift force is what makes flight possible. The drag is the need for power to keep the wing flying. A convenient figure of merit for an air foil is the ratio of lift to drag, called the "lift-drag ratio".

In sailing also this terminology is handy as a measure of the performance of a sail (and, usually, everything else above the surface of the water which feels the moving air) as it moves through the air or of the underbody as it moves through the water.

Frequently in many parts of this book we refer to these things in terms of the drag angle, marked δ in Fig. 1 ($\tan \delta = D/L$). One may think of the drag angle as the angle by which the resultant force on the body lags behind the perpendicular to the direction of the motion, or the lift component.

We recall, now, the "Course Theorem" (Chapter III), which states that $\beta = \delta_S + \delta_H$ (drag angle of rig, etc., in air and that of hull in water).

To complete this set of definitions we must introduce "angle of attack". It is the angle between the direction of motion and the "slope" of the wing or body, α in Fig. 1. In aeronautics, typically, the angle of attack of the wing is of great importance because the lift component of force varies rapidly with small changes in the angle of attack. In sailing we have two angles of attack, just as we have two drag angles. One is the angle of attack of the hull (with all of its underwater parts). In most boats it is the angle between the direction of motion and the centre line of the boat. Ordinarily we refer to it as the "leeway angle".

The other is the angle of attack of the sails (strictly, the composite of everything above water exposed to the wind). Normally this is taken to be the acute angle between the main boom, which is fairly representative of the chord of the curved sail, and the direction of the apparent wind.

A useful point in thinking of "foils" (in air or water) and the forces on them is that the resultant force tends to be nearly perpendicular to the chord in many common situations. Thus a force produced by a sail has its direction nearly perpendicular to the boom.

An "aside" may be appropriate here. Many people believe through intuition that one measure of good performance of a sailboat is to have the smallest possible leeway angle. This is a misconception. As Edmond Bruce points out in Chapter IV and elsewhere, the proper criterion is to realise the lowest possible drag angle of the hull, or the highest lift-drag ratio. This does not usually occur at lowest angle of attack. There may be, in fact, no inconsistency between a rather high leeway angle and a low drag angle. Off the wind there are situations in which the angle of attack of the sails is actually higher than the drag angle. (See Fig. 3 in Chapter IV.) We must not let intuition run away with us.

Sometimes one comes upon the statement that "induced drag", or the additional resistance to forward motion which exists when there is a leeway angle different from zero, is proportional to the square of the angle of attack, or in this case the leeway angle. That again suggests the desirability of keeping the leeway angle down. This, too, is misleading. It is a thought which we must set aside. The hull must develop a side force equal in magnitude to that of the sails. The size of it is set by the size and shape of the rig, the angle of sailing, the strength of the wind, etc., not by the hull. The hull must oppose it. As it does, we obviously want minimum resistance to forward motion. Here again we come back to the proper criterion, which is low drag angle or high lift-drag ratio.

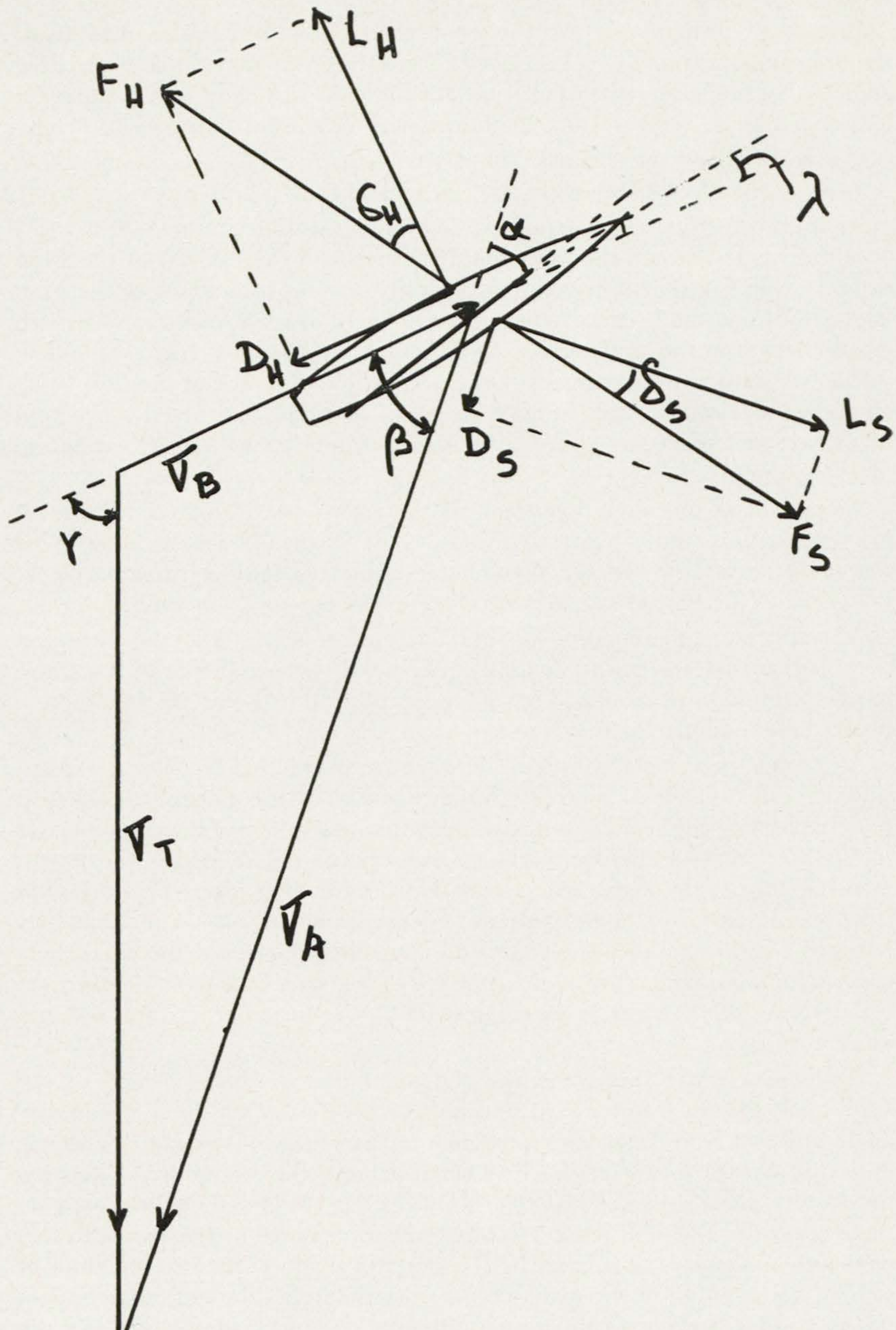


Fig. 2. The Sailing Triangle and the Principal Forces

Fig. 2 puts these things in their proper relationship. As has been noted, everything has been projected into the horizontal plane. The velocity vectors are known in length and direction and form a closed triangle, for sailing at constant speed and angle. The force vectors are somewhat defined in direction but not so far in magnitude.

Right here lies the major weakness of the "Course Theorem", the fact that it deals only in directions and angles. We must, therefore, resist the temptation to conclude from it that for best speed to windward we must sail at the lowest possible values of the two drag angles to produce the lowest possible beta. This is correct for sailing closest to the wind (direction), not for the best *speed* to windward (magnitude). Most boats, when sailed as close to the wind as possible, are being "pinched"—headed close at the expense of speed. There are, of course, times when this is just what is wanted.

As we keep coming back to consideration of drag angle, we must keep before us the fact that the drag angle is made up, in effect, of the *two* components of the resultant force, the lift perpendicular to the direction of the apparent wind or course and the drag in the line of the apparent wind or course, the motion of the boat. A drag angle may be improved by altering lift or drag or both. In the critical stages of design, both must have plenty of thought.

While this is not the place for extensive review of the possibilities, a few of them may be noted:

Lift of rig may be improved by alteration of the curvature and trim of sails, by careful adjustment of the "slot" between the jib and the mainsail, by bringing the foot of the sail close to the deck to reduce or eliminate losses due to eddies there, by reducing the diameter of the mast, and in many other ways.

Drag of rig (and everything else exposed to the wind) can be reduced by reducing the number and size of stays and the diameter of the mast, by "fairing" or smoothing all points of attachment of rigging, by streamlining the above-water portion of the hull (and crew), etc.

Lift of hull may be improved by certain changes in shape. Curved underwater foils are very tempting to try.

Drag of hull can be reduced by fairing, smoothing, and streamlining. Perhaps a rudder can be omitted or retracted. (See Chapter XXIX.)

All of these must obviously be kept within practical limits. That they can be highly rewarding has been shown over and over again. For instance, the 12-meter yachts show major improvements in their rigs in the last 15 years by careful attention to detail. Many winning skippers in many racing classes have improved their boats by careful tuning and by making the most of every detail.

Most of these adjustments, alterations, and redesigns will affect one or the other of the drag angles and hence the angle between apparent wind and course, as the Course Theorem teaches.

B. *Magnitudes of Forces and Force Coefficients.* To round out the picture insofar as is possible, we now bring in the magnitudes of the forces. As Edmond Bruce has shown in Chapter IV, one valuable way to do this is to express the equal and opposite sail and hull forces and set them equal to each other.

$$|F_S| = C_S \frac{\rho_A}{2} A_S v^2 \tag{A}$$

$$|F_H| = K_H \frac{\rho_W}{2} W^{2/3} V_B^2 \tag{B}$$

The vertical lines around F_S and F_H indicate magnitudes. The total sail and hull force coefficients C_S and K_H are defined by these equations when the forces are in pounds, ρ_A and ρ_W, the densities of air and water, are in slugs per cubic foot (0·0024 and 1·99), A_S is in square feet, W in pounds, v in feet per second, and V_B in knots. Now, since these are equal during sailing at equilibrium (no acceleration or deceleration),

$$\frac{V_B}{V_A} = 0{\cdot}585 \frac{\sqrt{A_S}}{\sqrt[3]{W}} \sqrt{\frac{C_S}{K_H}} \tag{C}$$

after the values of the densities have been put in and the units for apparent wind speed have been changed to knots. (This is all given in more detail in Chapter IV.)

An important caution here is that K_H varies strongly with drag angle and in most cases with speed. Hence "matching pairs" of values of V_B and K_H must be used in any calculation.

To a lesser extent, this is a problem also with C_S and V_A. The problem is not as serious because C_S does not vary with V_A. Often, also, within a useful working range, it does not vary greatly with angle of attack or drag angle. (Over a wide range of sailing angles, the sail force coefficient is at or close to the first peak of the polar curve for sail coefficients, as shown by Edmond Bruce in Chapter I.)

As we shall see, there are times when this expression would be more convenient in terms of V_B/V_T or V_{MG}/V_T. By applying formula (A) of the preceding chapter we can express it in the alternative forms

$$\frac{V_B}{V_T} = \frac{\sin\gamma}{\sin\beta} \times 0{\cdot}585 \frac{\sqrt{A_S}}{\sqrt[3]{W}} \sqrt{\frac{C_S}{K_H}} \tag{D}$$

$$\text{and } \frac{V_{MG}}{V_T} = \frac{\sin\gamma\cos\gamma}{\sin\beta} \times 0{\cdot}585 \frac{\sqrt{A_S}}{\sqrt[3]{W}} \sqrt{\frac{C_S}{K_H}} \tag{E}$$

These two equations require knowledge or assumptions about reasonable values of the angles. This extra complication proves to be worthwhile.

As a reminder of the interrelationships with which we are dealing, it is desirable to look back to Fig. 15 of the preceding chapter, the set of circles of constant values of V_B/V_A. Since V_B/V_A is just what we have in equation (C) above, we now know that along any one of those circles a given boat (fixed A_S and W) will have a constant ratio C_S/K_H. (Useful as this can be, it is not as broad as the statement suggests, because a given boat will not be able to sail over a wide range of values on any one of these circles of constant V_B/V_A.) The circles show that higher speed goes with higher values of V_B/V_A. Thus the equation (C) does tell us things we need to know about speed and designing for speed. An application of this is given in Chapter XXX.

In the form (C) the equation allows prediction of V_B/V_A in terms of a known or contemplated set of values of A_S, W, C_S and K_H. Alternatively, for an existing boat, the formula can be used the other way around to determine C_S/K_H by measuring V_B/V_A, perhaps on several courses and in varying strengths of wind. The boat's existing values of A_S and W will be used.

An energetic sailor may make "tethered tests" of his boat (Chapter I) and performance measurements (Chapter XI). Then, with the equation, he will be in a position to determine K_H.

Another sort of use of the equation is to predict the effect of changing one of the parameters which describe the boat. An example would be to estimate the effect of altering sail area, or to figure optimum sail area for a certain situation. (See Section J in the next chapter.)

A designer might very well find it valuable to assemble all available performance data (polar curves, etc.) and prepare for himself a listing or tabulation of values of the parameters versus type and performance. In the next chapter we shall do a little of this sort of thing as a sampling of the possibilities.

C. *Sail Area-Weight Ratio.* Over the years, various simple relationships between sail area and weight or displacement have been used. Most of them are not well adapted to comparisons of craft differing widely in type or size. The form of this ratio which appears in equation (C) does not have any such limitations. It is the square root of the sail area divided by the cube root of the weight. This ratio has the great virtue of being dimensionless. It can, therefore, be applied over a wide range. Experience suggests that for our purposes this ratio has more meaning than the use of its two components, sail area and weight, separately, as will be evident from the following. (This ratio is coming into more general use.)

Probably a fairly typical value of the ratio for modern, fast keel boats is in the neighbourhood of 1·0. This is about right for a 12-meter (Measured A_S about 1750 sq ft, W is 60,000 to 70,000 lbs, and $\sqrt{A_S}/\sqrt[3]{W}$ is 1·07 to 1·02). It is about right also for many cruising-racing craft.

For multihulls, the values are much higher. Close to the bottom of the range lie the heavier cruising trimarans and catamarans at around 1·25.

At the top of the range are the fastest racing catamarans (in classes B, C, and D) with values between 1·8 and 2·0.

(Since this ratio involves a square root and a cube root, modest changes in the ratio come from large changes in sail area or weight. For instance, taking out one-half of the weight of one of those fast keel boats with ratio 1·0 without changing the sail area would increase $\sqrt{A_S}/\sqrt[3]{W}$ only to about 1·25. This is in the order of leaving off all the ballast of the keel boat, redistributing the remaining weight, and finding oneself with a cruising trimaran. Or, in changing sail area, the "cruising trimaran" with ratio 1·25 would have to double her sail area to get the ratio up to 1·75.)

The dominant role played by this ratio is illustrated in a different way in sections K and L of the next chapter.

Inasmuch as all of the fastest water-borne sailing craft have this ratio at a very high value, it is a safe conclusion that for very high-speed sailing, $\sqrt{A_S}/\sqrt[3]{W}$ must be at least as high as 1·8.

D. *Sail and Hull Force Coefficients*. These two coefficients do not lend themselves to a parallel analysis. The problems become a good deal more complicated. Rather than attempt a broad and consequently vague statement about them, we shall proceed now to look at a few examples with the best numbers we can get—measured, estimated, or even only guessed.

In advance we should repeat the warning that the coefficients used in any calculation must be appropriate to the particular sailing situation which is being considered. Also we must keep in mind that these coefficients relate to the total or resultant forces on sail and hull, not just the drive and drag components.

E. *Effect of Variation in Wind Strength*. From the fact that we have expressed boat speed in the ratio V_B/V_T or the ratio V_B/V_A, a reader may be tempted to think that we are overlooking or ignoring the common observation that performance relative to wind strength falls off with increasing wind. Second thought should show that we are not. All of the foregoing discussion of the sailing triangle, the circles of constant beta and constant V_B/V_A, and the directions of forces applies for any wind strength as it does for any kind of sailing craft in any sailing situation.

In the area of the magnitudes of the forces and the relationships between sail and hull force coefficients, sail area, weight, and the elements of the sailing triangle, the discussion is also correct. Differences will be mostly in the two coefficients, which may be somewhat sensitive to wind strength. If values of these appropriate to the sailing situation of immediate interest are used, the variation of performance, with wind strength, will be properly reflected.

Strictly speaking, the same things can be said about the effects of waves or sea state, which also vary with wind strength. That introduces serious additional complications which we shall not try to handle here. For first simple understanding of the material covered, it is best to think of favourable, even ideal, conditions for the sailing.

CHAPTER X

ILLUSTRATIVE EXAMPLES AND APPLICATIONS

July 1973

by Henry A. Morss, Jr.

A. *The International 12-Foot Dinghy*. The boat described in most detail in this book (Chapters I and IV) is the International Dinghy. From Figs. 3, 4 and 5 of Chapter IV the data in Table A are derived, all for $V_B/\sqrt{L} = 1{\cdot}0$.

TABLE A
International 12-Foot Dinghy

γ	β	δ_S	δ_H	α	C_S	K_H	C_S/K_H	V_B/V_A	V_B/V_T
48°*	36°	18°	18°	26°	1·5	8	0·2	0·3	0·35
90°	60°	21°	39°	29°	1·6	3·2	0·5	0·5	0·55
180°	180°	90°	90°	90°	2·0	1·9	1·0	0·7	0·4

*Best to windward.

While somewhat rough, the figures in the table provide a good look at the values for one kind of boat. The values of sail coefficient are high, probably in part because of the fact that the rig consists of just one sail and a minimum of rigging. Total hull force coefficient is high when the boat is close-hauled. As she heads off, her K_H decreases sharply. The ratio V_B/V_A increases as the sailing angle widens, while the ratio V_B/V_T varies much less, with its best value for reaching and lower values close-hauled and off the wind.

B. "*Antiope*". The 5·5-metre racing class sloop *Antiope* is of particular interest because she is the only full-sized sailing yacht whose hull has been subjected to a thorough testing programme in a towing tank, the big tank of the David Taylor Model Basin of the U.S. Navy. (See reference in Bibliography.) Inasmuch as the data relate to the hull only, an extensive analysis is not possible. A few values of K_H are reproduced in Table B.

TABLE B
"*Antiope*"
(LWL = 22·7 ft; W = 5,650 lbs)

V_B Knots	Approx. $V_B/\sqrt{L}$	K_H (running)	K_H (windward)	$\delta_H$est. (windward)
3	0·6	0·5	2·0	18°
4	0·8	0·55	2·0	18°
5	1·0	0·6	2·1	18°
6	1·2	0·8	2·4	20°

The values for running before the wind should be reliable. Those for sailing to windward involve some question because of uncertainty as to the proper values of leeway angle, rudder angle, and heel angle for sailing close by the wind at these speeds. Data at the likely values are not provided. Thus it has been necessary to do some interpolating and some estimating. (This is more of a problem with data from towing tanks which attach the model to a carriage at two points than it is with the towing tank procedures described in Chapter XIX.)

It is worth noting that the authors of the report of the tank tests of the hull of the *Antiope* give an analysis for sailing by the wind at $V_B = 5$ knots which shows that the likely condition for that is with leeway angle in the neighbourhood of 1·6° and rudder angle also at 1·6° to realise L/D of 3 or $\delta_H = 18°$ approx. If the boat could be sailed at a leeway angle of 5° and the same rudder angle, she would realise L/D close to 6 and δ_H close to 10°. She cannot carry the sail area which would produce this. Thus, through her design, she falls far short of what looks to be possible. This is a graphic example of the desirability of *designing* for a leeway angle in the range of five degrees, as Edmond Bruce has emphasised so strongly. (See Chapter IV.)

A comparison of the values for the *Antiope* (Table B) with those for the International 12-ft dinghy (Table A) reveals much lower hull force coefficients. This is typical of heavily-ballasted, displacement boats. Also, here, we see that the coefficients increase with increasing boat speed.

C. *An Ocean-Racing Yacht Hull.* Herreshoff (see bibliography) gives data for "a modern ocean racing boat designed to the Cruising Club of America Rule" (1964). (Waterline length 33·2 ft, displacement 28,000 lbs.) Values corresponding to those for the *Antiope* are given in Table C.

TABLE C

Ocean Racing Yacht of 1964

V_B Knots	Approx. $V_B/\sqrt{L}$	K_H (running)	K_H* (windward)	δ_H* (windward)
5	0·86	0·50	1·6	$17\frac{1}{2}°$
6	1·03	0·53	2·1	14°
7	1·20	0·63	2·9	$12\frac{1}{2}°$
8	1·37	1·04	4·0	$14\frac{1}{2}°$
$8\frac{1}{2}$	1·46	1·45	4·9	$16\frac{1}{2}°$
9	1·54	2·0		

*From tests at $\lambda = 3°$ at varying angles of heel.

Here again the values of K_H for running before the wind are probably good. They are plotted in Fig. 1 to illustrate graphically the sharp rise with increasing speed. Significant increase begins at about $V_B/\sqrt{L} = 1$; steep increase, above $V_B/\sqrt{L} = 1·25$. This comes, of course, mostly from the "wave-making resistance" of the ballasted displacement hull. It can be

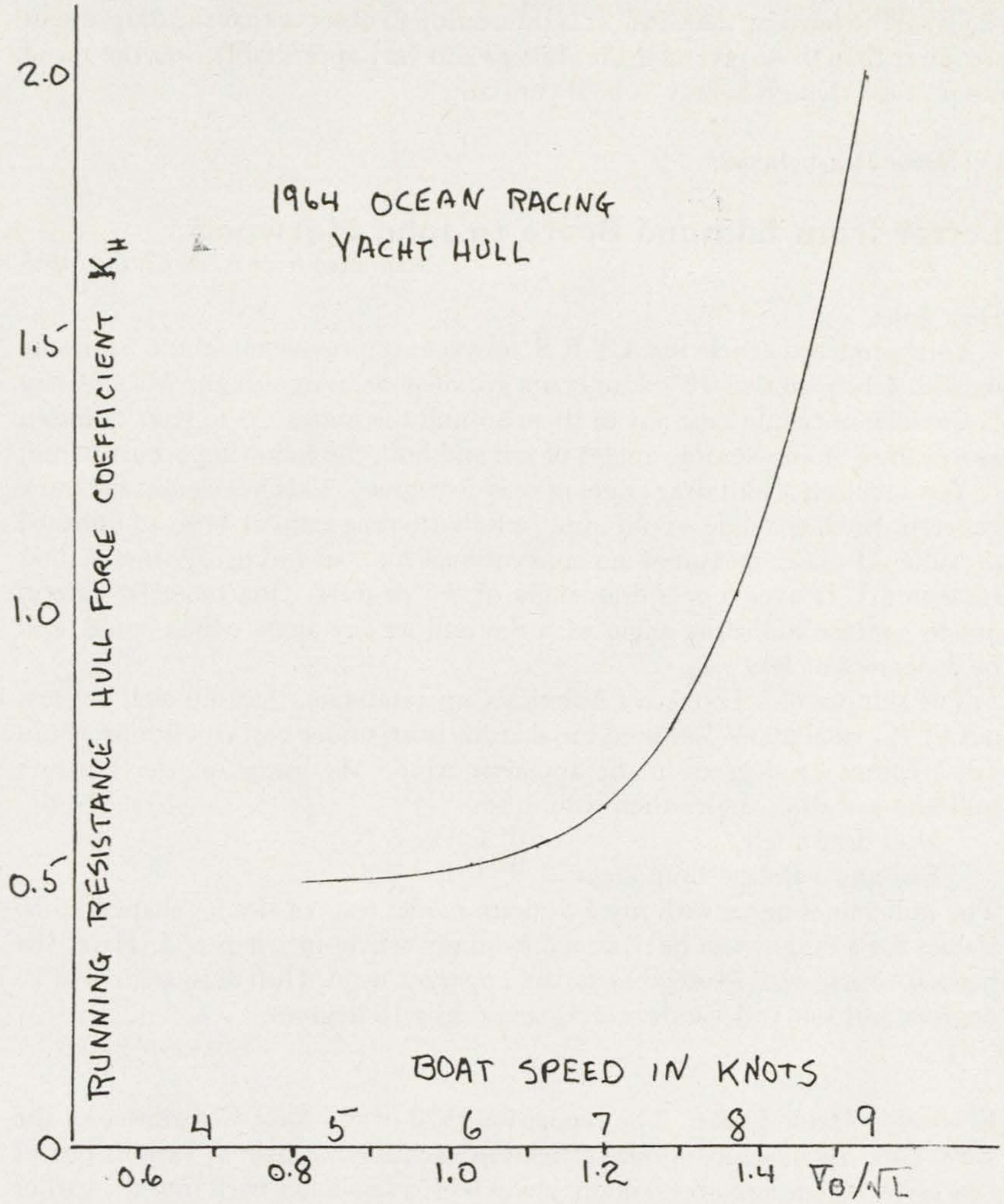


Fig. 1. Hull force coefficient for ocean racing yacht (1964) versus speed, for running before the wind

contrasted with the behaviour of light, long, slender hulls, whose wave-making is slight even at $V_B/\sqrt{L} = 3$ and which can, therefore, be driven much faster. (See the curves in Fig. 5 of Chapter XXII for the hulls with length to beam ratios of 12 and 16.)

The values in Table C for windward sailing are subject to the same kind of uncertainty as those for the windward sailing of the *Antiope* in Table B. The ones here for the ocean racing yacht hull are taken at a leeway angle of three degrees, as is noted at the foot of the table. We have no way of knowing how representative they may be of the condition of the full-sized boat when she is sailing hard by the wind. It is interesting to observe that the drag angles are lower than those given for the *Antiope* and vary appreciably over the speed range, even though leeway is held constant.

D. *Some Drag Angles.*

Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 53, Oct. 1965

Dear John,

Your proposed article for A.Y.R.S. on yacht improvement would be timely indeed. I believe that 12-metre boats are of poor basic design. Many Class C Catamarans could beat any of them around the buoys. As to your question as to values of known drag angles of sail and hull, the following occurs to me:

You mention a hull drag angle of only 5-degrees. This has caused me some concern. Such an angle would imply a hull lift-drag ratio of 11·4, an unheard of value. I have measured no conventional hull, including 5·5 meter, that measured L/D over 6 or a drag angle of 9·5 degrees. One must be careful not to confuse hull drag angle with the hull leeway angle which could well be 5 degrees or less.

The skipper of a 12-metre, America Cup candidate, that did well but lost out to "Constellation", assured me that his boat, under best conditions, could sail a course 18 degrees to the apparent wind. My guess on the separate hull and sail drag angles then would be:

Hull drag angle $=10°$ L/D—5·7
Sail and windage drag angle$=$ $8°$ L/D—7·1

The hull values agree with my 5·5 metre model tests of similar shaped hulls. Values for a dinghy can be obtained from my article in Chapter I. Here, the highest course was 34 degrees to the apparent wind. Hull drag angle was 16 degrees and sail and windage drag angle was 18 degrees.

EDMOND BRUCE.

E. *Twelve-Metre Yachts.* The report for 1970 of the Race Committee of the New York Yacht Club, several articles in yachting magazines, various bits of hearsay evidence and observation, along with a few looks back into the earlier pages of this book, make it possible to piece together a rough quantitative sketch of the performance of the 12-metre yachts. The preparation has been a devious one through trials of many combinations for each of the six sailing situations below, with each trial tested against available data, hunches, and intuition and tested for internal consistency. (Indeed some consistency has been sought between these six points for the "twelves" and the analyses of other craft in this chapter. The whole story of all of them is condensed into a single table in Appendix C.)

(1) *To windward in a 10-knot breeze.* Apparently the 12-metre makes good something like 5·6 knots dead to windward in a 10-knot wind. It is believed that she does this at $\beta = 22°$. From the orthogonal circles or by formula it is deduced that $\gamma = 37°$ and $V_B = 7$. The displacement W is 61,000 lbs. For

windward sailing the "measured" sail area will be used, 1,750 sq ft. (See previous chapter.) Then $\sqrt{A_S}/\sqrt[3]{W} = 1{\cdot}07$. These numbers can be used in equation (E) of the previous chapter to calculate the ratio of sail and hull force coefficients.

$$\frac{5{\cdot}6}{10} = \frac{\sin 37^\circ \cos 37^\circ}{\sin 22^\circ} \times 0{\cdot}585 \times 1{\cdot}07 \times \sqrt{\frac{C_S}{K_H}}$$

$$\text{and } \frac{C_S}{K_H} = 0{\cdot}49$$

For the rig with large overlapping genoa, we estimate C_S at 1·2 to find that K_H will be about 2·5. This is higher than the corresponding values in Tables B and C as may be expected, since the "twelve" sails appreciably closer to the wind. δ_H may be about 13° and δ_S about 9°.

(2) *To windward in* 20-*knot wind.* V_{MG} appears to be about 6·5 knots. By trial and error with a range of possible values of the angles and speeds, we conclude that C_S/K_H must be about 0·25, a rather low value which indicates a severe falling off of the relative performance in the heavier wind. If C_S is taken to be 0·9, lower than the value in a 10-knot wind to allow for lower efficiency and also less effective area because of the greater angle of heel, then K_H will have the rather high value 3·6. This also suggests poorer behaviour in the stronger wind and rougher water. Of the various combinations of β, γ, and V_B tried for this study, a likely set is $\beta = 27^\circ$, $\gamma = 38^\circ$, and $V_B = 8{\cdot}4$ knots. δ_S is probably 10° to 12° and δ_H, 17° to 15°.

(3) *Broad reaching in a* 10-*knot breeze.* The second and third legs of the America Cup course sailed by the 12-metre yachts in competition are designed to be at $\gamma = 135^\circ$. For these legs and for the dead runs, very large spinnakers are carried. Most likely a value of sail area larger than that used for sailing to windward will be appropriate. This becomes an element in the trial and error approach.

The most consistent results seem to come out if the effective sail area is assumed to be 2,250 sq ft (nothing like the total actual area of mainsail and spinnaker, but probably near the area of the windstream which is intercepted). $\sqrt{A_S}/\sqrt[3]{W} = 1{\cdot}20$.

The resulting boat speed is 7·6 knots with beta at 86°, V_B/V_A at 1·06 and C_S/K_H at 2·3. The best fit now is $C_S = 1{\cdot}5$ and $K_H = 0{\cdot}65$ with δ_S close to 20° and δ_H close to 66°.

(4) *Broad reaching in a* 20-*knot wind.* In this situation of broad reaching in a strong wind, the boat is presumably sailing at her maximum possible speed, which is near 10 knots. Again the sail area is taken to be 2,250 sq ft. The resulting numbers are $V_B = 10$ knots or very slightly above, $\beta = 106^\circ$, and $C_S/K_H = 0{\cdot}96$, less than half the value for reaching on the same course

in the lighter wind. Lower efficiency may be assumed all around. If C_S = 1·25, K_H is 1·3. Possibly each of these should be a bit higher.

(5) *Before a 10-knot wind.* The best aviator's parachute has a "sail coefficient" of about 2 related to its area when projected into a horizontal plane. For the 12-metre yacht before the wind, the efficiency will be lower. C_S will be taken to be 1·8. As an estimate of the projected area of the rig, the same figure 2,250 will be used for sail area as in the preceding two calculations, and $\sqrt{A_S}/\sqrt[3]{W} = 1{\cdot}20$. Boat speed will be in the neighbourhood of six knots. Then K_H will probably be close to 0·5 without much variation with modest changes in speed. With C_S and K_H given, the exact speed of the boat can be figured.

$$\frac{V_B}{V_A} = 0{\cdot}585 \times 1{\cdot}20 \times \sqrt{\frac{1{\cdot}8}{0{\cdot}5}} = 1{\cdot}33$$

Now since $V_B + V_A = V_T$ (before the wind)

$$\frac{V_B}{V_T} + \frac{V_A}{V_T} = 1$$

$$\frac{V_B}{V_T} + \frac{V_A}{V_B} \cdot \frac{V_B}{V_T} = 1$$

$$\frac{V_B}{V_T} = \frac{1}{1 + \frac{1}{V_B/V_A}} = \frac{1}{1 + \frac{1}{1{\cdot}33}} = 0{\cdot}57$$

Thus the boat speed is 5·7 knots and the apparent wind speed 4·3.

(6) *Before a 20-knot wind.* A key to the simplicity of the calculation for sailing before a 10-knot wind lies in the fact that with the boat speed below $V_B/\sqrt{L} = 1$, the value of K_H will not vary much with modest variations in boat speed. The same is not true for sailing before a 20-knot wind, because the boat will be approaching her maximum speed and will find her actual speed limited by the rapid increase in K_H. Therefore the calculation must test several values of K_H and assess which pair, K_H and resulting boat speed, is most probable. The same values of A_S and C_S will be used.

K_H	V_B/V_A	V_B/V_T	V_B
0·8	1·053	0·513	10·25
0·9	0·993	0·498	10
1·0	0·942	0·485	9·75
1·1	0·898	0·473	9·5
1·2	0·860	0·462	9·25

This table illustrates the sensitivity of boat speed to changes in K_H in sailing before a strong wind. Which of these is closest to the real performance? The source data do not suffice for a selection. A guess is that the speed will be 9·6 knots at $K_H = 1{\cdot}05$.

These detailed estimates of the numbers which characterise six points of sailing of the 12-metre yachts illustrate what can be done with very limited information. Probably the least reliable part of the calculations is in the estimates of sail areas and sail force coefficients. As more tests provide better values for these, the end results of calculations of this sort will be more accurate.

F. *The "Tornado"*, a class "B" racing catamaran. Reliable data on the performance of the fast racing catamarans are hard to find. Thanks to Professor Bradfield of the State University of New York at Stony Brook, there are data for a *Tornado* sailing in light winds. From the published polar curve it appears that she can realise $V_{MG}/V_T = 0{\cdot}7$ at $\gamma = 50°$ and $V_B/V_T = 1$, roughly. These figures do not fit together very well. When the trial and error process is put to work, it leads to the conclusion that the likely real performance is probably close to $V_{MG}/V_T = 0{\cdot}64$ at $\gamma = 50°$, $\beta = 25°$, $V_B/V_T = 1{\cdot}0$. $\sqrt{A_S}/\sqrt[3]{W}$ is taken to be 1·9. These lead to $C_S/K_H = 0{\cdot}24$. With beta as low as 25°, both drag angles are low. As a guess, $\delta_S = 12°$, $\delta_H = 13°$, $C_S = 1{\cdot}3$, and $K_H = 5{\cdot}3$. This last is slightly more than double the value of K_H for the 12-metre sailing by the wind in 10 knots of wind at the same estimated value of the hull drag angle. That is not a great surprise, because the running resistance coefficient is presumably somewhat more than twice as high.

The maximum speed of the *Tornado* is about V_B (max.)$/V_T = 1{\cdot}35$ or 1·4 with true wind just aft of the beam. If we choose $\gamma = 95°$ and consult the orthogonal circles again, we find $\beta = 38°$ and $V_B/V_A = 0{\cdot}84$ approximately. C_S/K_H is then about 0·6. To fit possible values of δ_S, δ_H, C_S and K_H here stretches the imagination harder than did the windward performance. Apparently δ_S must still be held down to 12° to allow 26° for δ_H. With C_S at 1·4, K_H will have to be about 2·4, a low value at $\delta_H = 26°$ but not unimaginable.

The *Tornado's* fastest progress to leeward appears to occur at relatively high boat speed at an angle rather far away from the direct downwind course. The problem in the trial and error process is to get C_S/K_H low enough to permit what are thought to be reasonable values of C_S and K_H. The conclusion is that best leeward progress is about 0·6 times the speed of the true wind at $V_B/V_T = 1{\cdot}05$, $\beta = 60°$, $\gamma = 125°$. These lead to C_S/K_H close to one and both C_S and K_H close to 1·5. If a slightly higher value of C_S were permitted, or a lower K_H, or both, the speed made good to leeward might be 0·65 times the speed of the true wind at values of the other quantities somewhere in the range of $\beta = 65°$, $\gamma = 130°$. Difficult choices in the absence of better raw material.

Dead before the wind, the calculation is a simpler one, as it was for the 12-metre yachts. The principal uncertainty is, as usual, in the value to select for the sail force coefficient. Probably the shrouds on the *Tornado's* mast prevent putting the main boom as far out as would be desirable. Probably also not much help is provided by the jib. To reflect these inefficiencies, C_S has been estimated at 1·25. K_H is taken at 1·05. Then V_B/V_T is about 0·55. If an even lower value had been assigned to C_S or a higher one to K_H, or both, the speed would have been somewhat lower.

An appraisal of these four calculations for the *Tornado* again points to the inadequacy of the source data. It may be noticed that with the values chosen for K_H, the *forward component* of that coefficient is 1·2 for sailing to windward and 1·05 on the other courses. Perhaps this is reasonable in the face of the much smaller drag angle for windward sailing.

G. "*Icarus*". *Icarus* is the Tornado catamaran which, fitted with hydrofoils to make her "fly", sailed at the second highest speed in the Player's speed competition in Portland Harbour, England, in October 1972. Her best V_B/V_T was probably about 1·5 in winds of 10 to 13 knots with gamma in the range of 100°. This requires beta to be 37°. V_B/V_A is about 0·9 and C_S/K_H must be near 0·65 if $\sqrt{A_S}/=\sqrt[3]{W}$ is taken to be 1·9, as for the *Tornado*. This is higher than the corresponding figure of about 0·6 for the regular *Tornado* and indicates that with her foils in this moderate wind, the *Icarus* sails with $K_H = 2{\cdot}1$ or thereabouts, a very good value with δ_H at 25° (δ_S still at 12°). (The same value 1·4 is used for C_S.)

The fastest speed of *Icarus* was 21·6 knots in a true wind of 19 knots, or $V_B/V_T = 1{\cdot}14$. If again γ is assumed equal to 100°, then beta must be about 45°. V_B/V_A will be 0·83 and C_S/K_H about 0·56. With C_S at 1·5, K_H must be about 2·7 with δ_H at perhaps 30° and δ_S at 15°.

These figures may be representative of the best performance to date of the flying hydrofoils. We have no other quantitative report against which to check.

H. "*Crossbow*". A "one-way proa" designed for the purpose, *Crossbow* won the Player's speed record in October 1972. She had a main hull 60 ft long and 2 ft wide, a "gondola" to windward on a long arm, a conventional-looking sloop rig with 932 sq ft of sail. In the agility of her crew of five lay most of her stability. Her weight, not exactly known, was probably about 2,400 lbs including the crew. The ratio $\sqrt{A_S}/\sqrt[3]{W}$ then was nearly 2·3. That is perhaps the highest ever on a water-borne sailing craft.

In light winds when sailing with gamma in the range of 100° to 110°, she probably sailed at twice the speed of the true wind. First thought suggests that that should work out easily, with her very high value of $\sqrt{A_S}/\sqrt[3]{W}$. Some exploration of the figures proves otherwise, however. With her speed a third higher than the *Tornado's* best, beta must be much smaller and consequently also the drag angles. This implies high K_H. The real problem is found right there; its solution is found in reducing the required value of beta.

For actual numbers it seems necessary first not to let the forward component of K_H be below 1·05. That is, $K_H \sin \delta_H$ must not be less than 1·05. Here are some trial calculations, with C_S taken at 1·5. The highest beta used is 30°, since that is known from Chapter VIII to be the largest beta at which V_B/V_T can be as great as 2.

β	V_B/V_T	$\gamma-\beta$	γ	V_B/V_A	C_S/K_H	δ_S	δ_H	C_S	K_H	$K_H \sin \delta_H$
30°	2·00	90°	120°	1·15	0·73	10°	20°	1·5	2·05	0·70
28°	2·00	70°	98°	0·95	0·50	10°	18°	1·5	3·0	0·93
26°	2·00	61°	87°	0·88	0·43	9°	17°	1·5	3·5	1·02
24°	2·00	54°	78°	0·83	0·38	8°	16°	1·5	3·9	1·07

Among other things, this tabulation shows that as beta decreases, so also does gamma. The report of the *Crossbow's* speeds indicates that they were obtained with true wind probably *aft* of abeam. As a compromise of all the considerations, $\beta = 26°$ seems the best choice. The other quantities will have the values given in the table on the line for $\beta = 26°$.

The record-winning speed of *Crossbow* was 26·3 knots in a 20-knot true wind, or $V_B/V_T = 1{\cdot}31$. In this case, if she sails at $\gamma = 110°$, beta must be about 44° and C_S/K_H about 0·52. The higher value in the higher wind strength occurs at a much higher value of beta and is, thus, not more difficult to justify. Obviously her relative performance has fallen off badly. Perhaps $\delta_S = 14°$, $C_S = 1{\cdot}3$, $\delta_H = 30°$, $K_H = 2{\cdot}5$ and the forward component of K_H will be about 1·25, up 20 per cent from its value in the lighter wind.

I. *An Ice Boat.* There is a report of a carefully-made measurement of an ice boat sailing at seven times the speed of the true wind. This calls for some extreme values. If we assume that this was a realisation of the maximum possible speed for given value of beta (see B (e) of Chapter VIII), then beta can be figured from the formula $V_B/V_T = 1/\sin \beta$. It is found that $\beta = 8{\cdot}2°$, a very low figure which indicates a highly efficient rig. An independent estimate of apparent wind angle made on board the boat was in line with this.

The Course Theorem, $\beta = \delta_S + \delta_H$, applies to ice boats as well as others. Thus the value of beta of 8·2° is the sum of the two drag angles. By broadside towing, δ_H has been measured at not much more than one degree after initial acceleration for a good ice boat with sharp runners on glassy ice. This gives a lift/drag ratio for the hull of 50, more or less. Most of beta is the drag angle of the rig. Almost alone, the rig determines minimum beta and maximum speed and is the basis of the very high speeds of good ice boats.

That is as far as our present theory will take us in analysing the behaviour of an ice boat, because the formula from fluid dynamics for hull force which went into equation (C) of Chapter IX may not fit the case of the "hull resistance" of a boat sailing on ice.

J. *Value of Measured Diagrams of Overall Sailing Performance.* (This section of this chapter was written by Edmond Bruce in 1969. It has not been published previously. Introductory parts which repeat material covered earlier in this chapter or in preceding chapters have been omitted.)

Optimum Sail Area

In light winds there is usually no sail area limitation due to heeling. Another type of sail limitation does exist. In the case of stronger winds, one is accustomed to believe that there is too much sail, when going to windward, if heeling is excessive. However, one wonders what would be the limit of worthwhile sail area if one or more canted water foils were used to neutralise the dynamic heeling due to strong winds. See Chapter XXV. Regardless of whether winds are strong or light, the sailing triangle provides positive sail area limitation.

Overall measured performance curves for a given craft show the course angle gamma to the true wind that must be sailed and its accompanying apparent wind course angle beta, to achieve the best speed "made good" to windward. The maximum possible speed to windward will be at $\gamma = 45° + \frac{\beta}{2}$ (from Chapter VIII). Any departure from this relationship indicates that the optimum sail area for best V_{MG} was not employed. The preferred value for beta is always close to the smallest course angle to the apparent wind that can be sailed without stalling the particular craft. The smaller the angle beta can be, the more sail area can be used. (For this we assume that sail and hull coefficients will not vary.) This always results in a higher value for maximum V_{MG}.

Performance Analysis Example

As a specific example of an analysis of overall performance data, *Coquí*, an Arrowhead trimaran, will be used. The performance is reported in Chapter XV.

Coquí presently employs 234 sq ft of sail. A calculation will be made as to the optimum amount of sail that this yacht could use in order to achieve its best V_{MG} to windward.

First, the ratio of the sail coefficient to the hull coefficient, C_S/K_H, that existed during the reported tests will be determined. For this, equation (C) of Chapter IX will be used.

As mentioned, the report states that the sail area was $A_S = 234$ sq ft. The total weight with crew and equipment was 1,600 lbs. This is quite heavy. With these, max. V_{MG} was obtained at $\beta = 37°$, where V_B/V_A was measured to be 0·32. Then,

$$0{\cdot}32 = 0{\cdot}585 \times \frac{\sqrt{234}}{\sqrt[3]{1600}} \sqrt{\frac{C_S}{K_H}}$$

Then $C_S/K_H = 0{\cdot}176$ existed during the tests.

It is known from unpublished tethered sail tests on *Coquí* that, in the presence of hull and rigging windage, the sail coefficient at highest lift was 1·25. Tethered sail tests were described in Chapter I. Thus $K_H = 1{\cdot}25/0{\cdot}176 = 7{\cdot}1$ at $\beta = 37°$. However, for our purposes, the individual coefficients are not necessary, only the ratio C_S/K_H.

The reported data indicate that the best V_{MG} was obtained for $\beta = 37°$. This means, by the "Course Theorem", that this is the sum of the hull drag angle and the sail drag angle. It also means that $\beta = 37°$ is the smallest useful apparent course angle for this hull and sail. These are not appreciably altered by a change in sail area.

By equation (I) of Chapter VIII the optimum speed ratio of this boat to the apparent wind at $\beta = 37°$ would be

$$\text{Opt.}\ \frac{V_B}{V_A} = \frac{\cos(45° + 18{\cdot}5°)}{\sin(45° + 18{\cdot}5°)} = \frac{0{\cdot}446}{0{\cdot}895} = 0{\cdot}50$$

This can also be found on Fig. 6 (or Fig. 2) of Chapter VIII.

Substituting this value of optimum V_B/V_A, also the ratio of coefficients and the weight into equation (C) of Chapter XI, we solve for sail area and find Opt. A_S = 528 sq ft. A summary of comparisons of measured and optimum values for best V_{MG} is shown in the following table for $\beta = 37°$ and W = 1,600 lbs.

	Sail area sq ft	$\frac{V_B}{V_A}$	$\frac{V_{MG}}{V_T}$	$\frac{V_B}{V_T}$	γ
Measured	234	0·32	0·26	0·42	52°
Optimum	568	0·50	0·33	0·74	63½°

It is interesting to observe in equation (C) of Chapter IX that a weight reduction can accomplish the same thing as a sail increase. This would be difficult to achieve since for A_S = 234 sq ft, W = 428 lbs rather than 1,600 lbs. Probably some weight reduction and some sail increase is the right answer.

Note that the table shows that, with an optimum sail area, a marked increase in V_{MG}/V_T is obtained. Yet the "pointing" or angle gamma to the true wind, on a plotted chart course, would be appreciably larger. A boat's merit should not be judged by the smallness of this angle. The larger true angle is the consequence of speed, as can be seen in Fig. 2 of Chapter VIII. However, a boat's minimum pointing angle to the apparent wind, beta, is a valuable indication of the boat's merit.

K. *For Sailing to Windward.* One way to get a deeper insight into the relation expressed in equation (C) of Chapter IX is to concentrate for the moment on sailing to windward at the highest possible speed for a given value of beta, as described in Sec. B (b) of Chapter VIII. The best V_{MG} is obtained at $\gamma = 45° + \frac{\beta}{2}$. Fig. 2 gives a family of curves of values of C_S/K_H versus beta for five set values of the ratio $\sqrt{A_S}/\sqrt[3]{W}$. Because of the fixed relationship between β, γ, V_B/V_T, and V_{MG}/V_T for this particular situation of max. V_{MG}/V_T, the values of γ, V_B/V_T, V_{MG}/V_T, and V_B/V_A are shown, also, along the bottom of the graph.

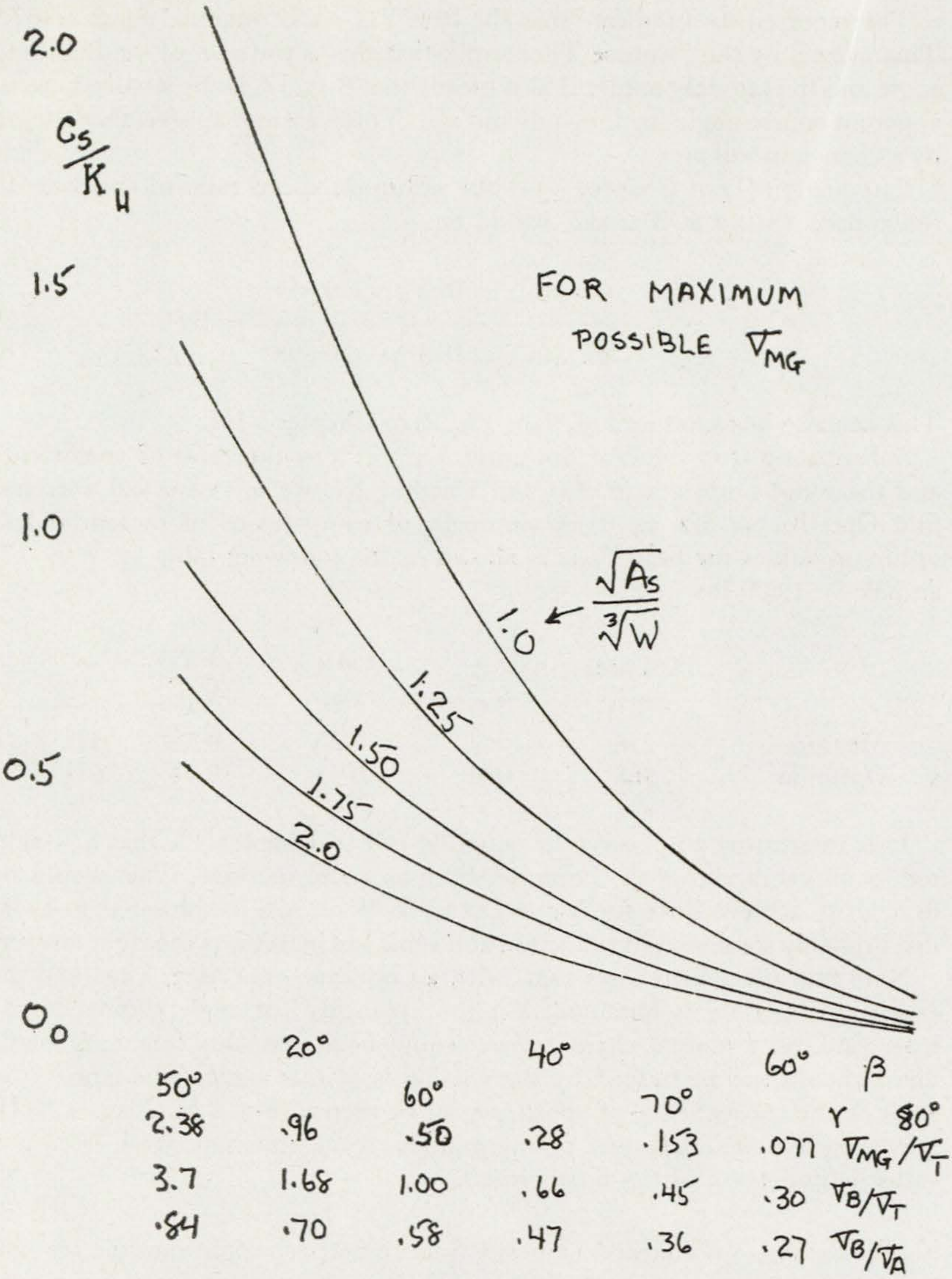


Fig. 2. For maximum possible speed to windward. C_S/K_H vs. β at selected values of $\sqrt{A_S}/\sqrt[3]{W}$. Values of other parameters noted

The relatively large gains which can accrue from sizeable increases in sail area stand out in this drawing. By contrast, impossibly big demands are put on C_S/K_H if that is the only route to improvement.

L. *For Maximum Possible Boat Speed.* Section B (e) of Chapter VIII showed the relationships which must be met to realise the maximum possible speed with a given value of beta. Fig. 3 is a set of curves patterned after those of Fig. 2, but to reflect this situation of maximum possible speed.

These curves look very different from the ones of the previous graph. A bit of study of Figs. 5, 8, 9 and 10 in Chapter VIII reveals that for a given

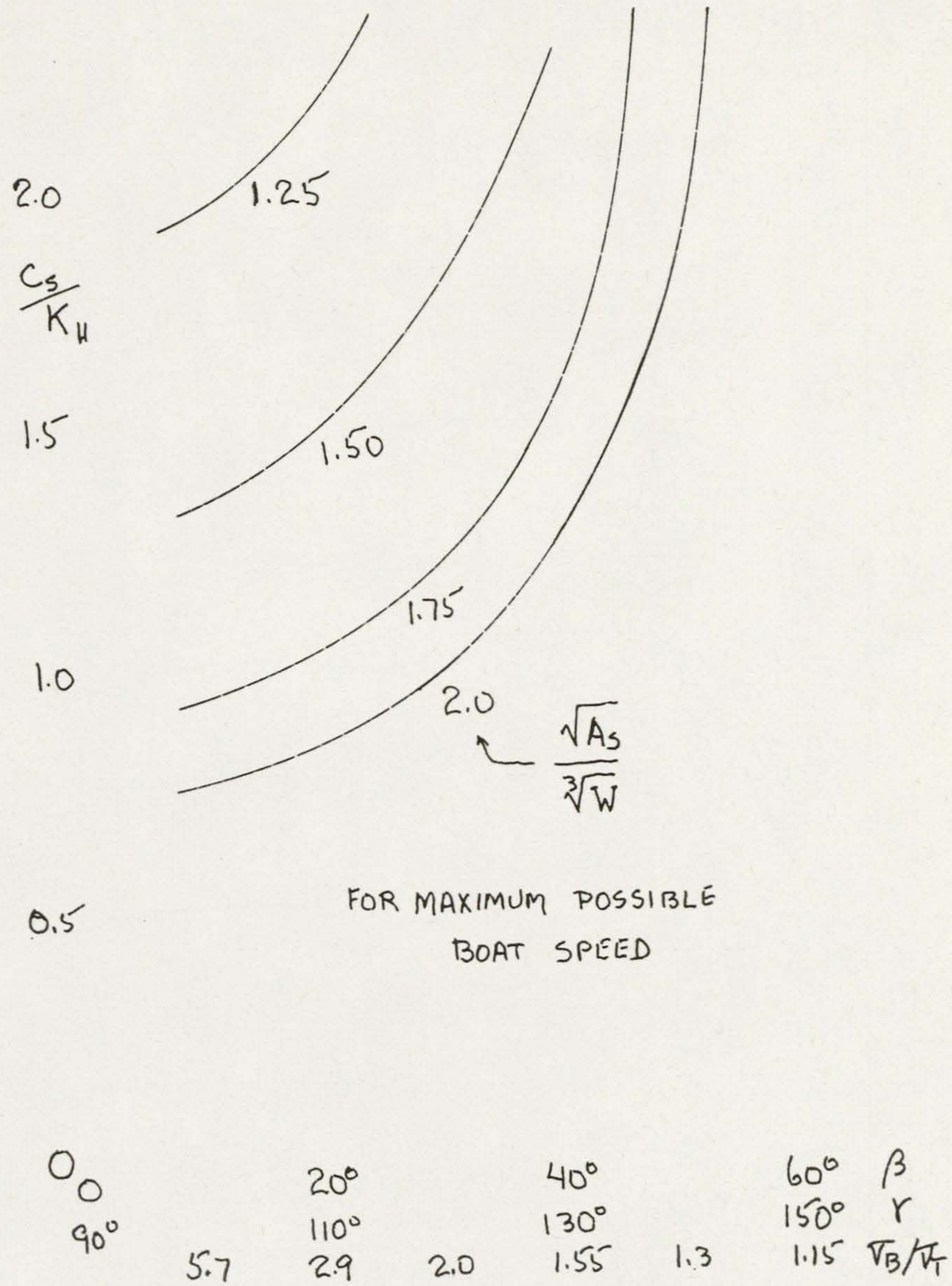


Fig. 3. For maximum possible boat speed, C_S/K_H vs. β at selected values of $\sqrt{A_S}/\sqrt[3]{W}$. Values of γ and V_B/V_T noted

value of beta the values of V_B/V_A increase rather rapidly from one to the next. If we had included a family of curves of the present type to match each of those earlier drawings, we should have seen a more gradual change in the character of the curves than we have by looking only at the end members.

Here is seen the need for C_S/K_H or $\sqrt{A_S}/\sqrt[3]{W}$ or both to be very much

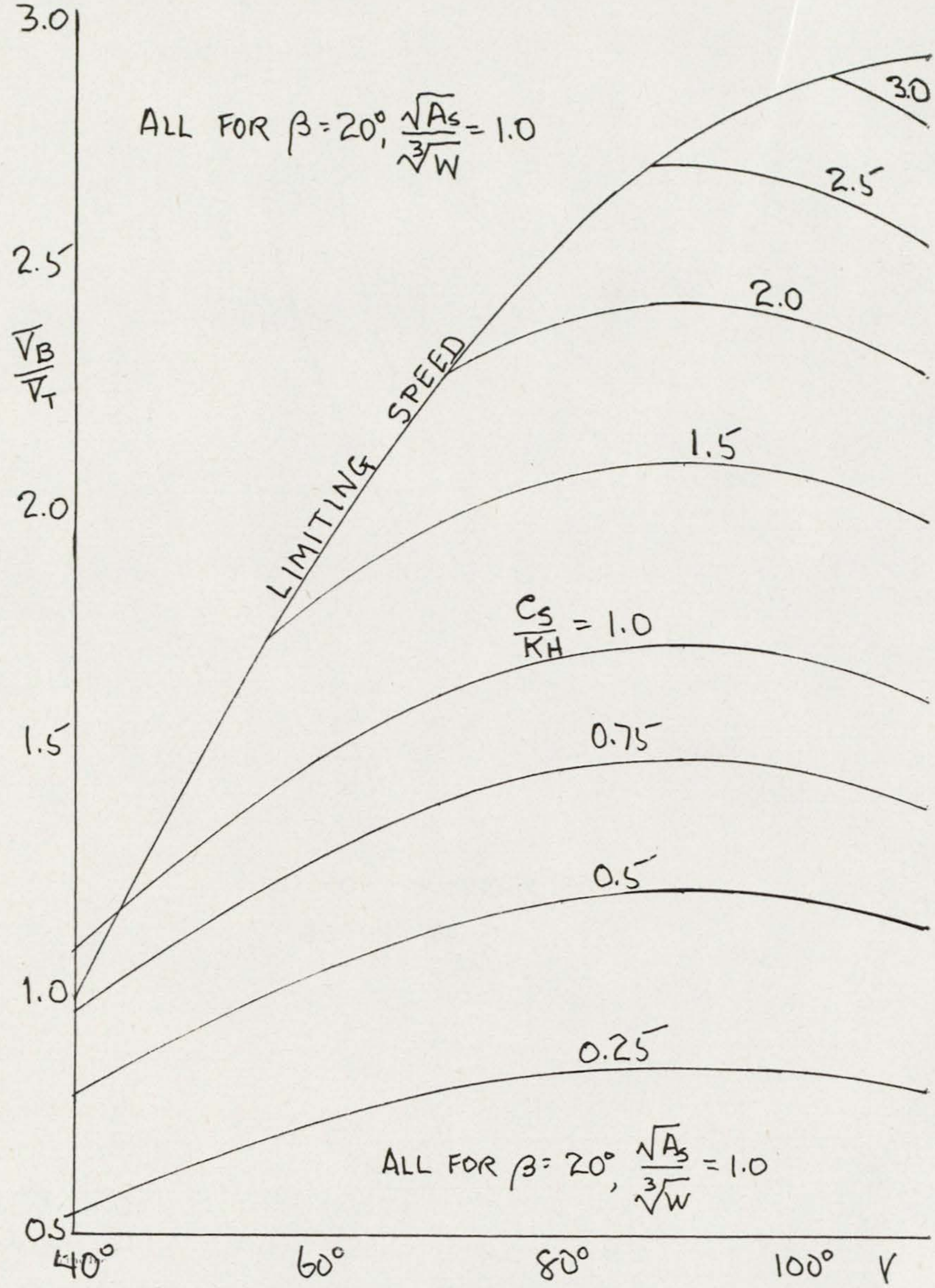


Fig. 4. V_B/V_T vs. γ at $\beta = 20°$ and $\sqrt{A_S}/\sqrt[3]{W} = 1$ for selected values of C_S/K_H

higher for absolute maximum V_B/V_T than for maximum V_{MG}/V_T, as just discussed. A design goal of $V_B/V_T = 2$ looks pretty high.

M. *A Different Look.* As possible assistance to the reader who may still want a better "feel" for this problem of many variables, the relationships of

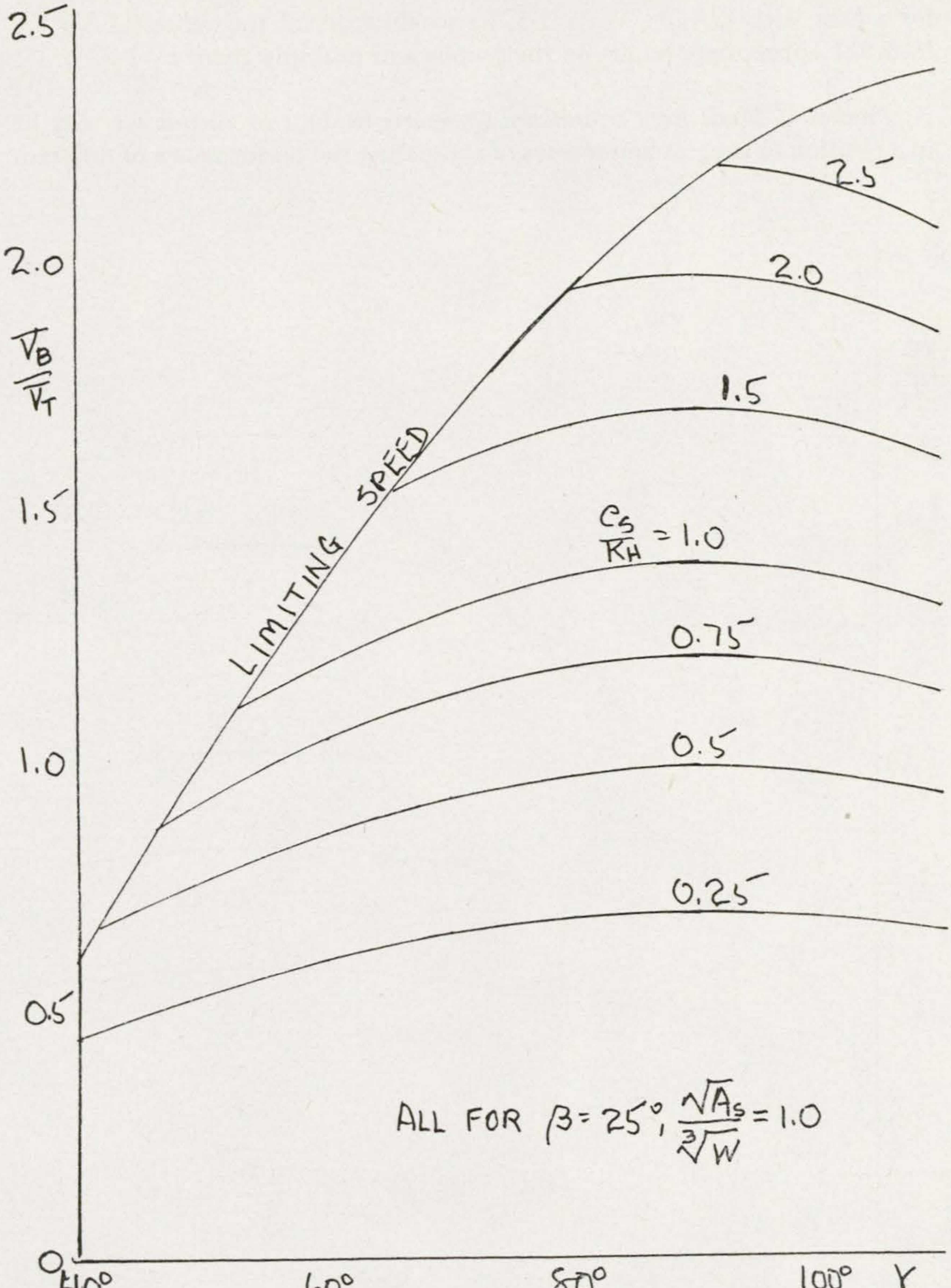


Fig. 5. V_B/V_T vs. γ at $\beta = 25°$ and $\sqrt{A_S}/\sqrt[3]{W} = 1$ for selected values of C_S/K_H

the parameters over a useful but not a complete range are plotted in Figs. 4, 5, 6 and 7. Each graph is for just one value of beta. V_B/V_T is plotted against γ for selected values of C_S/K_H. For all of them, the ratio $\sqrt{A_S}/\sqrt[3]{W}$ has been assumed to be equal to one. This is not a serious constraint, because in the formula, V_B/V_T is proportional to that ratio. Thus it is easy to extend to other values. For instance, if one wishes to find values of V_B/V_T for a boat with $\sqrt{A_S}/\sqrt[3]{W} = 1{\cdot}5$, he would read off the values of V_B/V_T from the appropriate points on the graphs and multiply them by 1·5.

N. *Figures of Merit for Performance Comparisons.* Out of all this we may be in a position to suggest better ways of comparing the performance of different

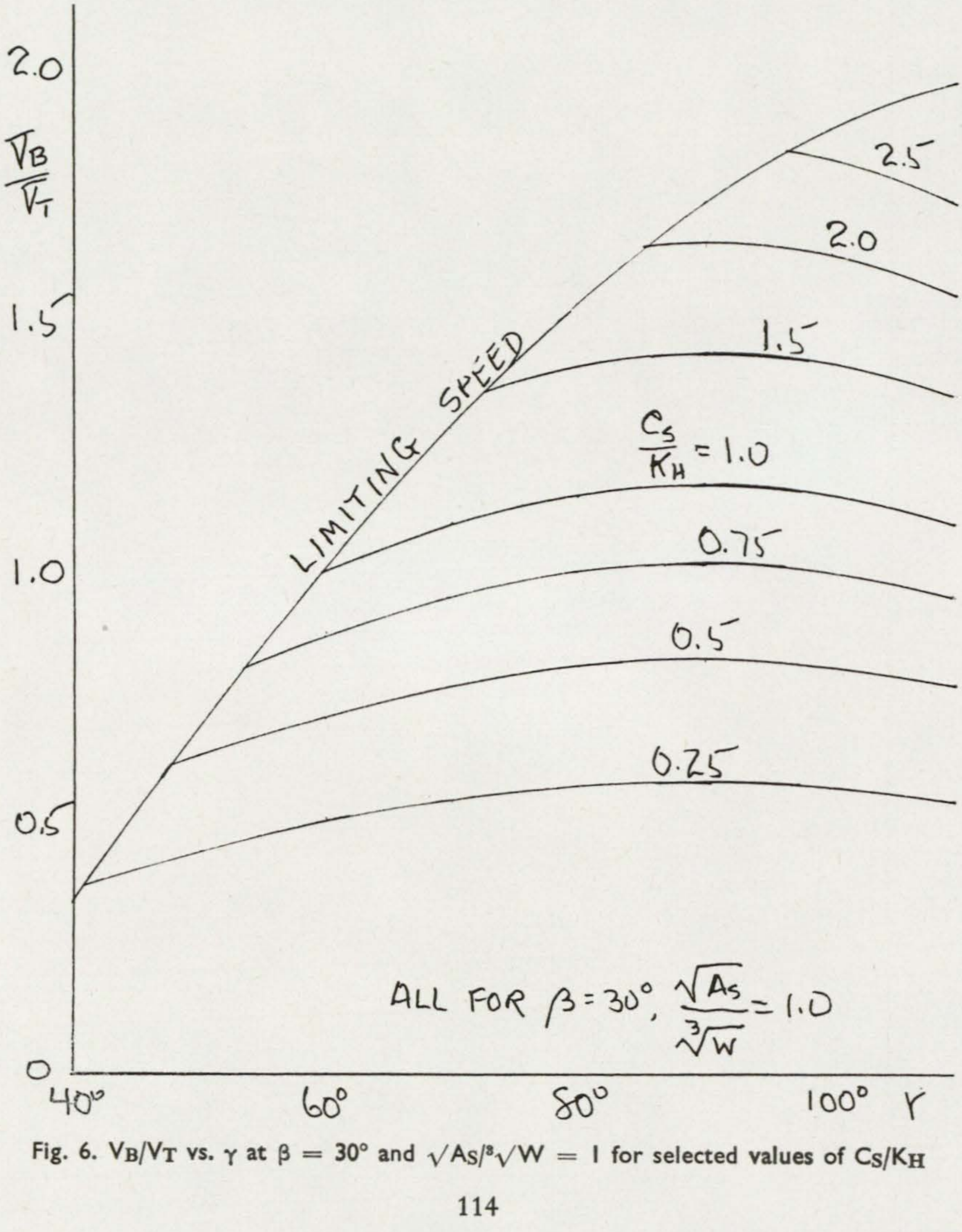


Fig. 6. V_B/V_T vs. γ at $\beta = 30°$ and $\sqrt{A_S}/\sqrt[3]{W} = 1$ for selected values of C_S/K_H

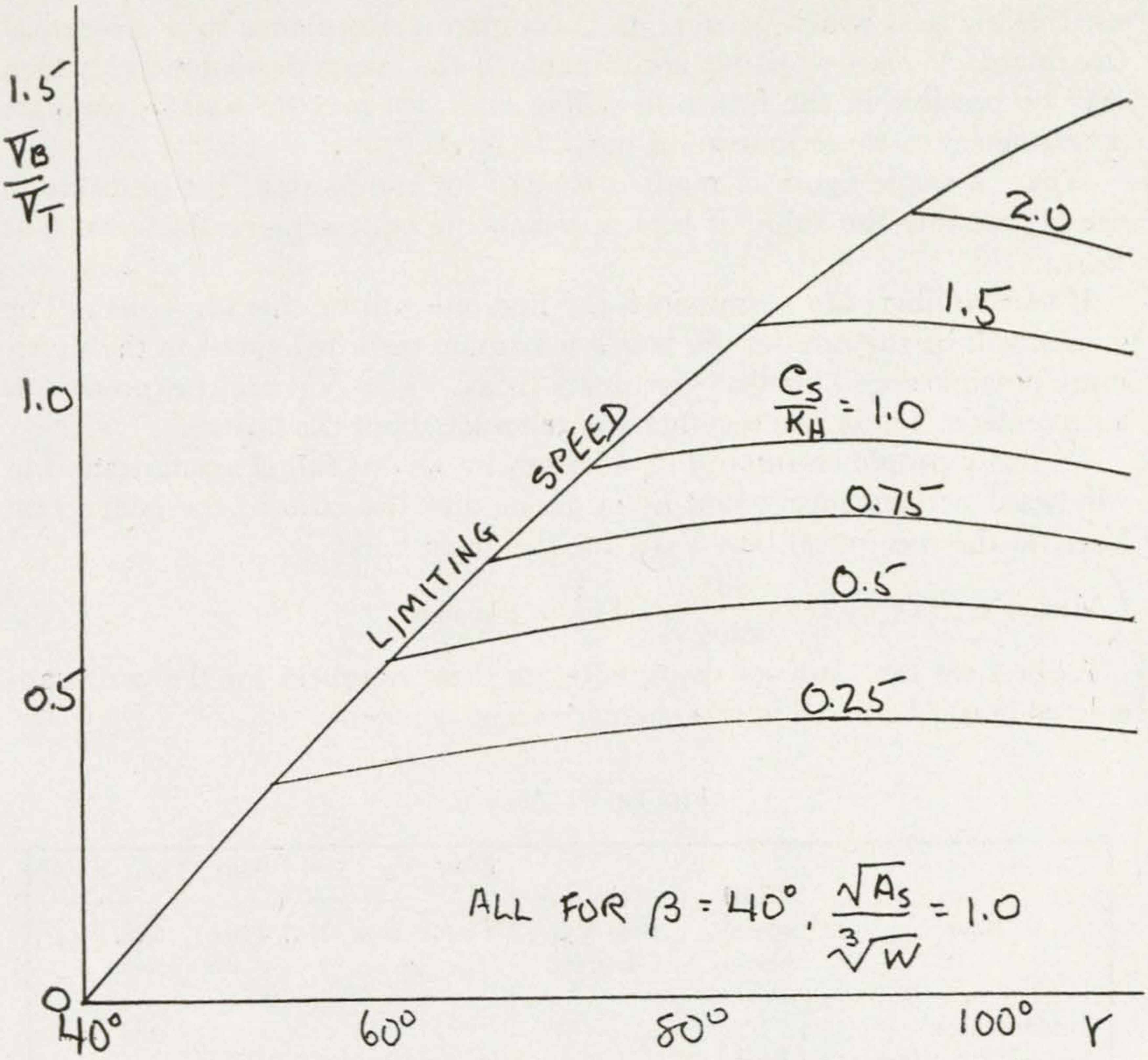


Fig. 7. V_B/V_T vs. γ at $\beta = 40°$ and $\sqrt{A_S}/\sqrt[3]{W} = 1$ for selected values of C_S/K_H

boats. Usually in the past this has been done somewhat casually in various ways:

1 Relative windward speed
2 Maximum speed
3 Ability to point high
4 Qualitative comparison of polar curves
5 In terms of modified Froude Number, $V_B/\sqrt{L}$
6 Others.

All of these have limitations. Clearly there can be no one correct way to compare a plump, old-fashioned cat boat with a 12-metre or a 'C'-class racing catamaran. Indeed, in very light winds they may all sail at nearly the same speed on the same course, yet their speeds reaching in a moderate or a fresh breeze will be far apart.

The fact that handicapping systems have failed to produce close racing in a wide variety of conditions of wind and sea even among boats rather similar in type, if not in size, is itself evidence of the difficulty if not the impossibility of solving the problem.

We cannot solve it. We do have a frame of reference not much known and used in the past which permits us to compare performance to a theoretical maximum. At least when we are thinking of the major developments which may be possible in the future in sailing craft, we may do well to compare performance to these maximum possible levels.

Where a single figure of merit is wanted for comparison, the best one to use is probably the value of beta at which the craft achieves her own best V_{MG}.

If two numbers are permissible, the first one will be that same beta. The second will be the ratio of the boat's maximum recorded speed to the maximum possible speed for that given beta (Max. $V_B = V_T/\sin\beta$) expressed as a percentage. Those two together will tell a lot about the boat.

To many people an interesting addition by way of full characterisation of windward performance would lie in giving also the ratio of the boat's best V_{MG} to the theoretical best V_{MG} for the given beta

$\left(\text{Max. } V_{MG}/V_T = 0{\cdot}5\,(\frac{1}{\sin\beta} - 1)\right)$ in per cent.

As best we can estimate them, here are these numbers for the craft considered in this book (all in this chapter except as noted):

FIGURES OF MERIT

Boat	Wind speed knots	Beta for Best V_{MG} degrees	$\frac{\text{Max. } V_B \times 100}{\text{Theor. max. } V_B \text{ for given } \beta}$	$\frac{\text{Max. } V_{MG} \times 100}{\text{Theor. max. } V_{MG} \text{ for given } \beta}$
International 12-ft dinghy	Light	36	32	66
Coquí (Chapter XVII)	Light	37	32	79
Coquí Improved (Chapter XVIII)	Light	34	36	80
12-meter yacht	10	22	28	67
12-meter yacht	20	27	23	55
Tornado	Light	25	59	90±
Icarus	10–13	(37)	(90)	—
Icarus	19	(45)	(80)	—
Crossbow	Light	(26)	(88)	—
Crossbow	20	(44)	(91)	—
Ice boat	Mod.	8·2	100	—

The figures of merit for *Icarus* and *Crossbow* are in parentheses because the data do not show that these beta values are the ones at which those boats would sail most effectively to windward.

An inspection of the table confirms the importance of beta as the first criterion of performance. When it is rather large, as for the International Dinghy and the original *Coquí*, the performance may not be very high even though the figures in the third column, by themselves, look rather good. The relative windward speed (third column) of the 12-metre in a 10-knot wind is in the same range, but at *much* lower beta. In a 10-knot wind, the actual V_{MG} of the dinghy is 2·3 knots while that of the "twelve" is 5·6, nearly two and a half times as great.

"*Coquí* improved" sailed three degrees closer to the apparent wind (beta) (and had three degrees lower hull drag angle) than the original *Coquí* and yet made somewhat higher speeds—a remarkable change.

Icarus, the flying hydrofoil boat, at $\beta = 37°$, was sailing as close to the apparent wind as such craft are known to have done up to the present time. She probably is not very fast to windward.

The *Crossbow* in light to moderate wind sailed at less than the limiting value of beta for her maximum speed. (She appears to have sailed at $V_B/V_T = 2$ at $\beta = 26°$. The largest possible beta for that speed is 30°.) The present authors suspect that she could sail closer to the apparent wind, if that were her objective, with a larger centreboard, and possibly slightly faster also on a reach.

No windward speed is given for the ice boat. It is presumed that the figure could be 100 in that column if she could reduce sail area without increasing drag angle.

It should be re-emphasised that there is crude information and guessing behind some of these figures. Hence they should not be interpreted as highly accurate.

A much more detailed tabulation of all the data of this chapter and some from other parts of the book is given in Appendix C.

PART THREE

ON-BOARD INSTRUMENTS

CHAPTER XI

PERFORMANCE MEASURING INSTRUMENTS FOR SAILING CRAFT

Reprinted from AYRS 56, July 1966

by Edmond Bruce

Present Situation

During his career, the writer had occasion to study closely the organisations and methods employed by research groups working in several of the "pure" and applied sciences. Most have become amazingly sophisticated and productive. However, even though sailing has had the benefits of several thousand years of experience, it is the most backward of all these sciences, in this writer's opinion, in applying a powerful research tool known as the "scientific method".

One of the basic requirements of any well-functioning scientific programme is to demand a mutual confirmation between theory and experimental measurement. One without the other as a cross-check is of little value. Alone, the accuracy and worth of either are not at all convincing.

Almost all sailing craft are designed, currently, merely by hunches and guesses at the drawing board. Anything radical is seldom attempted for fear of the publicity of a failure in the hands of a purchaser. Unjustified secrecy is another great retarding factor. As a result, sailing-craft progress has been exceedingly slow. Where are the confirming measurements, *on a numerical basis*, of the performance of full size sailing craft? Even when models and towing tanks are employed, the agreement of measurements, on the final full-size boat, with the model measurements is seldom obtained.

The fact that boat A has beaten boat B in a race, possibly by luck, does not give information as to how it would fare against boat C. Numerical measurements of their important performance characteristics would provide answers suitable for most any comparison. These measurements plus enthusiastic, widespread cooperation are essential if rapid progress in the science of sailing is to be expected.

Within the AYRS the writer described some of his attempts at full size measurements in publication No. 40 (Chapter I of this book). In these attempts, the sail and the hull were measured separately. Then these results were combined to predict the overall performance. With the experience of these performance-measuring attempts and some others, we are now in a position to conceive and develop still more advanced measuring means. This has become the objective of several of us in the American Section of AYRS.

In this article, the writer intends to discuss some of the problems of instrumentation. Obviously, the instruments and methods must be thoroughly investigated before any elaborate programme of sailing craft measurement is worth while.

Some Problems

Owners of sailing craft have purchased hull speedometers in the belief that these would assist them in determining the optimum adjustments of sail trim, etc. I have found no one willing to state that their speedometer is an unqualified success. The truth of the matter is that, since the wind is so rapidly variable in both strength and direction, by the time one makes a readjustment, the wind has changed and creates confusion. It was incredible to read that the "secret weapon" on one 12-metre racer was an electronic speedometer that could be read to a tiny fraction of a knot. What good is this by itself in the presence of variable and turbulent winds?

In attacking this measurement problem, it was realised that, since increased wind usually means increased boat speed, the ratio of boat speed to apparent wind speed might be a steadier criterion than knowing only the boat speed. This will prove to be valuable.

Sail force, for a fixed trim and angle of attack, is directly proportional to the square of the apparent wind velocity. Also, up to the speed of appreciable wave-making, the hull's resistance is closely proportional to the square of the boat's velocity. Thus, in the range of boat speeds from zero to about $V_B/\sqrt{L} = 0{\cdot}6$, a ratio of boat speed to wind speed would seem to vary hardly at all, for a fixed course to the wind and other fixed adjustments. This is true provided that one has waited until a "steady-state" or zero acceleration balance between the average wind and hull speed has been achieved.

If one can simultaneously observe an instantaneously indicating anemometer and the hull speedometer, the readings of the anemometer probably will jump around while the hull speed will change only slowly. This is because the inertia of the moving parts of the anemometer is very small whereas the hull's inertia or mass is great.

It has been found that the time-constant of response of the anemometer can be made about equal to that of the hull speedometer by adding an appropriate mass to the rotating impeller of an anemometer. A selected size of a bevel edge, thick, bronze disc was placed on contact with the top surface of a vertical-axis impeller, so as to keep the total surface area the same. This was found to provide the desired time constant without affecting the initial steady state calibration at all. Now, the wind velocity meter and the water velocity meter changed readings at about the same rate. Even if not precisely equivalent, their readings are more easily averaged because of their slow responses.

For a selected course to the apparent wind, we are now in a position to read the boat speed meter, then the wind speed meter. Their readings can be recorded and their ratio calculated. However, this procedure does not permit precisely simultaneous readings of the two meters, which is desirable for greatest accuracy. This situation can be improved with some electrical help. This can be obtained by means of a balanced null-meter and a ratio adjustment to be described later.

Instrumentation System

Before getting into instrument details, a "systems analysis" is in order. The first objective is to devise the simplest instrumentation which will accurately measure boat speed through the water versus apparent wind speed, for sailing craft on all possible courses in respect to the direction of the apparent wind. Apparent wind speed and apparent wind direction are chosen, rather than the true wind, for simplicity. These are what an observer sees aboard a moving boat.

Beside the measurement of the two mentioned speeds, the direction of the boat's course to the apparent wind must be determined. This is the sum of the angle of the apparent wind to the boat's heading and the angle of this heading to the boat's course or, in other words, the hull's leeway angle. Thus four quantities are required to be measured by the chosen instruments. A recording of the rudder angle to the centreline is also advisable unless a centre-helm sail balance is continuously maintained.

A method for the direct measurement of the single angle of the apparent wind to the course can be devised. However, an independent knowledge of the leeway angle is so important, in judging a hull's highest windward ability, that it is included as a separate item.

The best hull leeway angle for a course is one that produces the required lateral lift, to counteract the sail side force, with the least possible drag. For high pointing, the highest possible lift-drag ratio must be achieved. A lesser leeway angle than optimum for this course means too much lateral plane. A greater one means too little, when the boat is balanced and the tiller is centered. Many designers do not seem to understand this. They incorrectly strive for a minimum leeway.

All sensor indications should appear at a common, convenient location for the observer. This almost necessitates that "transducing" to electrical voltages be used. For accuracy in reading, throughout the ranges of indication, and for simplicity of any later calculating instrumentation, the indications should be as linear as is practical.

Possibly three sets of instrumentation should be considered. One would be an assembly which could readily be moved from boat to boat. AYRS might own these instruments and loan them out, on some systematic basis, and publish the measured results. Another form would be for private ownership and permanent installation on an owner's boat. The third would be instruments mounted on a motor-driven pursuit boat. Here again the instruments would be provided to enable the accurate following of a sailing craft's course at a constant distance. Such a procedure verges on being a bit sneaky. However, it could rapidly measure many boats and would save the effort of equipment installation on these boats.

Two types of wind sensors (velocity and direction) and two corresponding water sensors are required. It is desirable to determine the best locations for these pairs of sensors.

If the wind sensors were mast-head mounted, they would encounter relatively clean air, without interference, in all directions. However, since both apparent wind speed and direction will vary with height above the water, the average conditions encountered by the sails would not be determined correctly.

To obtain average sail conditions, a better height for the wind sensors would be that of the geometric centre of the combined sail areas. At this height, mounting locations, such as forward, aft or abeam, all would encounter interference by the sails on some particular course. However, on any one tack, a mounting fairly well outboard of the windward shrouds would be substantially free of blanketing or interference. Should doubt exist about the symmetry of performance on the two tacks, measurements could be made with the instruments mounted alternately in the starboard and in the port shrouds. Of course, duplicate sets of sensors can be installed if cost is not important.

The water sensors would find their best location forward of the bow, just beyond the region of the bow's pressure wave. At any other location, adjacent to the hull, an accelerated water flow would be encountered due to the hull's sectional dimensions. Behind the boat, a vortex wake followed by the turbulent wake would extend to greater distances. Taffrail logs and hull-mounted speedometers must be corrected to allow for these disturbances.

Instrument Details

When measuring relative movement, in respect to the boat, of wind or water, one has the choice of using either dynamic pressures or velocities. Exploring the field of available instruments, velocity-to-electrical transducers appear to be more highly developed and accurate than are pressure-to-electrical transducers, although some of the newer solid-state-junction strain gauges show promise for the future. The writer plans to investigate this approach later.

In the velocity category, R. A. Simerl of Annapolis, Maryland, U.S.A. produces a fine, low-friction, weather-proof, corrosion-proof, electrical anemometer generator that was chosen from several possibilities for the present project. It is brushless since magnets revolve in a stationary field winding. Air-core coils are used to avoid magnetic drag. Stainless-steel, instrument ball-bearings are employed. These are permanently lubricated with silicone grease. A pair of internal rectifying diodes and a centre-tapped coil cause full-wave rectification of the generated AC to produce a pulsating DC. The author's tests showed that electrical filtering added nothing to accuracy, but it prevented pulsing of the indicating meters at very low speeds.

Identical generators are used for both wind and water, with appropriate impellers, to permit a proper null-balance between them. This will be described later.

Fig. 1 is a photograph of the pair of wind sensors. The Simerl generator with its Simerl wind-impeller appears on the top. The under part shows a split-tail, weight-balanced wind-vane which operates a low friction, military

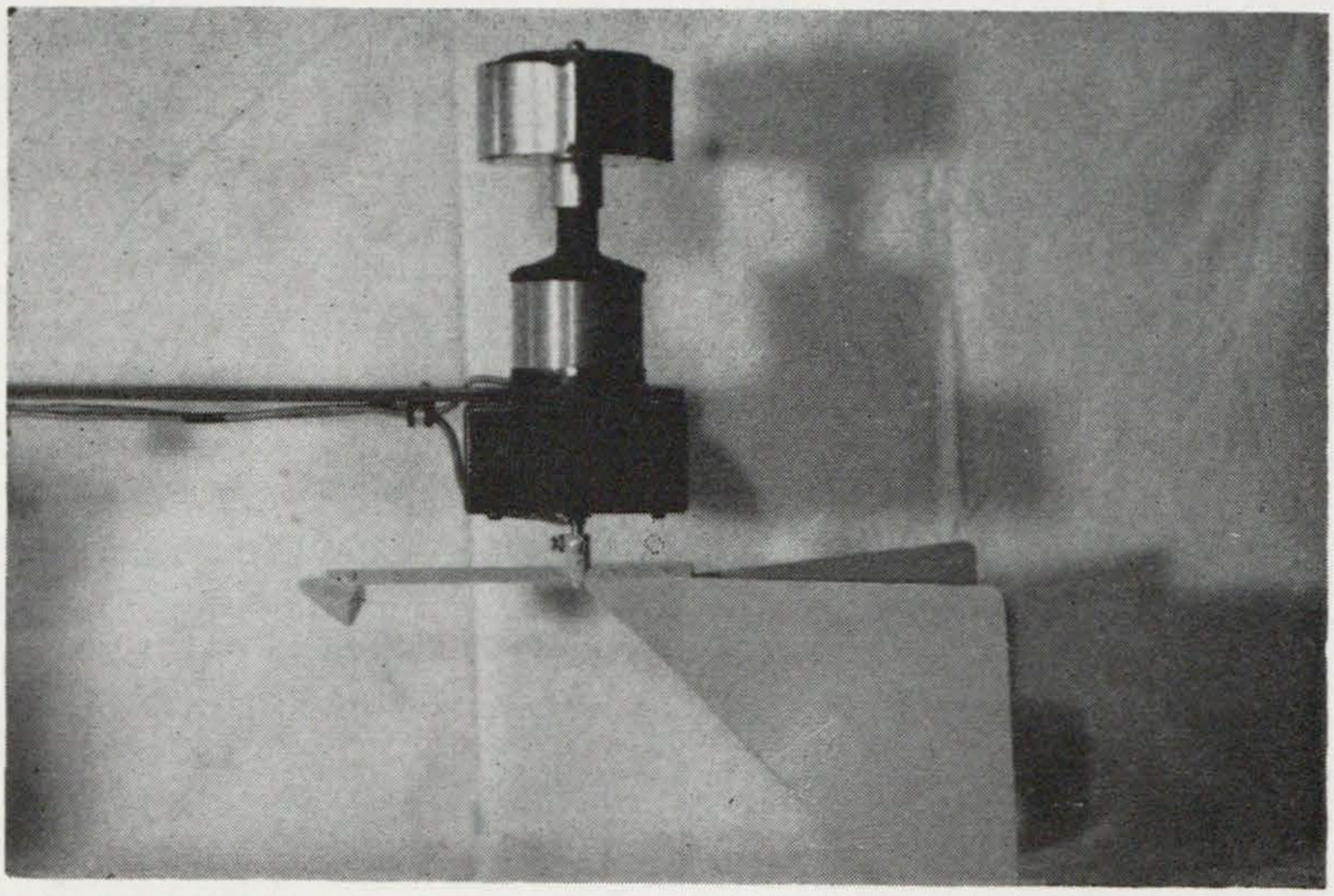
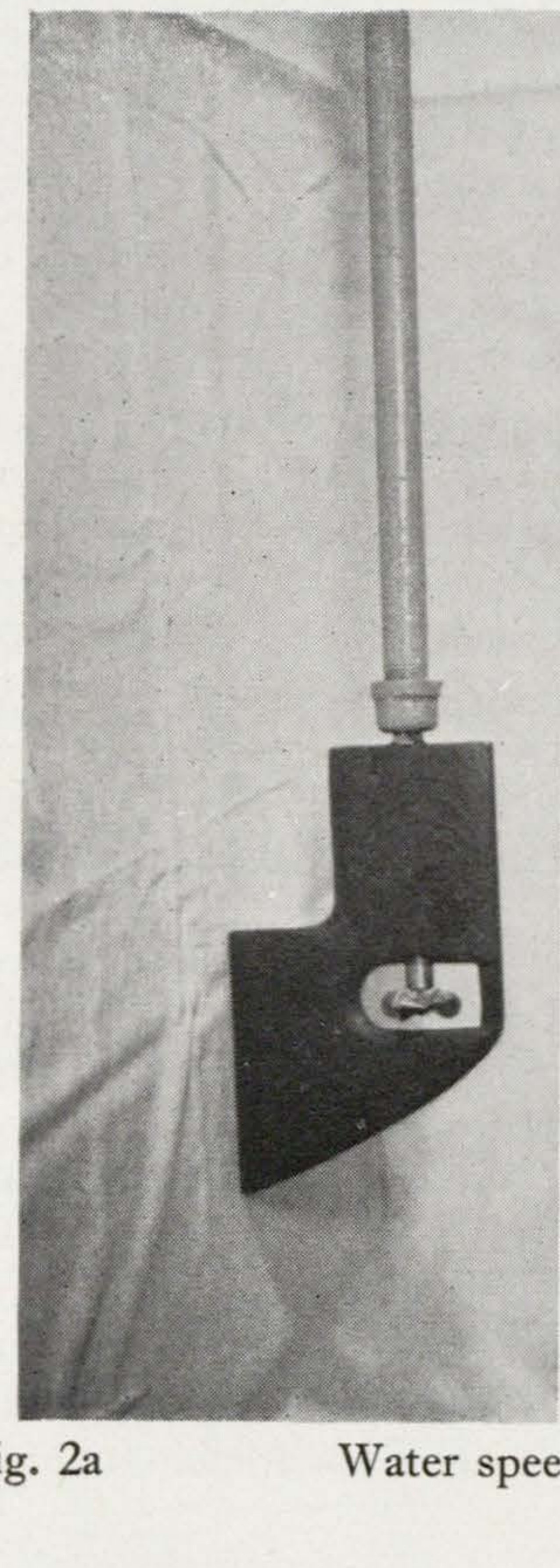


Fig 1. Wind speed (top) and wind direction (bottom) sensors



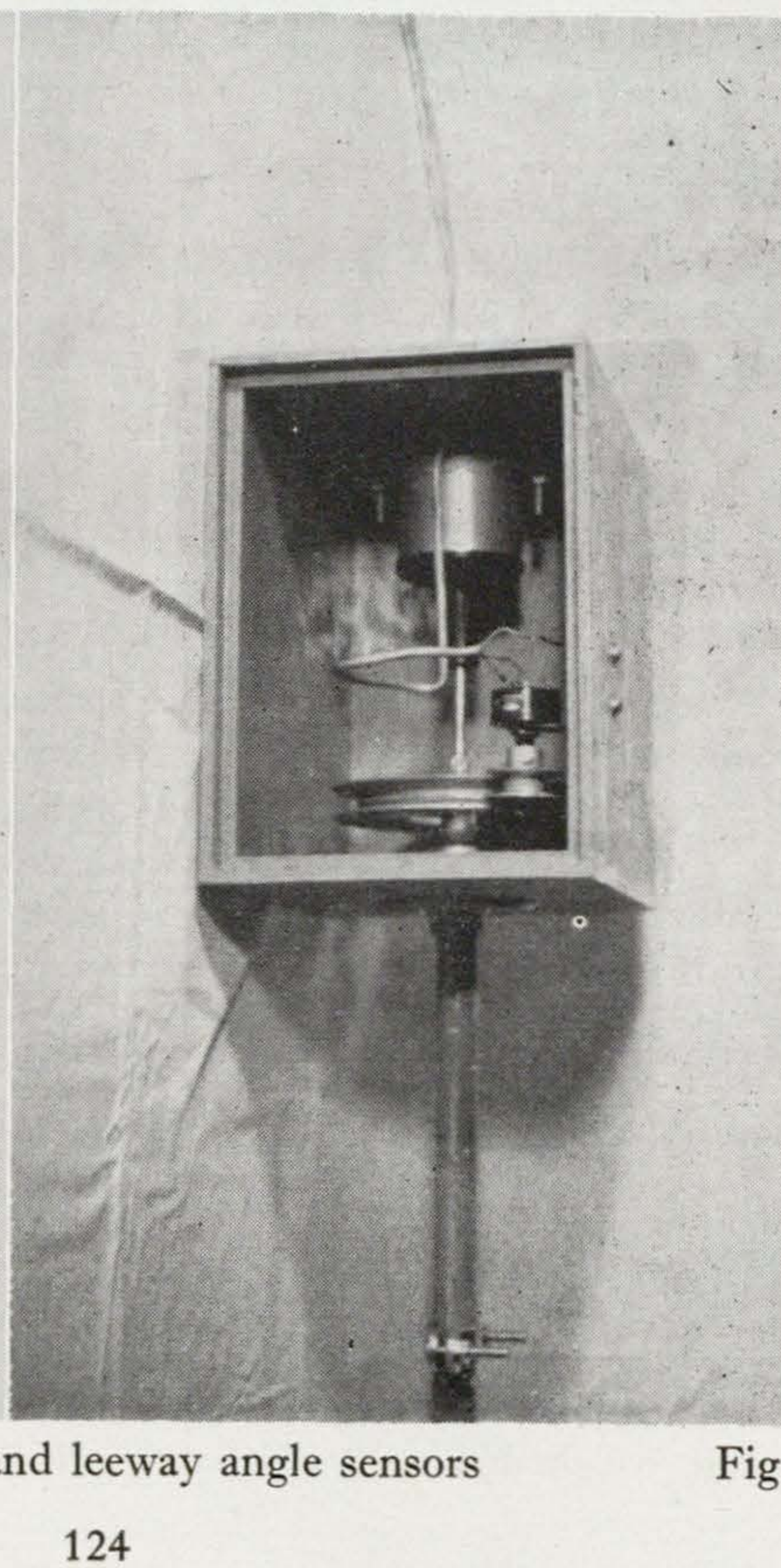


Fig. 2a Water speed and leeway angle sensors Fig. 2b

type, "Spectrol" potentiometer requiring a driving torque of only 0·2 inch-ounces.

Figs. 2A joined to 2B form a complete photograph of the water speed and leeway angle sensors. A small stainless steel, four-cone impeller is fabricated from a single sheet. It is mounted within an aperture in the water vane for protection and weed shedding. Note that both water and wind impellers are non-directional. This, of course, is not true in the case of usual propellers.

The upper, water-tight box, in Fig. 2, contains the second Simerl generator and another "Spectrol" potentiometer. These are driven, respectively, through a concentric shaft within a rotating hollow tube. The underwater extension of this tube is enclosed in a streamlined form to reduce drag. This is a continuation of the water vane. The out of water portions of the mentioned tube and shaft are inside of a protective external fixed hollow pipe. The vane employs a 6 to 1 pulley step-up to drive the potentiometer through a multi-turn, anchored belt. The whole assembly is mounted on a retractable support, not shown, over the bow of the boat. This support is tailored to fit each particular boat. It contains adjustments for both depth and heel angle.

Fig. 3 is the measurement console containing five indicating meters, all controls, switches and balance-calibrating batteries. This console is mounted at a location most convenient for the observer.

Fig. 4 is the present electrical wiring diagram for the entire equipment. It is self-explanatory to those skilled in electrical construction. Many details will be found upon close study. Note that adjustable battery sources have

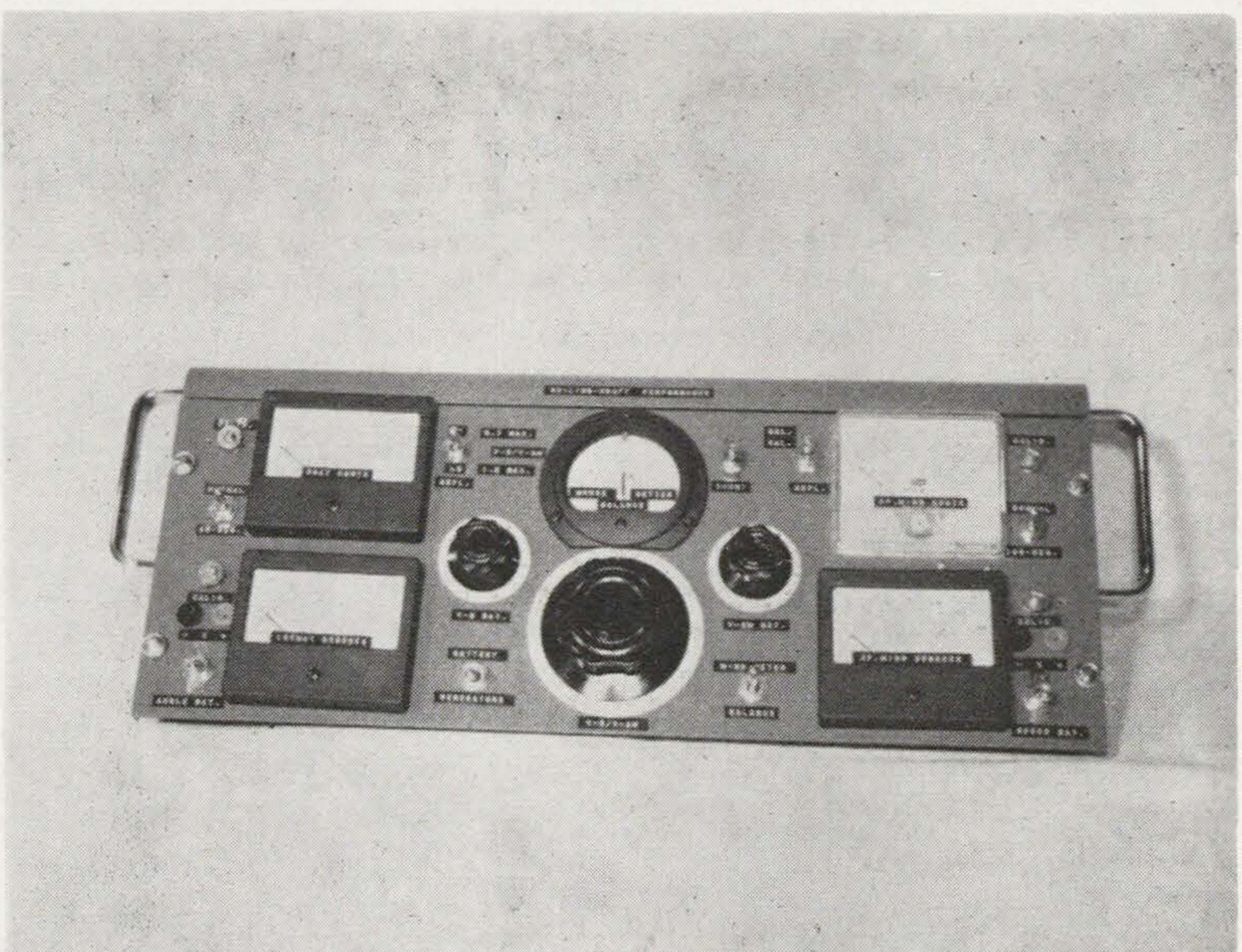


Fig. 3. Edmond Bruce's Measurement console

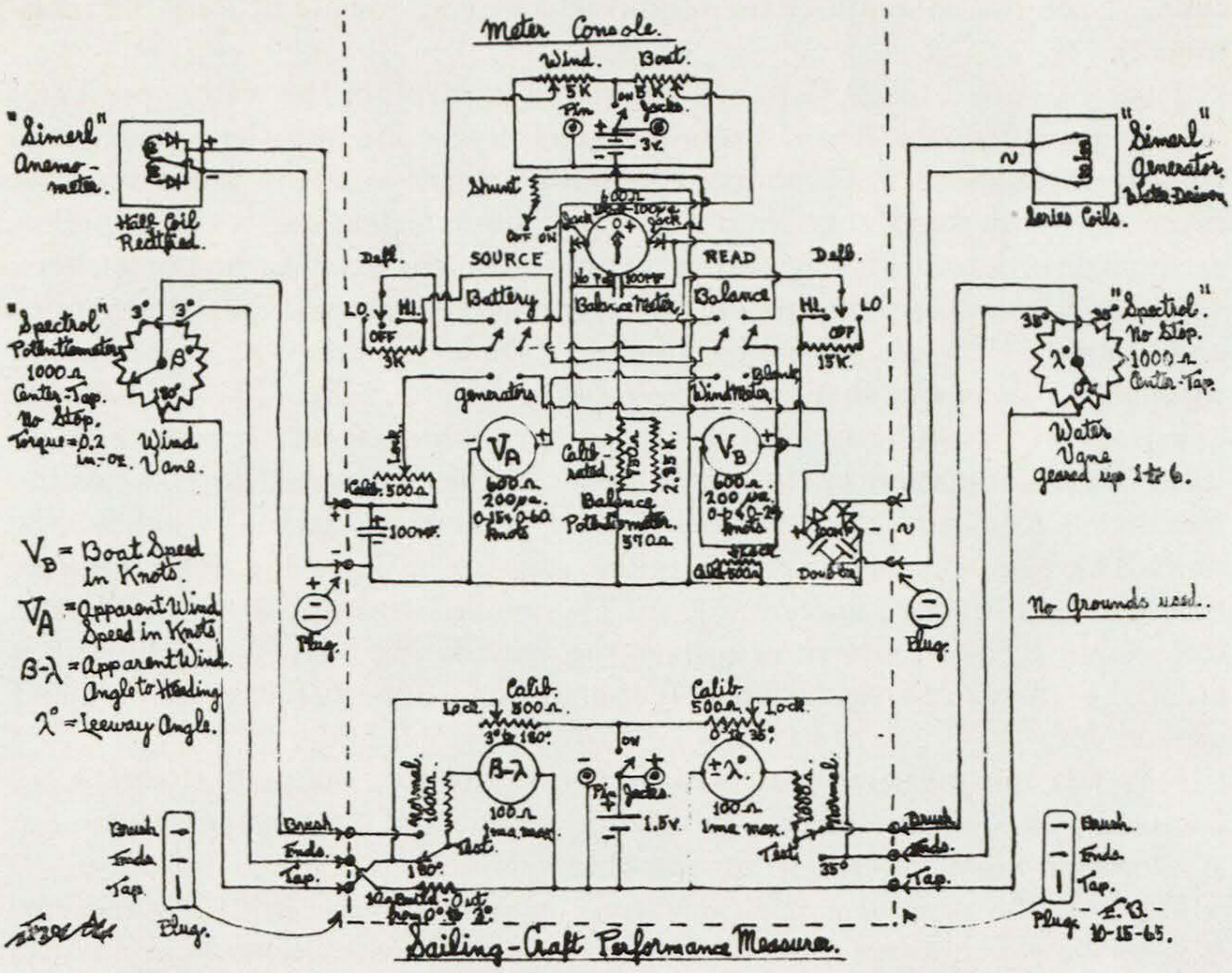


Fig. 4

been included to assist in balance calibrations. Fig. 4 may be passed over by those not deeply interested in details.

This assembly of instruments will be improved upon, by the writer and others, from time to time in the light of further experience under use. A recent improvement was the incorporation of double range measurements in both speed sensors. The smaller ranges produce greater sensitivity below about 6 knots for both wind and water. The manufacturer of the generator is also working on this problem.

Another important improvement was an optional, plug-in, solid-state, operational amplifier for the "better-worse" null meter. Several observers have stated that this sensitive means of optimising sailing craft adjustments is the most valuable part of the entire instrumentation. It dramatically and easily indicates each adjustment optimum when properly used.

When the assistance of the null amplifier is called upon, great care must be exercised in the manipulation of its "gain" control and the meter shunt so as to avoid damage to the null-meter by over-deflection. Without the amplifier plugged in, no harm can come to the null-meter but its deflections are much smaller but still useful.

The better or worse readings are not at all dependent on the accuracy of the calibrations of speeds. They tell whether a readjustment of any kind is an improvement or not over a previous one. Calibration accuracy is required for the absolute data so that results can be compared even though by other sets of instruments on various boats.

Operating Procedure

Before recording much data, it is wise to determine, for each course, the optimum adjustments for the sails, centreboard, balance, etc. This can be done readily with the help of the null-meter together with the adjustment of a zero balance between the boat and the wind speeds. Any change of the boat speed in respect to the wind speed, as a result of a readjustment, will cause the meter to swing in either the marked "Better" or "Worse" direction.

It has been found that, should scattering of plotted data occur, it is not usually caused by measurement inaccuracies. It is more apt to be due to sensitive departures from the best boat adjustments. This emphasises the importance of the crew's good judgement in addition to the merit of the boat's design.

After being satisfied with the boat adjustments, data may be recorded. Actual speeds and the resulting speed ratios, between boat and wind, permit comparison with similar data from other boats. Also, one must not overlook that this can alert a racing crew to examine adjustments if the performance is less than has been recorded previously.

In addition to the angle of the helm for a straight course, one records the apparent wind velocity, the boat's speed, apparent wind angle to the boat's heading and the leeway angle. The sum of the latter two angles consolidates into the desired single angle of the course to the apparent wind. While these three interrelated values can be employed for final plotting, many may prefer the more revealing dimensionless ratios of boat speed over apparent wind speed, V_B/V_A, and the speed-length ratio of the boat $V_B/\sqrt{L}$, for plotting against the course angle. The merits of boats, even of various sizes, can then be fairly compared.

To obtain the ratio V_B/V_A, one has a choice of calculating from the separate meter readings or of employing the pre-calibrated balance adjustment. The latter has the advantage of precisely simultaneous readings. An advance calibration can be accomplished with the help of the adjustable battery supplies to produce any desired meter readings. Then the balance adjustment that produces a null reading is observed. A calibration curve of this balance setting at various speeds is essential since the speed meters' calibrations are not strictly linear.

In gathering data, one has no control over the magnitudes of the wind or the resulting optimum boat speed, for a given course. However, the course can be chosen at will. To obtain the most meaningful data between three related variables, a series of measurements should be made while holding one variable constant. This constant value can be the chosen course angle. This process is then repeated at other fixed course angles.

A fixed course suggests an adjustable marker on the wind-angle meter. The helmsman carefully maintains a course that keeps the meter indicator on this mark during each series of measurements. Complete runs are taken for a family of wind headings from hard on the wind to 180°. Several selected days may be required to encounter light, medium and heavy winds on each course.

The author has to maintain a fixed course during such measurements, by careful manual steering while watching the wind angle meter. Henry Morss, of the AYRS group working on this problem, has a similar set of instruments. He also has an electrical automatic pilot which can be changed from the customary magnetic-compass control to wind-vane control.

The most difficult course to steer by hand is hard on the wind. This is due to a great change in boat speed with small changes in course angle on this heading. My experience with Henry Morss' automatic pilot, during these types of measurements in variable winds, is that it far excels human ability to steer an accurate windward course. His pilot is described in Chapter XIII. Even the sailing helmsman is being threatened by automation!

Up to this point, the discussion has mentioned only the overall performance of the combined sail and hull. Some readers may be interested in a procedure that enables a separate determination of the sail force, when running. This sail force, of course, exactly equals the hull's resistance. Thus, both sail force versus apparent wind speed and hull resistance versus boat speed can be determined, for a running course.

After first plotting a range of boat running speeds for various speeds of the apparent wind, a drogue with a spring-scale attached to its line is dragged astern. Simultaneous readings are taken of the spring-scale force, the wind speed and the boat speed. Next, the wind speed for this same boat speed is extracted from the previously plotted curve, where the drogue was not employed.

Equal boat speeds, with and without the drogue, result from different apparent wind speeds. The spring-scale force reading is due to the *difference* in these wind speeds, acting on the sails. These measurements permit the mathematically inclined to calculate the force versus speed relationships for sail and hull, as well as their coefficients.

Data Plotting

The reader may be curious to see plots of actual measured data which compared different boats as well as the effects of various adjustments on a given boat. It is hoped that other members of the American Section of the AYRS will report on these when sufficient data have been accumulated. It is a large and time-consuming job to get adequate data which must involve a range of weather conditions.

The writer has made measurements more to check out the instrumentation and its calibrations than for study of particular boats. In this process, Fig. 5 resulted. It can serve as one preliminary example of what may be expected.

There are many ways in which data can be plotted, each of which may have certain advantages. For example, two dimensional polar plots, of boat speed versus the apparent wind direction, for various fixed apparent wind strengths, permit determining the magnitude and direction of the true wind with the help of a simple construction. Another simple construction can show the "speed made good" into this true wind.

Fig. 5 employs dimensionless ratios rather than the absolute values because this permits comparison of the merit of different size boats. The mentioned advantages of the polar plot are retained and the constructions are shown in the figure. The boat speed to wind speed ratio, V_B/V_A, is plotted against various angles of the apparent wind for a single fixed value of the boat's speed-length ratio, $V_B/\sqrt{L}$. This, in effect, shows how hard the apparent wind must blow for a given boat speed on any course. This curve was made

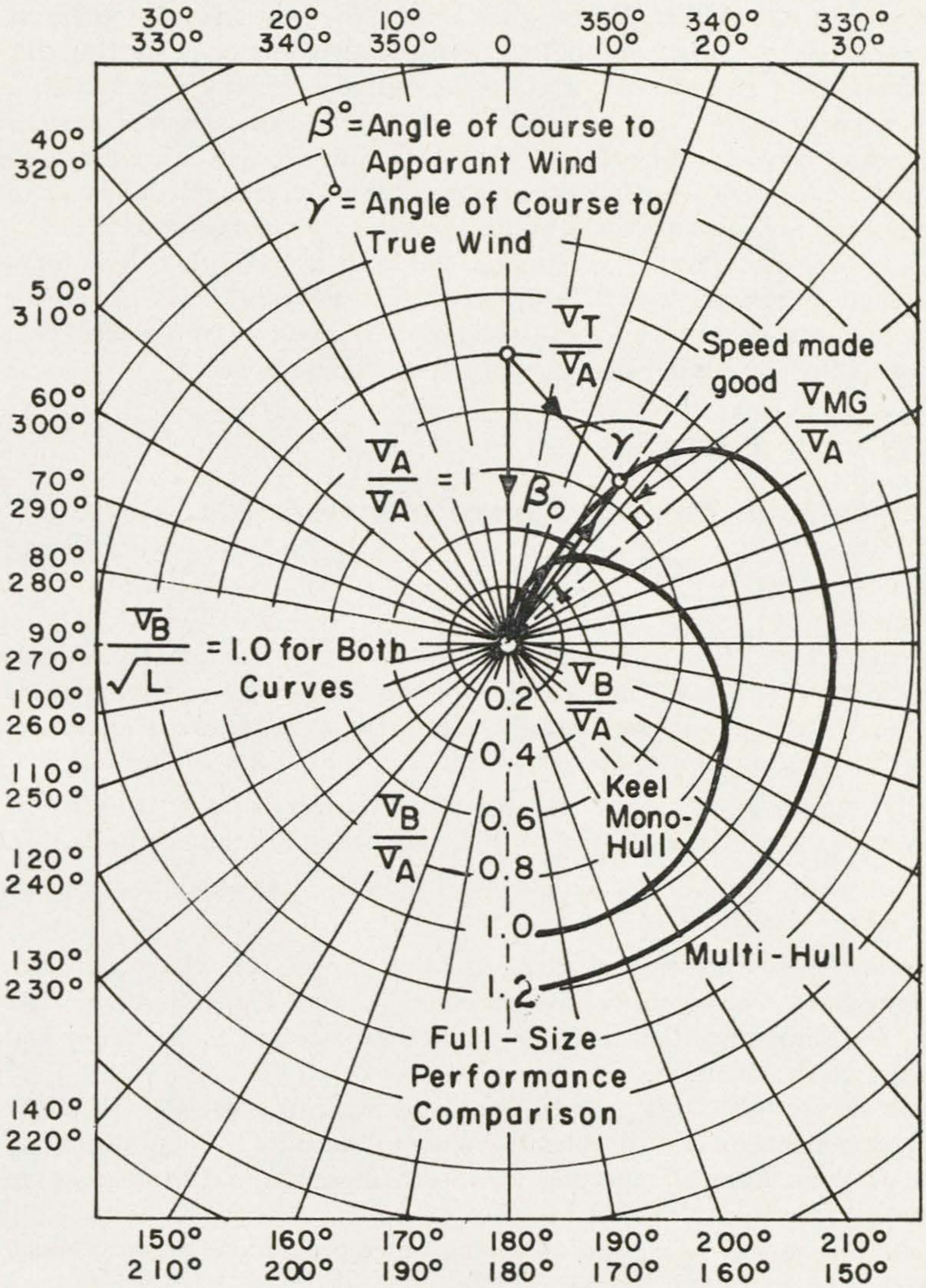


Fig. 5

E

possible by extracting points from a family of curves each of which represented a different but fixed course angle to the apparent wind. To obtain actual velocities, all speed ratios except $V_B/\sqrt{L}$ can be multiplied by the value of V_A occurring for the particular point.

The velocity triangle, plotted in Fig. 5, can be in terms of the three speed ratios to the apparent wind, as shown, or the three speeds directly. Henry Morss ingeniously uses such triangles to determine the validity of his measured data.

The measured apparent wind speed, the boat speed and their included course angle $\beta°$ are plotted. Drawing the third side of the triangle represents the theoretical true wind speed that would satisfy these data. Also, the *theoretical* angle $\gamma°$ for the true wind to the course is thereby determined.

The *measured* angle $\gamma°$ can be obtained by observing the compass' angular change on identical but opposite tacks and dividing by two. The measured angle and the theoretical angle $\gamma°$ must agree or the data are faulty and should be thrown out. This is an elegant means for checking the data accuracy.

Fig. 5 compares a racing keel mono-hull with a good multi-hull for a speed-length ratio equal to 1·0. A discussion of such results will be left for later AYRS articles, as mentioned previously. However, it would seem that "America Cup" racing is being carried out in "house-boats".

NEED FOR DATA

Letter to John Morwood from Henry A. Morss, Jr.

Reprinted from AYRS 51, April 1965

Dear John,

The more I see, hear and read about the endlessly fascinating business of sailing, the more I am impressed with the desirability of having more quantitative data and more precise understanding about it. Therefore I write to ask you to consider doing two things in the AYRS publication.

(1) To appeal to the members and other readers to make and report measurements of the performance of their boats. You are the one to do this.

(2) To solicit, through the bulletin, and publish ideas about instruments useful to the foregoing.

Together, these constitute a big and valuable project, one which could run for a long time. You might consider sections entitled something like "data sheets" and "instrument corner" for publication as often as the editor had anything worth inclusion.

If you decide to do this, you will probably wish to start off with rather careful statements of the problems. What to measure? What degree of accuracy? What form of reporting for easiest digestion and comparison of information from many sources?

To me this appeals as a significant, long-range programme of work which might well be sponsored by the AYRS.

HENRY A. MORSS, JR.

CHAPTER XII

PREPARATION OF DATA FOR POLAR DIAGRAMS

Letter from Edmond Bruce to John Morwood

dated January 14, 1970

Reprinted from AYRS 76, April 1971

Dear John,

Now that the AYRS programme for Polar Performance Curves has been launched, I hope that members do not think that one has to wait for a specific value of apparent wind velocity before making measurements. This would be almost impossible to do accurately. A cross-plotting technique of all the random measured bulk data can be employed to obtain the desired values of V_B versus β for a fixed apparent wind velocity V_A as described below.

The only parameter choice possible is the steered course β, to the apparent wind, as shown by the wind-vane plus the leeway gauge. The resulting boat velocity V_B and the existing apparent wind velocity V_A must be accepted after the optimum sail adjustments, etc., are made.

These data may be plotted on rectangular co-ordinates for each of a number of selected apparent course angles β, as shown in Fig. 1. Many measurements are preferable in at least three different wind conditions, namely in light, medium and strong winds.

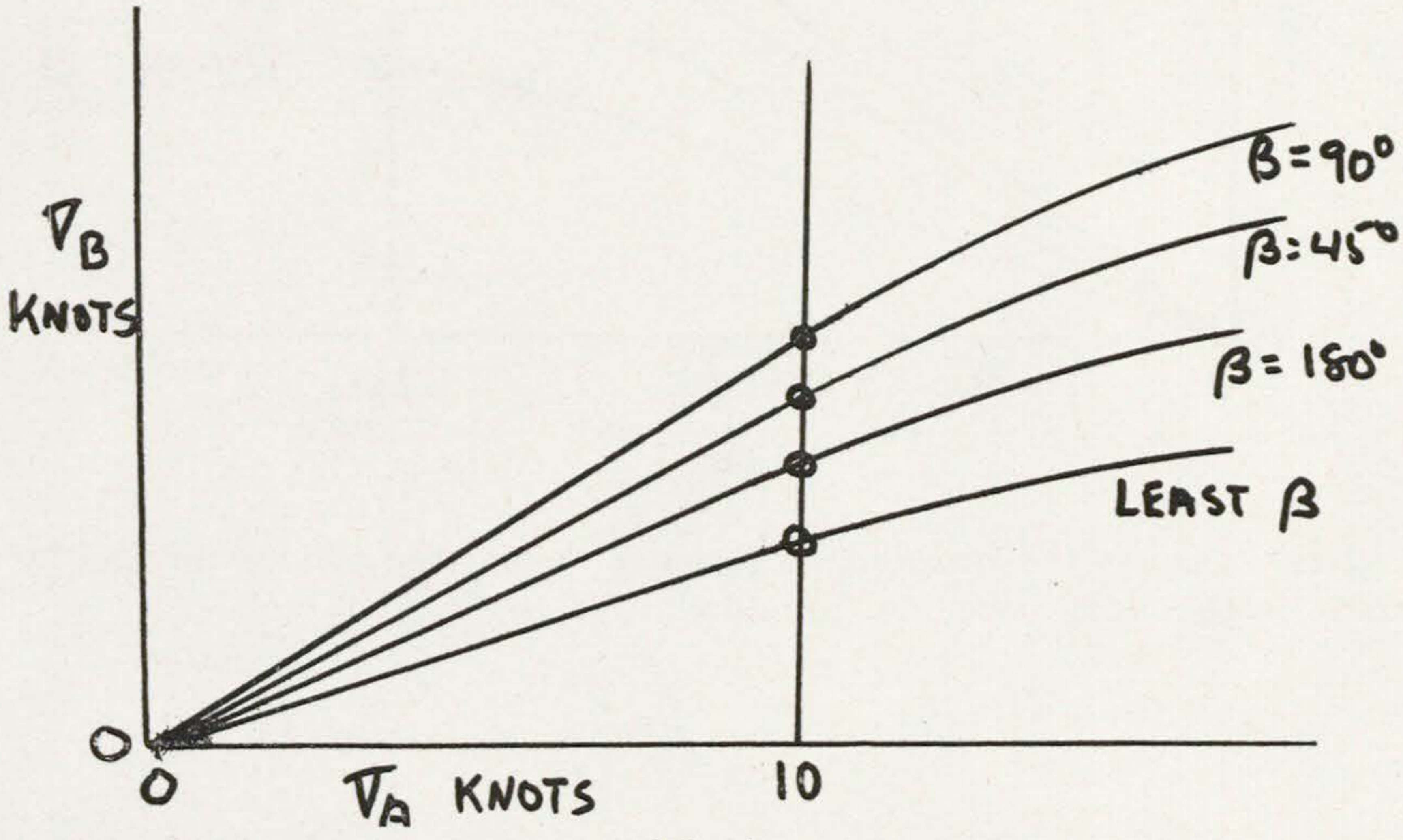


Fig. 1

If one desires to obtain the boat velocity V_B for a definite value of the apparent wind velocity V_A, on each of the given steered courses β, a vertical line, such as at $V_A = 10$ knots in Fig. 1 will provide the answers by its intersections with the plots representing the various selected apparent courses β. Thus the necessary data can be obtained for plotting the apparent wind portion of the AYRS polar diagram of performance.

The data for the true wind portion of the AYRS polar diagram can be derived from the previous data as follows:

For all the original apparent wind measurements, calculate the corresponding true wind velocities V_T from the formula,

$$V_T = \sqrt{V_A^2 + V_B^2 - 2V_A V_B \cos \beta}$$

These V_T results should be plotted on rectangular co-ordinates versus boat speed V_B for each of the previous *apparent* courses β as shown in Fig. 2. In a manner similar to that already described, the boat velocity V_B for a fixed true wind velocity V_T and *apparent* course β can be determined by the curve intersections with a vertical line drawn along a desired value of V_T as shown.

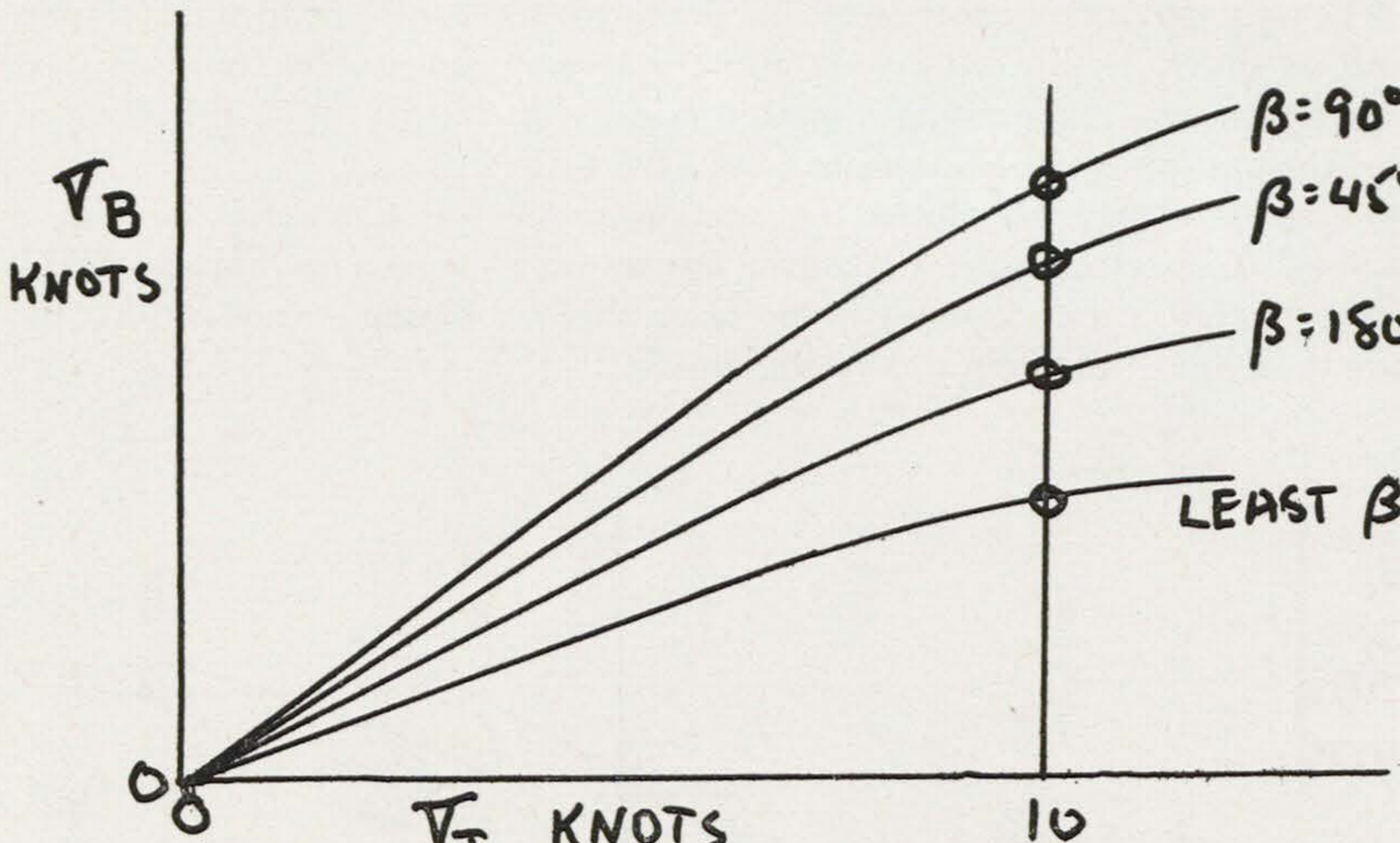


Fig. 2

Next calculate the corresponding course to the true wind γ for each of these intersections using the formula,

$$\tan \gamma = \frac{\sin \beta}{\cos \beta - (V_B/V_A)}$$

Thus one obtains the boat velocities V_B versus courses to the true wind γ for each of the fixed true wind velocities V_T, as chosen. These are the data required for the true wind portion of the AYRS polar diagram of yacht performance.

A good polar performance diagram contains much hidden information of value. I hope to prepare a future article on how to extract this knowledge from the diagram.

As one example of the previous statement, one can rate the merit of a yacht by its minimum possible course angle β and on its percentage V_{MG} compared with the ultimate possible at that angle, in a given true wind velocity V_T.

Another example of extracted information is that optimum sail areas for best V_{MG} can be calculated readily when heeling is not the sail area limitation.

EDMOND BRUCE

Ed: Another way of converting $V_A = \beta$ to V_T and γ is to use Harry Morss's orthagonal curves as described in Chapter VIII. This is a quicker way and avoids the above tedious calculations at the expense of a little accuracy.

CHAPTER XIII

WIND-CONTROLLED AUTOMATIC PILOT

Reprinted from AYRS 53, Oct. 1965

by Henry A. Morss, Jr.

Introduction

More data about the performance of sailing boats are needed to round out our understanding. As members of the AYRS, we are more aware of this than are many other sailing enthusiasts. With AYRS communication and our varied backgrounds, we should be able to bring many talents to bear on all sorts of subjects.

Foı plotting on a polar diagram*, the data must include all of the following at least:

1 Angle between apparent wind and boat's heading

2 Leeway angle, or angle between boat's heading and actual course

3 Speed of apparent wind

4 Speed of boat through water.

Usually a record will also be kept of the sails' set, trim, the loading or weight of the boat, the weather and sea conditions, etc.

There are problems in making tests. One is to muster the necessary patience and persistence. Another is to find suitable instruments. A third is to assure good steering.

Edmond Bruce has suggested a scheme which can help. He proposes to steer a boat by an automatic pilot controlled by a wind vane rather than the usual control by compass. If this can be made to work well, it will improve the quality of the whole effort by solving the problem of good steering, by indicating the value of one of the variables to be recorded (the angle between apparent wind and boat's heading), and by reducing the magnitude of the job the observer will have to do. Indeed it should enable one person to do the whole job single-handed. In this busy world, it is much easier for one person to find the time for a job like this than it is to assemble two or three people willing to give the time and effort when the conditions are right.

Previous Applications

The idea of automatic steering closely related to the apparent wind is old. Those who have made long passages under sail single-handed have done it in one way or another. (The AYRS book *SELF STEERING* goes into this subject at length). Sailing models have for decades been equipped with various

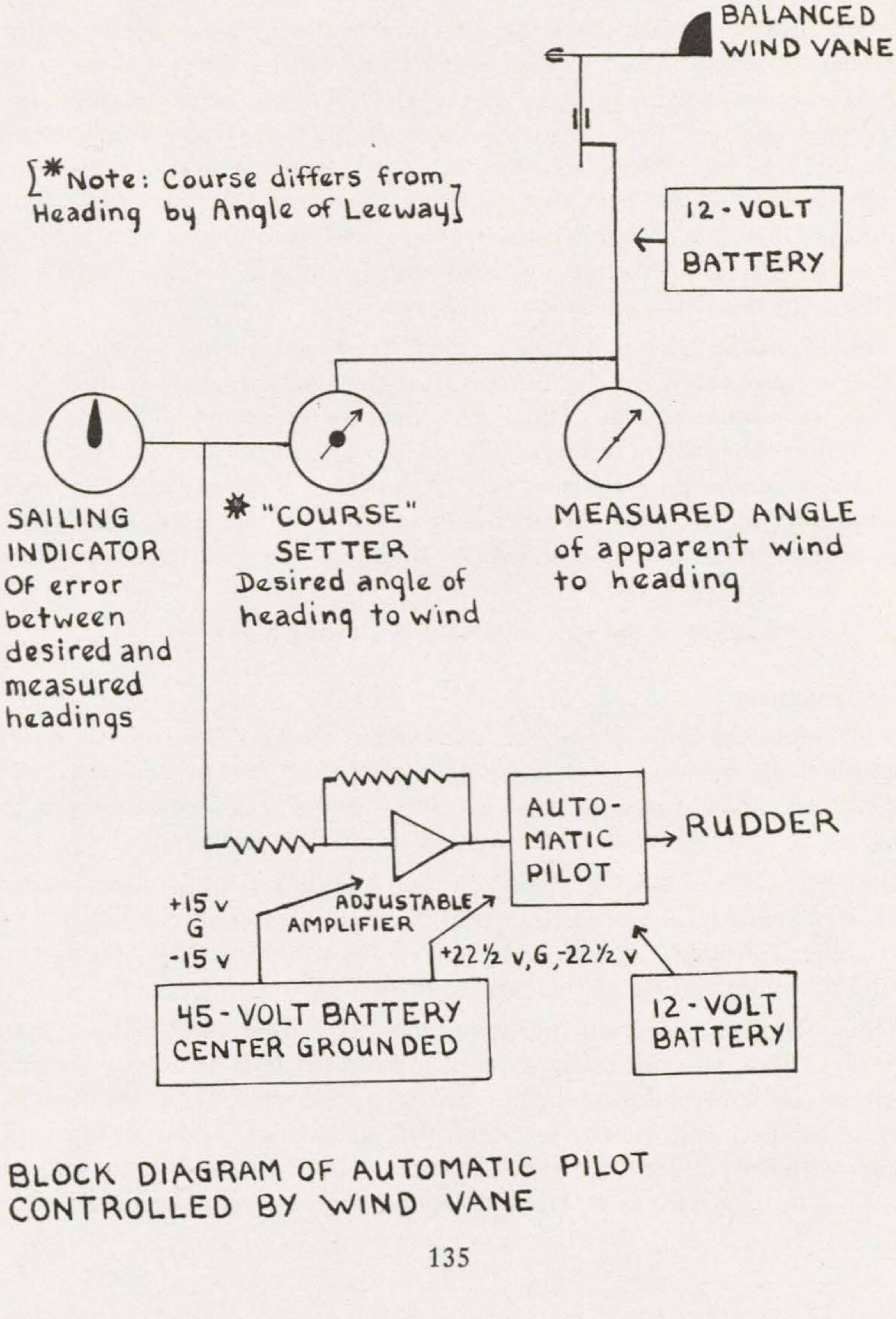
*See, for example, AYRS No. 38 (p. 17), AYRS No. 40 (p. 50), and AYRS No. 45 (p. 43). The second of these references is in Chapter I of this book.

means to accomplish the same result. Even an automatic pilot controlled by a wind vane is known to have been used on at least one boat as long as 25 years ago.

The Present Application

For our present purposes, a wind-controlled automatic pilot seems to be very useful. It imitates most precisely the things which a good human helmsman tries to do. If successful, it will have a steadier hand than a human helmsman over hours of painstaking work.

During the late summer of 1964, satisfactory trials were made of the following device.



BLOCK DIAGRAM OF AUTOMATIC PILOT CONTROLLED BY WIND VANE

Description of Apparatus

A "Wind Set" made by Thomas Walker & Son Ltd., was connected through an operational amplifier with adjustable gain to an automatic pilot made by Kelvin & Wilfrid O. White Co.

The "Wind Set", which draws about 50 ma. from a separate battery, consists of four principal parts:

1 The wind vane and transmitter

2 A wind direction indicator dial

3 A "Course Setter" dial

4 A "Sailing Indicator" dial.

The wind direction dial gives the direction of the apparent wind relative to the boat's heading. The "Course Setter" dial can be set to a desired angle between apparent wind and boat's heading to give an "error" reading on the "Sailing Indicator" dial. Thus the latter dial is a very convenient steering indicator. It points to zero (straight up) when the boat is on course and swings to left or right as the boat deviates from the desired course. The "Sailing Indicator" meter is a damped, centre-zero, DC voltmeter which reads zero when the boat is on course and reads plus or minus voltage roughly proportional to the deviation when she is not.

The automatic pilot is a transistorised, feed-back circuit which turns the rudder in proportion to the deviation of the boat's bow from the desired course. Its input is a DC signal matching the error in the boat's course. The required signal is substantially greater in magnitude—perhaps 10 or 20 times—than is the output of the "Wind Set". This explains the need of an amplifier at the point of interconnection. The one used, made by the Nexus Instrument Co., is designed for a voltage swing in the output circuit from +10 to –10 volts.

A block diagram of the apparatus is given in the figure.

Performance

When connected and turned on, the system worked! In smooth water it controlled the course nicely. In rougher conditions, it worked hard. It then did the job, but not as smoothly. As one would expect, behaviour was most sensitive to roughness when the course was set close to the wind.

The gain of the amplifier was the one significant adjustment available. This was found to be not at all critical in smooth water. Probably the action in rougher conditions would be improved by a more careful determination of the optimum setting of the gain control.

One complication should be mentioned. It is that the feedback system described here does not really attempt to hold the boat at exactly the preset angle to the apparent wind except in the special case where the boat is in perfect balance with the rudder amidships. If balance (and a steady course) occurs with the rudder somewhat off centre, then the equilibrium established by the control system is at a point varying slightly from the preset course.

The variation is a qualitative indication of the unbalance, a fact of interest in itself.

Because of this, the recorded value of the angle between the apparent wind and the boat's heading must be read from the wind direction indicator dial, not from the "course setter".

Steadiness

The principal problem with this apparatus is fluctuation due to rough water and rapid variation in wind direction. This can be smoothed out by incorporating a circuit of suitable time constant at the input of the operational amplifier. The "Wind Set" contains such electrical damping in its "error" circuit. For these experiments it proved sufficient and was used without modification.

In any case, this particular problem is not severe when the objective is the present one of getting good performance data, because to do that we must have smooth and favourable conditions. Perhaps one day in the future it will be appropriate to broaden the scope of the experiments to include performance in rougher water. (Much of this kind of work is being done nowadays in the testing of power-driven commercial vessels). When that occurs, the question of best damping of the circuit will require closer attention.

Leeway Angle

During the work described above, some attempt was made also to measure the leeway angle. This was done at the bow to assure that the reading would be taken in undisturbed water. Vanes of wood, metal and weighted cord partly and fully submerged were tried without full success. Those partly out of water were subject to some error from wind pressure. All of the ones which relied on the motion of the water at and near the surface were troubled by the erratic water motions of even small surface waves. One attempt with deeper immersion was plagued with vibration and considerable drag. Since it would be desirable to know the leeway angle to one-half or perhaps one quarter of a degree, these difficulties must be remedied.

In AYRS publication No. 47, Howard K. Morgan spoke of measuring leeway angle at the bow. He seems to have been more successful than the present writer. It would be helpful if he would publish a fuller description of his instrument.

Conclusion

This is a report of preliminary work only. The value will lie in getting good performance data for the boat, once all the necessary measuring instruments are available. It is hoped that the next sailing season will be productive along these lines.

CHAPTER XIV

POLAR CURVE OF COQUÍ, ARROWHEAD TRIMARAN

Reprinted from AYRS 70, Nov. 1969

by Henry A. Morss, Jr.

LOA	24 ft	Rig	Sloop
LWL	19 ft 4 in	Sail Area	235 sq ft
Beam	14 ft	Weight (sailing)	1,600 lbs

Designer: Robert L. Taber
Builder: Warren Products Inc., Warren, R.I., U.S.A.

After more than four summers of fussing with instruments and trying to get readings with them, and after time out for every imaginable trouble (damp weather killing off one wind vane, balkiness in the outboard motor which was needed to calibrate the boat speed meter, malfunction of the roll-furl mechanism for the jib, and many another), a mountain of effort has brought forth a mouse. A few things have been learned along the way. (My wife thinks that instrumentation should somehow be easier!).

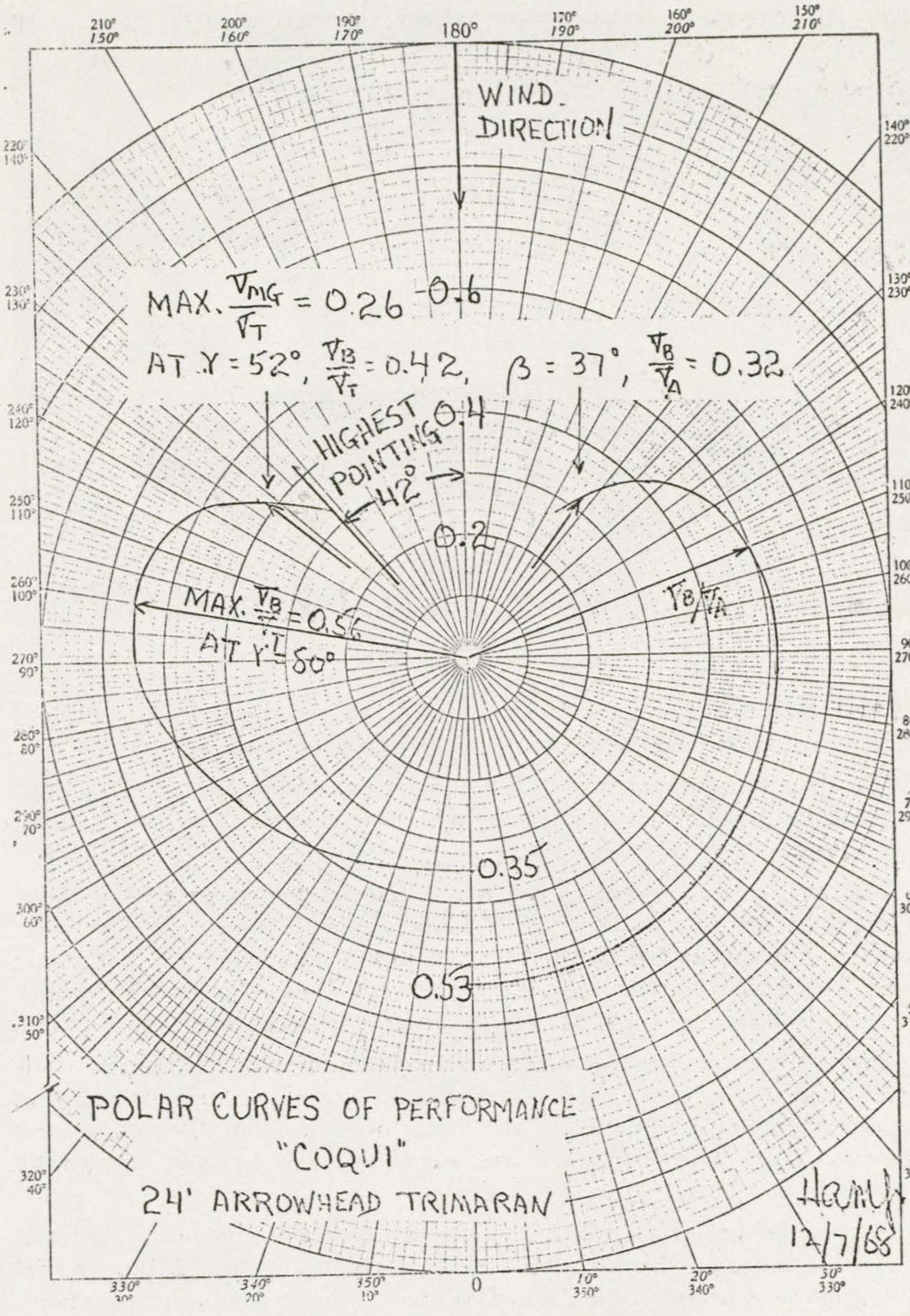
The graph shows the performance of the *Coquí* as measured with instruments patterned after those described by Edmond Bruce in Chapter XI, including the "better or worse meter". The wind instruments are at the top of the mast. Wind speed is corrected to that at the height of the centre of effort of the sails by the seventh root law (wind speed proportional to seventh root of height above water).

During some of the observations the boat was steered by automatic pilot guided by wind vane (Chapter XIII).

The data are plotted as ratio of boat speed to apparent wind speed versus angle between course and apparent wind in the right half of the diagram, and as boat speed to true wind speed versus course angle to true wind in the left half. The data reflect performance in true wind speeds of about 6 to 12 knots. Through that range the ratio of boat speed to wind speed is about constant on the same point of sailing.

The curves have been drawn somewhat arbitrarily through a great number of widely scattered individual measured points to show the boat's good performance—better than average but not nearly as good as "best".

Probably a principal reason for the wide scatter in the original data lies in the relatively unsatisfactory conditions of sailing under which the observations were made. It was essential to find smooth water. Salem Harbour was chosen for most of the measurements to meet this need. In Salem, because



of the proximity of land, wind strength and di. ction were very unsteady. Sailing distances for a given reading were too short for optimising and checking adjustments.

Another likely reason for the scatter in the original data is variation from the assumed relationship between wind speed and height above water and the consequent use of erroneous values of wind speed in the calculations.

Coquí

At best, the seventh root law does not always hold. In the variable conditions in Salem Harbour, the assumption may be less good than usual.

The data do not characterise a fast trimaran, probably mostly because sail area was too small for a boat of her weight, estimated for these tests at about 1,600 lbs.

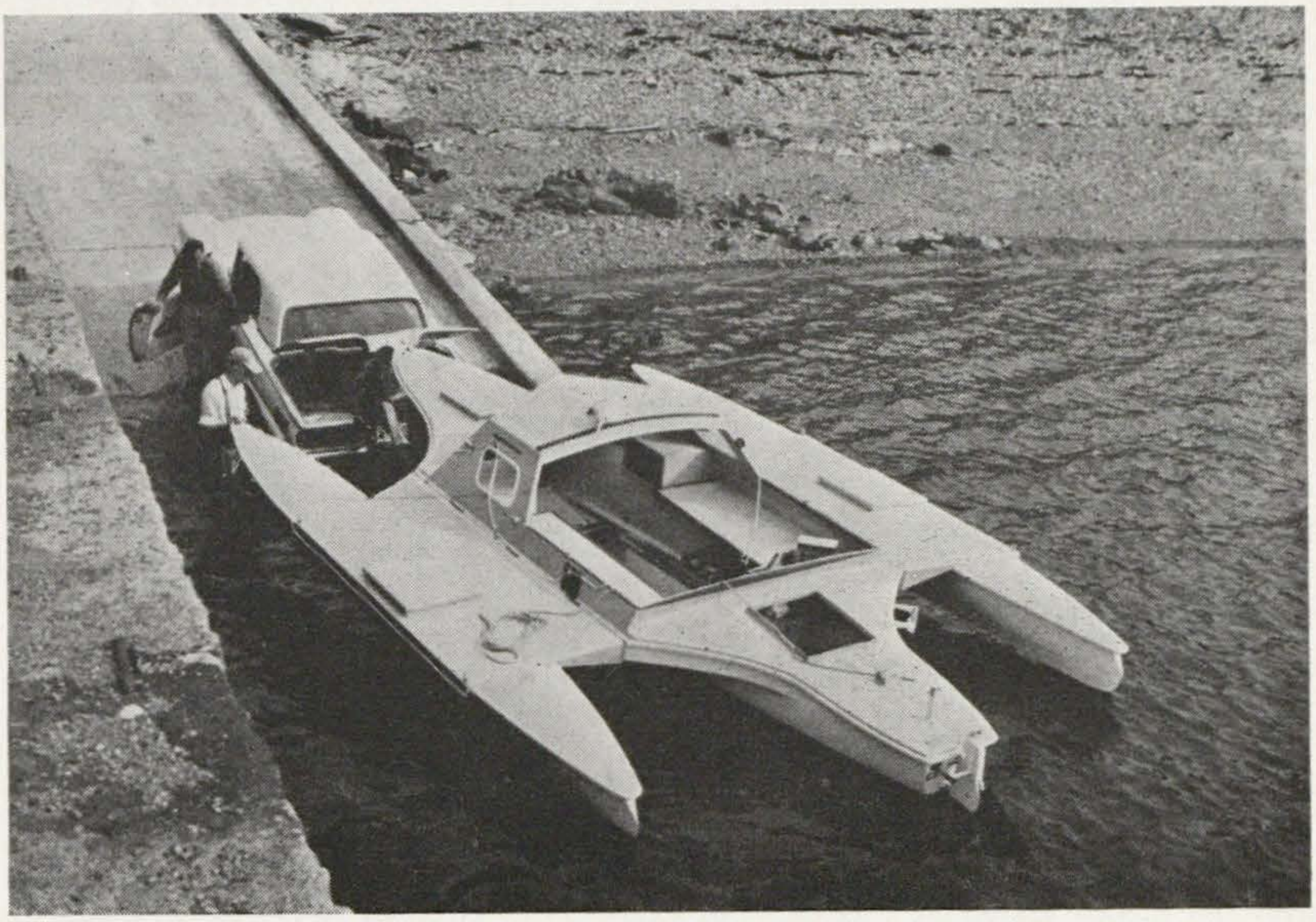
The regular centreboard of the *Arrowhead* design has an area of about 4·5 sq ft and an aspect ratio of about 3. Its location is too far aft. The *Coquí* has also a small forward board, 1·5 sq ft, aspect ratio about 1·5. Both were used during all the tests reported here (except when sailing off the wind). Even with the two of them, the *Coquí* carries a lee helm when by the wind.

Two experimental arrangements were tried in an effort to improve windward ability. One was a crude "curvable foil" of about 10 sq ft area and aspect ratio about 0·6; the other was a pair of 45°-sloping "Bruce foils" on the outer hulls. Their combined area was about 15 to 16 sq ft, aspect ratio about 0·8.

Because neither of these installations was clean and fair, boat speed was somewhat impaired. Nevertheless, the boat pointed higher. A proper trial of one of these, probably the "Bruce foils" is on the docket for next summer.

The "Bruce foils" had a remarkable effect of reducing the already small angle of heel of the trimaran, even though they were not nearly far enough out to the side to create the non-heeling situation. This observation lends more interest to this intriguing concept.

The *Coquí's* mainsail has the usual roach of a sail designed for a boat with a permanent backstay. It has five full-length batten pockets. Thus either



Coquí

full-length or short battens can be used. Both were tried. No difference between the two was found in tests of sailing to windward.

The wind vane-automatic pilot combination has proved to be a superb helmsman, especially in steering to windward.

Edmond Bruce has given examples of polar curves of performance and discussed them in AYRS *publications* 40 and 56 (Chapters I and XI); John Hogg in No. 61.

CHAPTER XV

COQUÍ IMPROVED

Reprinted from AYRS 76, April 1971

by Henry A. Morss, Jr.

LOA	24 ft	Rig	Sloop
LWL	19 ft 4 in	Sail Area	235 sq ft
Beam	14 ft	Est. weight, sailing, including two people	1,600 lbs

Designer: Robert L. Taber
Builder: Warren Products Inc., Warren, R.I., U.S.A.

"Of course" was the instant reaction of Edmond Bruce when I told him that the *Coquí* sailed at least 25 per cent faster (except before the wind) in 1970 than in previous years. My own reaction as the facts began to unfold, early in the summer, was "incredible".

Even now I find it incredible. I'll give the story and all the explanations I can think of. Can any of our readers improve the explanations?

The earlier story of *Coquí* has been given in publications 70 (the preceding chapter of this book) and 74. For this report, we'll ignore the results in

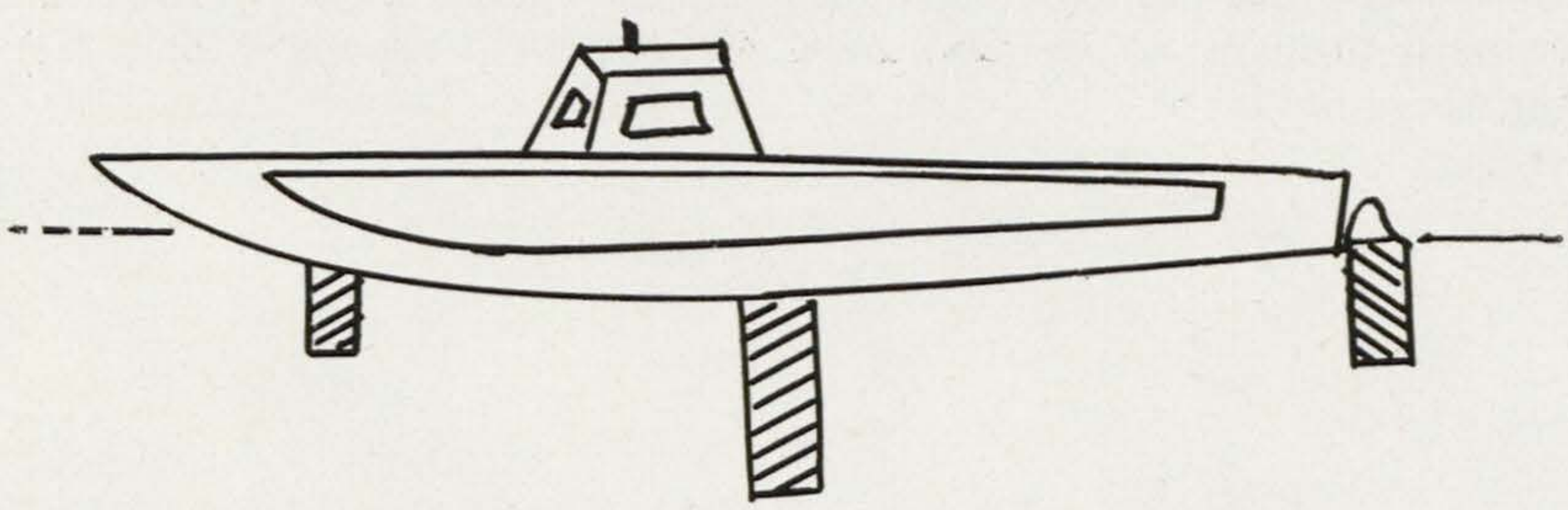


FIG. I.

Coquí-1969 as found in No. 74 since speed was not good. There was too much parasitic resistance from the mechanically crude arrangement.

Design

The changes in the boat which have to explain the enormous improvements in speed are entirely in the underwater profile. Fig. 1 shows the configuration with which we sailed in 1968 and earlier years. Fig. 2 shows the configuration with which we sailed in 1970, the one which was much faster.

In 1968 the *Coquí* had two pivoted boards on the centre line. The main board had an aspect ratio in the neighbourhood of 2·5. In 1970 she had a "keel" made of $\frac{3}{4}$ in plywood and a larger rudder than before.

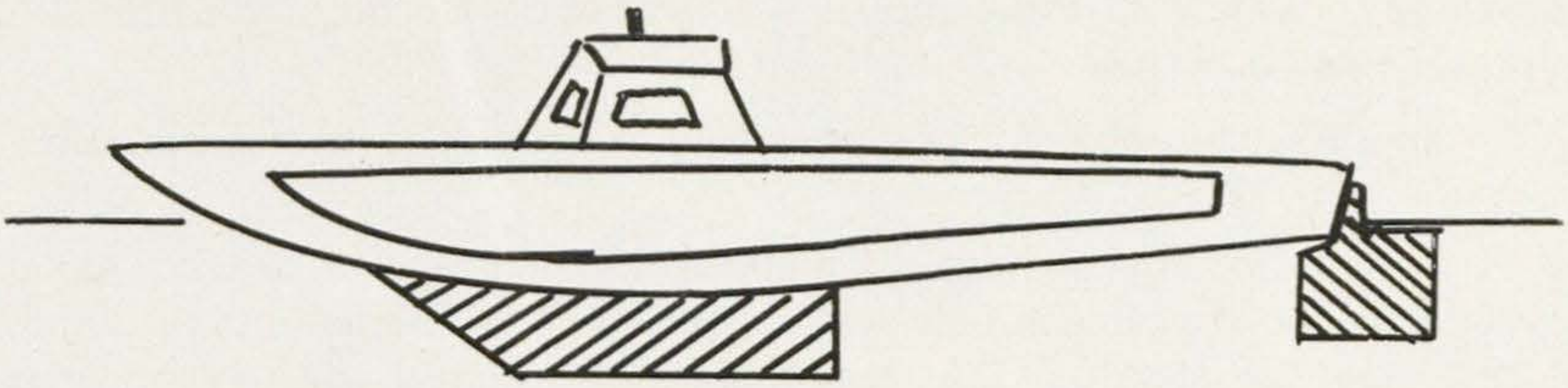


FIG. 2

Differences

The following seems to be a complete catalogue of changes:

1 The keel has an area nearly double that of the two boards in the earlier design.

2 The keel is centred well forward (almost two and a half feet) of the position of the original main board.

3 The keel has a very low aspect ratio.

4 With keel in place of pivoted boards, there is no centreboard box to produce turbulence and absorb energy. Instead, there is a nice, smooth fillet at joint of keel and hull. The bottom is "clean".

5 Rudder area has been more than doubled.

Corollary Differences

Those physical differences produce the following:

1 Wetted surface is appreciably increased. (At least 20 per cent for main hull and appendages and perhaps 15 per cent for the entire underbody in a typical sailing situation with one outer hull clear of the water.)

2 Reduced leeway angle surely helps. "Induced drag" is proportional to the square of the leeway angle, other things being equal. In this case other things are not equal, but probably this is an important gain nonetheless.

3 With the immersed lengths of keel and rudder both greatly increased, the Reynolds Numbers for flow of water by these appendages, considered separately, will be much increased and resistance coefficients somewhat reduced.

4 The elimination of lee helm presumably contributes significantly to improvements in windward performance. It probably does only a little for speed on a reach.

Qualitative Behaviour

That the performance was greatly improved is evident from the following observations:

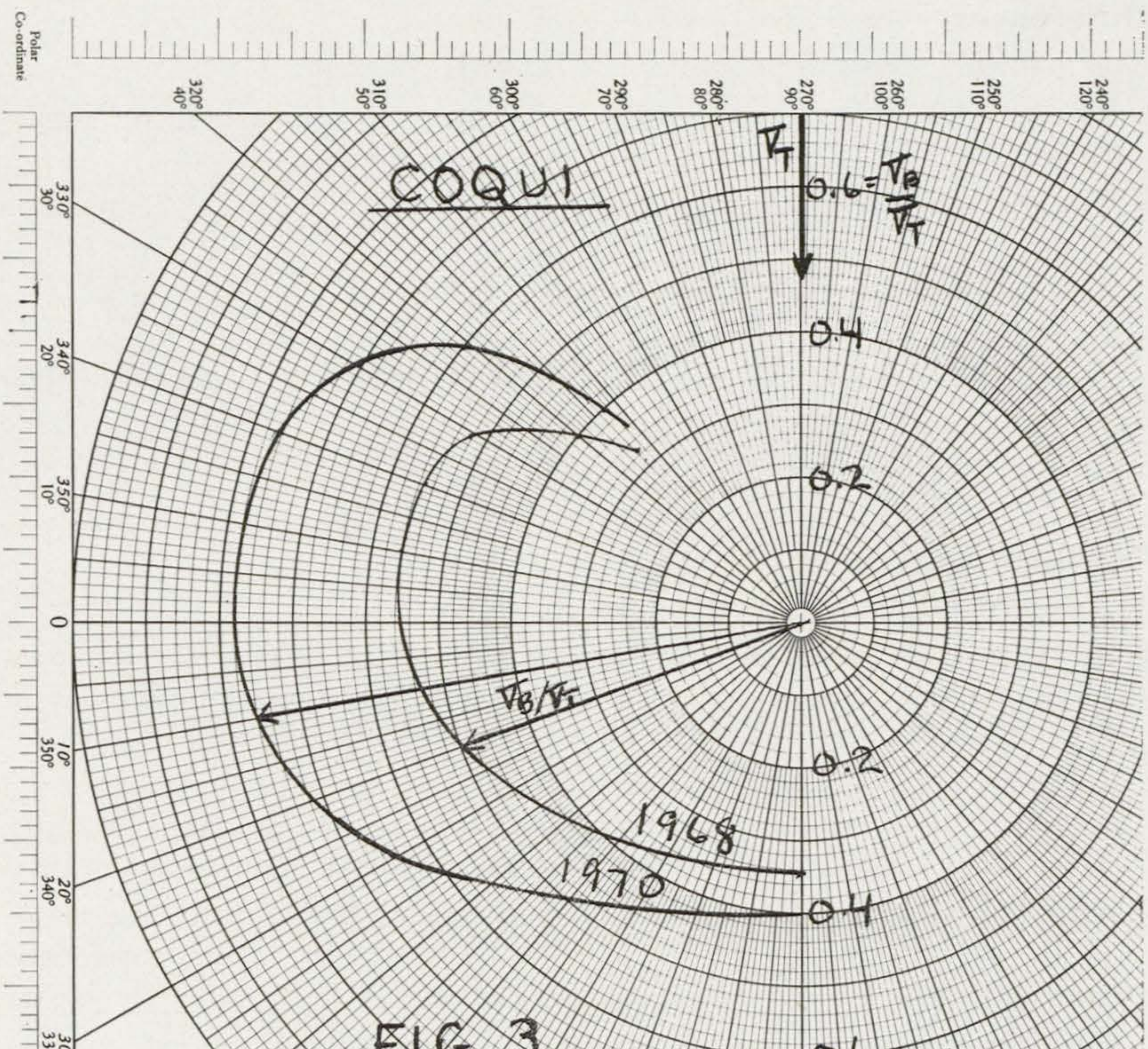
1 *Coquí* kept up with some boats and outsailed others which had been faster than she in previous years.

2 Sailing to windward was a pleasure. It was easy. We quickly acquired a whole new confidence.

3 Tacking was *no* problem. She came about as handily as most good sailing craft.

4 The process of approaching the mooring was like that of ordinary good sailing boats. We came in to leeward of the mooring, headed into the wind, and "shot the mooring". (A short "shoot", but a real one.) In previous years we were much more likely to sidle up to it.

5 She did well on every point of sailing under jib alone. The extreme demonstration of this came on a breezy day early in the summer. In at least 20 knots of wind and a steep, short head sea we got to windward satisfactorily



under the jib alone. While tacking was accomplished with little to spare, it was successful every time we tried. On that same day we had no trouble picking up our mooring in a crowded anchorage under jib alone. (In the harbour the water was smooth and the breeze more moderate.)

In short, we now had a trimaran which was a delight to sail.

Quantitative Performance

Fig. 3 reproduces as the inner curve the one given for the old configuration of the *Coquí* in the previous chapter; the outer curve gives the performance in 1970. In both cases the length of the vector from the centre to a curve is the ratio of boat speed to true wind speed. The curves are fairly representative of speed in smooth water in true wind speeds up to 10 knots or so.

A comparison of the curves shows that with her new underwater profile the *Coquí* is closer winded, can "make good" to windward a speed roughly 25 per cent greater than she did earlier, and is something like that degree faster on all courses except before the wind.

The data come, as in previous seasons, from readings made with instruments patterned after those described by Edmond Bruce in Chapter XI. I did change to a different speedometer, a small "paddle-wheel" type mounted through the hull.

Unfortunately, I do not have great confidence in the data. On two or three days in the middle of the summer the data looked better than those in the attached curve. Later in the summer the performance seemed to back off somewhat—to values plotted here.

After the close of the sailing season I started to look for an explanation. The obvious one to expect was that the boat's bottom was not clean. In fact she was pretty clean when she came out of the water.

But another trouble appeared in a rather thorough checking of the instruments. The new "paddle-wheel" type boat speedometer is battery powered. It turns out to be much more sensitive to changes in battery voltage than I had realised. Perhaps, then, the lower measured speeds toward the end of the season can be attributed to a gradual running down of the battery, a dry battery which was not renewed all summer.

Needless to say, this trouble will not be allowed to continue in future.

These rather minor difficulties do not alter the fact that the *Coquí* is now a vastly better sailboat.

Summary Explanation

Mr. Bruce to the contrary notwithstanding, I feel the need to try to understand the very great improvement in the performance of the *Coquí*. This has led me to list all the things which have contributed. My present list, which hardly seems adequate, is as follows:

1 Enough area of underwater profile.

2 Proper position of the "keel".

3 Smooth fillet at point where keel joins hull.

4 "Clean", fair bottom.

These offset the effect of an increase in wetted surface to produce proper balance, reasonable leeway angle, and reduced resistance. To me, the result is spectacular. What next?

CHAPTER XVI

SIMPLE INSTRUMENTATION FOR MEASURING SAILING PERFORMANCE

November 1972

by Edmond Bruce

Purpose

In the sailing speed-trials, using shore-based instruments, reported in AYRS No. 66-A, page 14, Fig. A, several of the multi-hulls somewhat exceeded the true-wind speed ratio of $V_B/V_T = 1{\cdot}4$ with the true-wind abeam, that is $\gamma = 90°$. I, myself, have measured similar speed ratios for a *Phoenix* catamaran and for my own canted-foil proa from an instrumented, pursuit motor-cruiser.

This writing will attempt to demonstrate two facts:

1 A vast amount of information about performance can be extracted from the above single polar-coordinate point of a performance diagram.

2 This speed ratio point could have been measured aboard the boat in question, rather than ashore, using only the angular heading indication from a wind-vane plus a small leeway angle obtained by sighting on the wake using markings on the rear deck.

Calculations

To be conservative and to allow for possible "scattering" of data, let us select for examination, as the true value, $V_B/V_T = 1{\cdot}4$ at $\gamma = 90°$. Referring to Fig. 1, with the true wind abeam and thus forming a sailing right triangle,

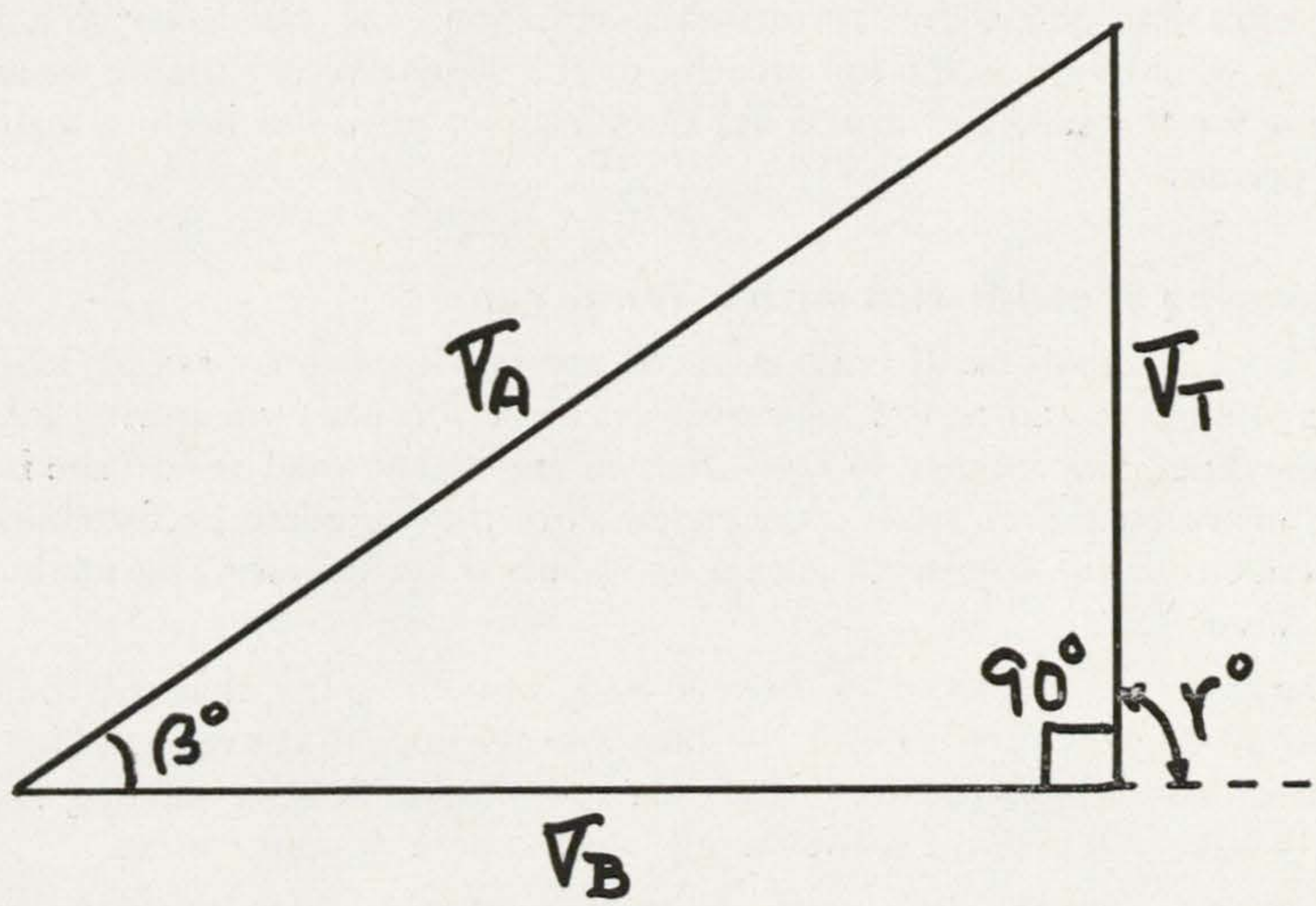


Fig. 1. Sailing Triangle for True Wind Abeam

we have, from trigonometry, cotan $\beta = 1{\cdot}4$, therefore the course angle to the apparent wind is found to be $\beta = 35°$.

Also, in Fig. 1, it is seen that $V_B/V_A = \cos \beta$. Thus, if $\beta = 35°$, $V_B/V_A = 0{\cdot}82$. Once we know V_B/V_A, the important ratio of the sail coefficient C_S over the hull coefficient K_H for the course can be calculated from the formula. $V_B/V_A = 0{\cdot}585 \sqrt{A_S}/\sqrt[3]{W} \; . \; \sqrt[2]{C_S}/\sqrt[2]{K_H}$ when the sail area A_S in square feet and the total weight W in pounds are known. This basic formula for sailing was derived by the writer in an article, "Designing for Speed to Windward" in Chapter IV. For a C-Cat, having a sail area $A_S = 300$ sq ft and total weight $W = 750$ lbs, this calculates to be $C_S/K_H = 0{\cdot}54$ at $\beta = 35°$.

A physical mathematician should be thoroughly aware of the physical meaning of each term of an equation. In the above, the sail area A_S represents the magnitude of the potential total driving power for the given total weight W. When written $\sqrt{A_S}/\sqrt[3]{W}$, it is linear and in a dimensionless form or a pure numerical ratio. This makes it a measure of the craft's speed potential, for a given shape of sail and hull. For this reason, it can be scaled to any size of similarly shaped craft, model or full size. High values currently approach 2·00 while below 1·00 can be considered low. For the case of the mentioned C-Cat, this ratio calculates to be 1·90.

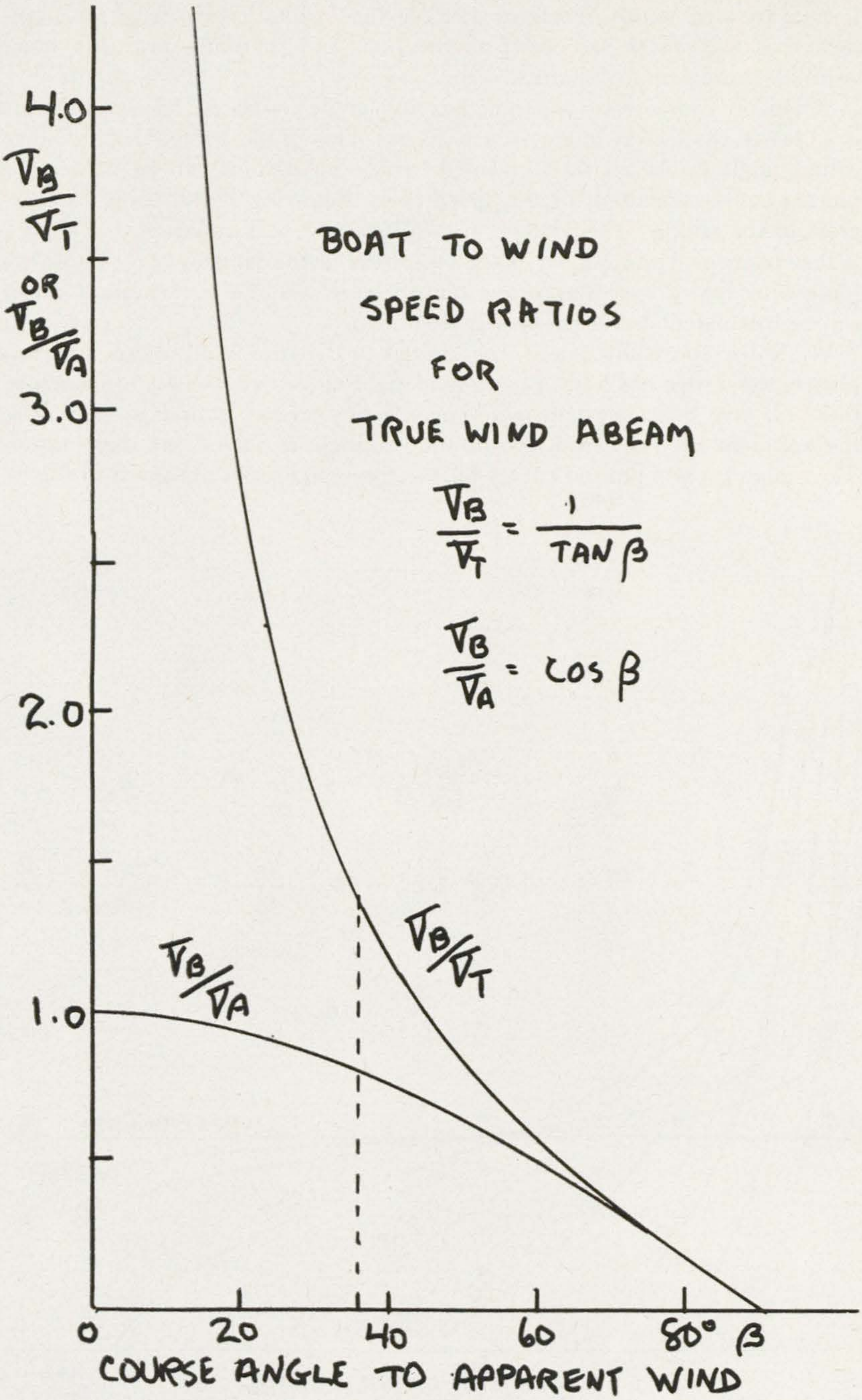
The shape merit of the sail, independent of size, is represented by the total sail coefficient C_S. The water resistance's inverse merit, due to the shape of the hull, independent of its size, is indicated by the coefficient K_H for the particular course and boat speed as discussed in the mentioned article. Thus, from the single performance measurement we have determined the overall shape's merit ratio C_S/K_H, which otherwise would have required both a towing-tank and wind-tunnel to determine. Substituting this ratio into the above performance equation, one can determine how V_B/V_A would vary as the sail area A_S or the weight W is varied over small ranges for the same wind and apparent course, provided heeling stability will permit.

Measuring Speed-Ratios with a Wind-Vane

The crew of small multi-hulls at speed are much too busy sailing to have time to observe and record a sizeable set of performance measuring instruments. They may be glad to know that an angle-calibrated wind-vane is the only instrument they really need to measure the complete performance of the craft with the true wind abeam or on any other course. The method is as follows:

Marks should be placed on the rear deck, near the stern, that will indicate up to 10 degrees each side of the boat's centreline. A convenient sighting point is chosen as the centre of the polar calibration. A brief sighting on the boat's wake will give the leeway angle λ when on a desired course.

A course with the true wind abeam can be steered fairly accurately by keeping the craft parallel with the wave-fronts of the water-waves or ripples



4.0
3.0
2.0
1.0
V_B/V_T OR V_B/V_A
BOAT TO WIND SPEED RATIOS FOR TRUE WIND ABEAM
$\frac{V_B}{V_T} = \frac{1}{\tan\beta}$
$\frac{V_B}{V_A} = \cos\beta$
V_B/V_A
V_B/V_T
0
20
40
60
80°
β
COURSE ANGLE TO APPARENT WIND

Fig. 2

formed by local winds. A flag or weather-vane ashore can be used for alignment but the waves are closer to the boat and therefore probably more accurate in non-uniform winds.

When on course, the apparent heading angle indicated by a wind-vane is added to the leeway angle viewed astern. This gives the apparent wind to course angle β. At a later convenient time, calculations can be made or a plotted curve consulted for the speed ratio. Knowing β and using the diagram of the sailing right-triangle, shown in Fig. 1, it is apparent that V_B/V_A is the cosine of β and V_B/V_T is the reciprocal of the tangent of β. These are plotted in Fig. 2 and may prove quite useful. From the formula, C_S/K_H can be calculated also as previously described.

While the above discussion was limited to the true wind abeam for simplicity, the writer has built a hand-held sighting device, similar in principle, that will give boat-speed to wind-speed ratios on any course in respect to the apparent or true wind. An oblique triangle is solved for these ratios. The equations and plotted curves for the true wind ratios are given in Fig. 3.

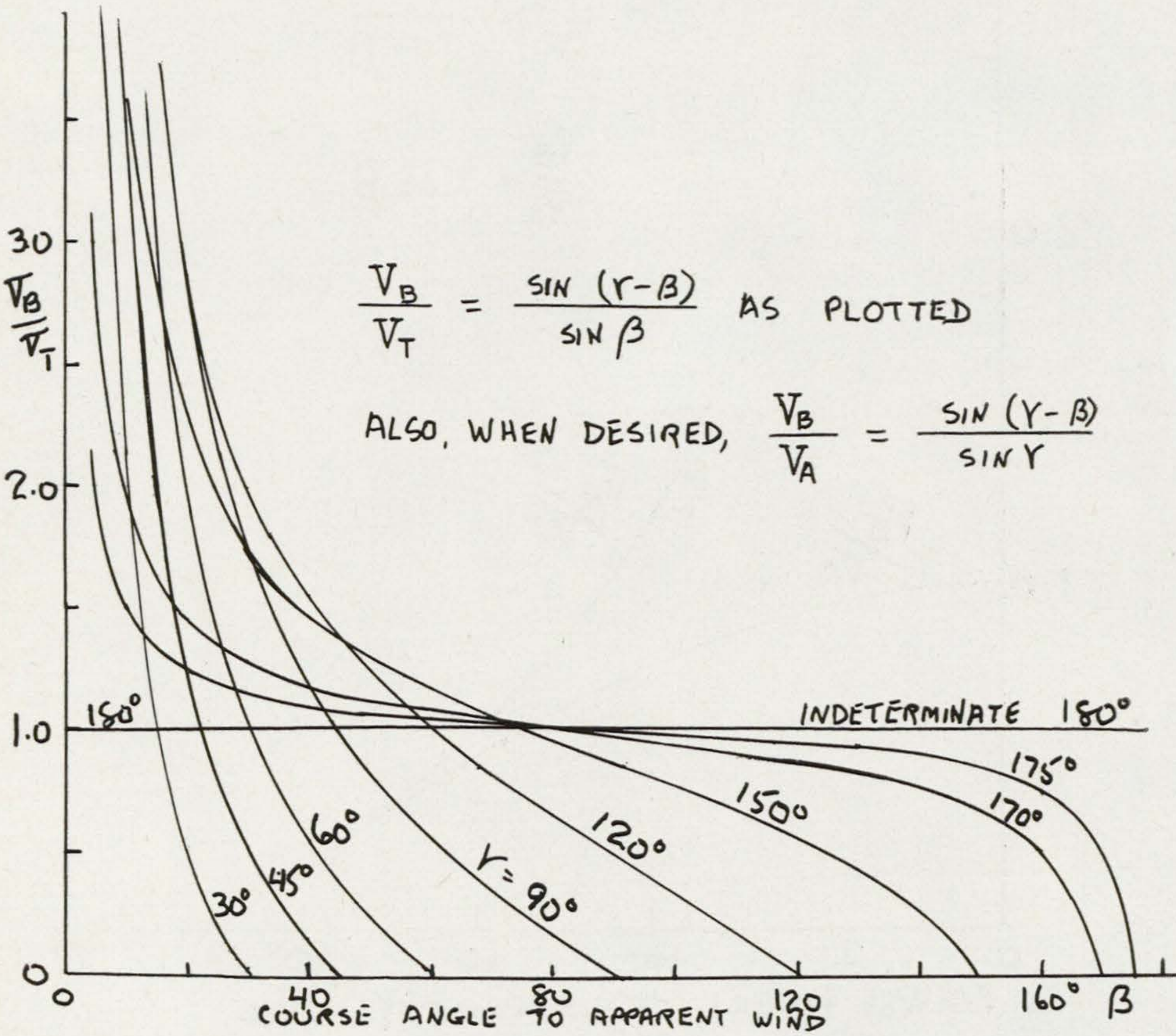


Fig. 3

Others, including manufacturers, may want to experiment with and use similar inexpensive devices. If new in concept, I am giving the idea free to the "public domain" as I want it and other sailing instruments and computers I have developed to be devoid of patent restrictions. Sailing urgently needs an abundance of performance data to progress rapidly. A simple, inexpensive means of measurement should make such measuring a wide-spread practice.

CHAPTER XVII

SKETCH OF IDEA FOR SAILING PERFORMANCE INDICATOR

by Edmond Bruce

Sketch made August 1964
Introductory note March 1973

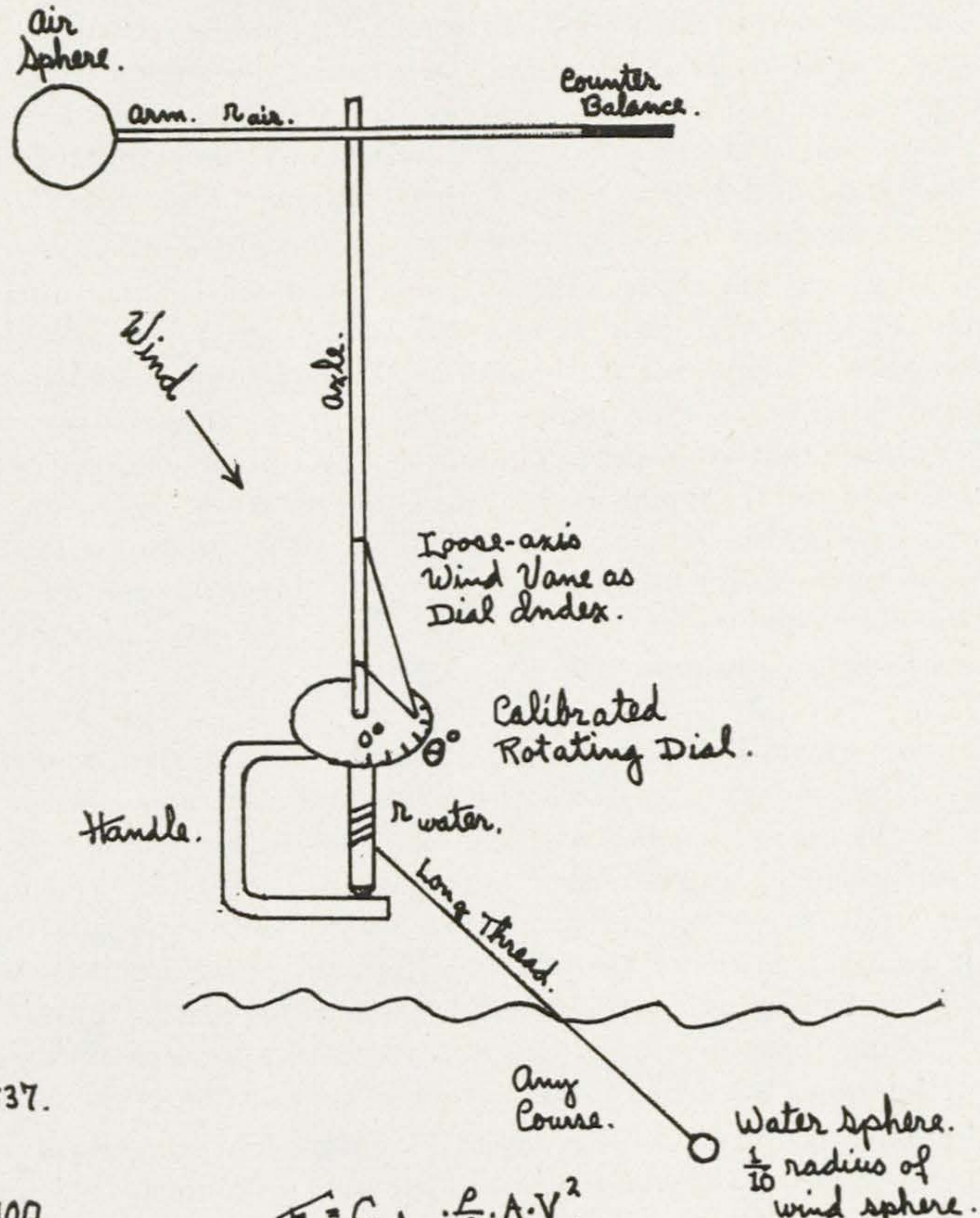
Many of us keep searching for less expensive types of instruments for measuring the performance of sailing craft. Improvements along these lines are bound to be made from time to time.

The attached sketch is probably self-explanatory. The wind acting on the upper sphere on an arm wants to turn the vertical shaft against the contrary torque from the pressure of the water on the smaller, lower sphere, which acts through the small arm length of the radius of the drum on which the cord is wrapped. At equilibrium, the pointer indicates V_B/V_A (by calibration of θ).

Is this practical? It has never been tested. Does it suggest another new possibility to a reader?

Sailing-Craft Performance Indicator.

(Readings should be plotted against wind or boat speed).



$$\frac{\rho_{water}}{\rho_{air}} = 837.$$

$$\frac{A_{air}}{A_{water}} = 100$$

$$\frac{r_{air}}{r_{water}} = \text{adjustable.}$$

$$F = C_{sphere} \cdot \frac{\rho}{2} \cdot A \cdot V^2.$$

$$\frac{V_{water}}{V_{air}} = \sqrt{\frac{\cos\theta \cdot r_{air}}{8.37 \cdot r_{water}}}.$$

F.B.
Aug. 2, 1964.

CHAPTER XVIII

NEW GENERATION OF INSTRUMENTATION

July 1973

by Edmond Bruce

A. *Previous Instruments.* My prior articles about on-board instrumentation for sailing performance measurements, including Chapter XI, have covered a span of about 10 years of experience. Discussed were such essentials as the necessary means for accurately averaging variable wind speeds and directions. Pointed out was the desirability for simultaneous readings of boat and wind speeds through their ratioing. Also considered was the range of constancy of these ratios over various wind strengths.

In reviewing the experiences of using the described instruments, out of dozens of boats that have been measured, ranging from dinghies to 12-metres, not a single one was found which had been customarily sailed or raced with all of its adjustments optimised for best speed on each course. It is a shame that improper operation usually completely overshadows some hard-earned improvement in the boat's design. Accurate pre-race measurements and identification of the locations of optimum adjustments will become essential for racing success when this situation becomes better known. The competitive records of the boats that were improved by these means became outstanding.

B. *Pursuit Boat.* For greatest convenience in optimising adjustments, the instruments undoubtedly should be aboard the boat being measured. However, in the case of small boats that could not accommodate a measurer and his instruments, "walkie-talkie" radio phones have been used between the sailing craft being measured and an instrumented pursuit motor boat. Such a pursuit boat can also make performance measurements without the crew of the sailing craft being aware that it is taking place. On the other hand, those taking these measurements have no assurance that optimum adjustments for speed are being used. Complete cooperation is the best situation.

A pursuit boat may steer so as to be abeam and to leeward of the boat being measured. It is making identical progress if it adjusts to the same speed and maintains a constant distance abeam. Its instruments will read substantially the same as they would if they were aboard the craft being measured.

A number of boats can be measured quickly using the pursuit method. The work and time of changing a given set of instruments and sensors from boat to boat are avoided. A careful calibration can be maintained without being disturbed. For these reasons, comparative performance measurements between boats can be of excellent relative accuracy.

Pursuit boat measurements initially proved to be a three man job. After the measuring boat was manoeuvred to be abeam on the leeward side of the boat being measured, one man continually took abeam sights on the measured boat's mast and adjusted the throttle to achieve the same speed.

A second crewman steered a course identical to that of the measured boat. This was done with the help of a "side-looking" electronic echo-sounder. A constant distance abeam, therefore a corresponding course, could be kept at ± 2 ft when using an adequately powered sounder. The first instrument tried proved to have insufficient power to permit being satisfactorily remote from small boats Echo transmission, which is more or less parallel to the water surface, may present a somewhat difficult problem. Interference by surface reflections makes things more difficult than in ordinary depth sounding. Ample power is essential.

A third crewman directed the work. He also manipulated the measuring instruments. After getting assurances that the pursuit boat was both on a proper course and at the same speed as the boat being measured, he would record four readings as follows:

1 Course speed V_B in knots.

2 Apparent wind's average speed V_A in knots or, better still, the ratio V_B/V_A.

3 Average course angle β in degrees to the apparent wind.

4 Time of measurements and remarks.

From these data, all necessary performance data were calculated and plotted at a later, less busy time.

Other pursuing measuring methods have been studied and some tried. Optical ranging or distance off was determined by the constancy of the angle subtended by the height of a mast or the length of the boat being measured. Only a constant reading is necessary, not the absolute distance. Wave motion and sighting vibrations sometimes make such measurements difficult.

Ranging with radar or infra-red light using a small retro-directive mirror on the boat being measured are better possibilities. In these cases, the pursuit boat might best follow astern, directly in the measured boat's wake. Then the speed would be controlled by observing the ranging equipment.

C. *New Ideas*. The writer has a number of experimental programmes laid out in an attempt to further improve the speeds of sailing. However, optimising adjustments on existing boats, through measurement by instruments, has been so productive that this programme has been given high priority for further improvement and development of instrumentation techniques.

It would be ideal if the helmsman of an instrumented boat could obtain visually a complete calculated answer to any problem that concerns him without manipulation or calculation help from anyone. The answer also could be automatically recorded at the push of a button, for further study, if desired. Small and relatively inexpensive analog computers are beginning to invade the field of sailing craft racing. We will be seeing more and more of these. This will be discussed in the remainder of this article.

So far, we have considered only the measurements of speed parameters such as V_B, V_A and the apparent course angle β of the sailing triangle as extensively discussed in Part II. There, it was shown what a wealth of information could be calculated from these parameters, which are those observed aboard a moving sailing craft. Every calculation discussed, no matter how complicated, can be "programmed" into a small analog computer which will give instant answers. The observer has no need to know how they work. He merely uses the resulting answers to his advantage.

D. *Analog Computers*. Above, I have suggested using an analog computer, not the digital computer about which we hear so much. The analog computer needs far less equipment. It can be quite inexpensive. Its error magnitude need be no greater than that of the indicating meter. Digital computers are required only when a much higher accuracy is desired or a larger amount of stored information required for reference. In general, "slide-rule accuracy" is all that is needed in practical physical problems such as sailing. An answer cannot be more accurate than the input data supplied by the sensors.

This article will not be a text on analog computers. It will only point out the types of sailing calculations that can be solved inexpensively. In the appendix will be "short-hand" computer diagrams for many of these cases for the benefit of those knowledgeable about computers.

Any equation, no matter how complicated, can be solved almost instantly by electronic analog computation. It excels at giving numerical answers for even elaborate differential equations in calculus which man may not know how to solve. This disproves the often heard statement that computers can be no smarter than the individual that programmes them.

The heart of an analog computer is the so-called "operational amplifier" whose symbol is simply a triangle whose apex points in the direction of information flow, as shown in the appendix diagrams. We do not need to know about all of the many transistors and complicated connections that are inside. The computer builder merely connects these operational amplifiers in various combinations to obtain solutions for his particular equation.

The principal cost of an analog computer is in these operational amplifiers and an appropriate output meter. Input data are obtained from the craft's regular sensors. When the writer first started experimenting with analog computer applications to sailing problems, some 10 years ago, operational amplifiers, of which a number are usually needed, were bulky and cost about \$35 apiece. Today, the electronic surplus market is flooded with them, in micro-electronic form, at \$0·41 apiece. A highly satisfactory operational amplifier is the tiny Fairchild, Type No. 741. It is about the size of a large pea. It is probably the best bargain in precise electronic equipment that can be found anywhere. Sailors, who are not acquainted with such things, can get help from friends who are electronic enthusiasts to assemble a computer that can solve any given equation.

E. *Sample Problems*. It is assumed that linear voltages versus V_B, V_A and β are obtained from the craft's regular sensors. Since boat speed variations with adjustments mean nothing without knowing the changes in wind speed, for a given direction, ratioing these readings after averaging has been recommended previously. Amplifier gain adjustments should be provided so that both of these speeds are indicated correctly to the same scale and within the computer's range. Since the ratio V_B/V_A, which is the boat speed in knots over the averaged apparent wind speed in knots, is basic to nearly all of our more elaborate calculations, it is most important. It is valuable even when used alone. Most other analog computations of sailing are performed by adding appendage modules onto this one. Many sailors may find that this single module is sufficient for their needs together with the apparent course angle β.

The required equation for the above basic module is simply:

$$\text{Output ratio} = \frac{V_B \text{ knots}}{\text{av. } V_A \text{ knots}}.$$

Its short-hand schematic diagram for those knowledgeable in analog computation is shown in Appendix D. A photograph of the complete instrument is shown in Fig. 1 of this chapter. It will be discussed later.

For about five years, the writer has used the ratio of the boat's speed "made good" to windward to the true wind speed as indicated by an analog computer. It has been described in my lectures to several sailing clubs. I

Fig. 1

donated the idea to the "public domain" therefore it is not patentable. The ratio was derived from the sailing craft's sensors which included a heading angle wind-vane and a leeway angle gauge which determined the course angle to the apparent wind β. The computation used was:

$$\frac{V_{MG}}{V_T} = \frac{\dfrac{V_B}{V_A}\cos\beta - \left(\dfrac{V_B}{V_A}\right)^2}{1 - 2\dfrac{V_B}{V_A}\cos\beta + \left(\dfrac{V_B}{V_A}\right)^2}$$

The computer schematic diagram for this equation appears in Appendix D.

The angle of the boat's course γ to the true wind is given by:

$$\tan\gamma = \frac{\sin\beta}{\cos\beta - (V_B/V_A)}.$$

Its computer schematic is shown in Appendix D.

The ratio of the boat's speed to the true wind speed is obtained from the formula:

$$\frac{V_B}{V_T} = \frac{V_{MG}}{V_T} \cdot \frac{1}{\cos\gamma} = \frac{\sin(\gamma-\beta)}{\sin\beta}.$$

Its computer schematic module also appears in Appendix D.

Many additional computer modules have been devised. One tells the helmsman the best magnetic heading to steer when tacking up-wind or down-wind regardless of wind shifts. It follows that since such a helmsman is merely following instructions, an auto-pilot could take over the helm, this eliminating the helmsman. Here the skipper's job would be tactics, crew instructions and availability to take over the helm, if necessary, to avoid obstructions or in an emergency. Could the skipper do a better job if relieved of routine helmsman's chores? Would sailing be spoiled by having the machine age take over these routines?

As previously mentioned, Fig. 1 is a photograph of a newly designed V_B/V_A calculator. It can be operated by the helmsman alone on an equipped sailing craft or on a pursuing motor craft. No manipulations or manual recordings of readings are necessary.

The box on the left, in the photograph, is a battery supply. Rechargeable nickel-cadmium batteries are used. One charge lasts several months in normal use.

The speed-measuring calculator box, in the centre of the photo, is capable of indicating the charge condition of the batteries as well as the desired speed measurements. A choice of boat-speed V_B, apparent wind-speed V_A, the ratio V_B/V_A or the battery charge is indicated by the single meter through switching.

Any meter indication can be recorded by one of the two pens of the "Rustrak" strip-chart recorder shown on the right in the photograph. A momentary push of a button actuates it whenever desired by the helmsman.

The second recording pen, on the recorder, is connected to the craft's separate wind-vane. Thus the strip record gives two simultaneous magnitudes so that either of the speeds or their ratio can be recorded versus the heading angle to the apparent wind.

The craft's leeway angle is measured independently if the instruments are aboard the sailing craft. This is unnecessary aboard a pursuit boat since it follows the course angle directly. Heading and leeway angles can be added easily by the computer as shown in Appendix D. Thus the second pen on the strip chart or a meter reading could indicate directly the course angle rather than the heading.

For on-board measurements, the normal procedure is for the helmsman to carefully steer a constant selected course as shown by the wind-vane indication. A separate pointer on its meter is suggested which can be manually adjusted as a reminder of the desired course. When a range of readings versus wind angles is required, the helmsman, when ready, momentarily presses the recorder button at each angle. The strip tape moves only during such intervals. Desired courses are numbered in advance. Counting the sequence number of the recordings determines which readings were involved if any special notes have been made for that reading.

Pursuit boat measurements are similar. However, in this case, the recording button is pressed on each course only when an identical speed and course have been achieved with the boat being measured. These occur when the bearings and the range have been made constant.

F. *Sensors*. Fig. 2 is a photograph of the Simerl anemometer and an early prototype of a Simerl under-water impeller used as a boat-speed sensor. The anemometer design is excellent. The underwater impeller is being redesigned. The latter gives a much larger electrical output than is needed. A redesign will permit a much smaller unit as well as better weed-shedding. These two sensors can be installed permanently on the larger sailing craft or on a pursuit boat. To achieve easy portability to enable changing rapidly from boat to boat, those illustrated in Fig. 2 are mounted at opposite ends of a long demountable pole which is usually positioned vertically on the windward side of the craft to avoid interference by the sails. An installation forward of the bow also has been used to avoid water accelerated by the hull's form. Here, running courses are not measured because the anemometer is not in clean air when in this position.

Fig. 3 is a photograph of an excellent, low-friction, wind-vane capable of accurate readings to a fraction of a degree. Most wind-vanes, that use a sliding brush on a potentiometer, have far too much friction for the desired accuracy. The secret of the illustrated wind-vane is that rather than a resistance potentiometer, it uses instead a *ball-bearing*, variable, semi-circular

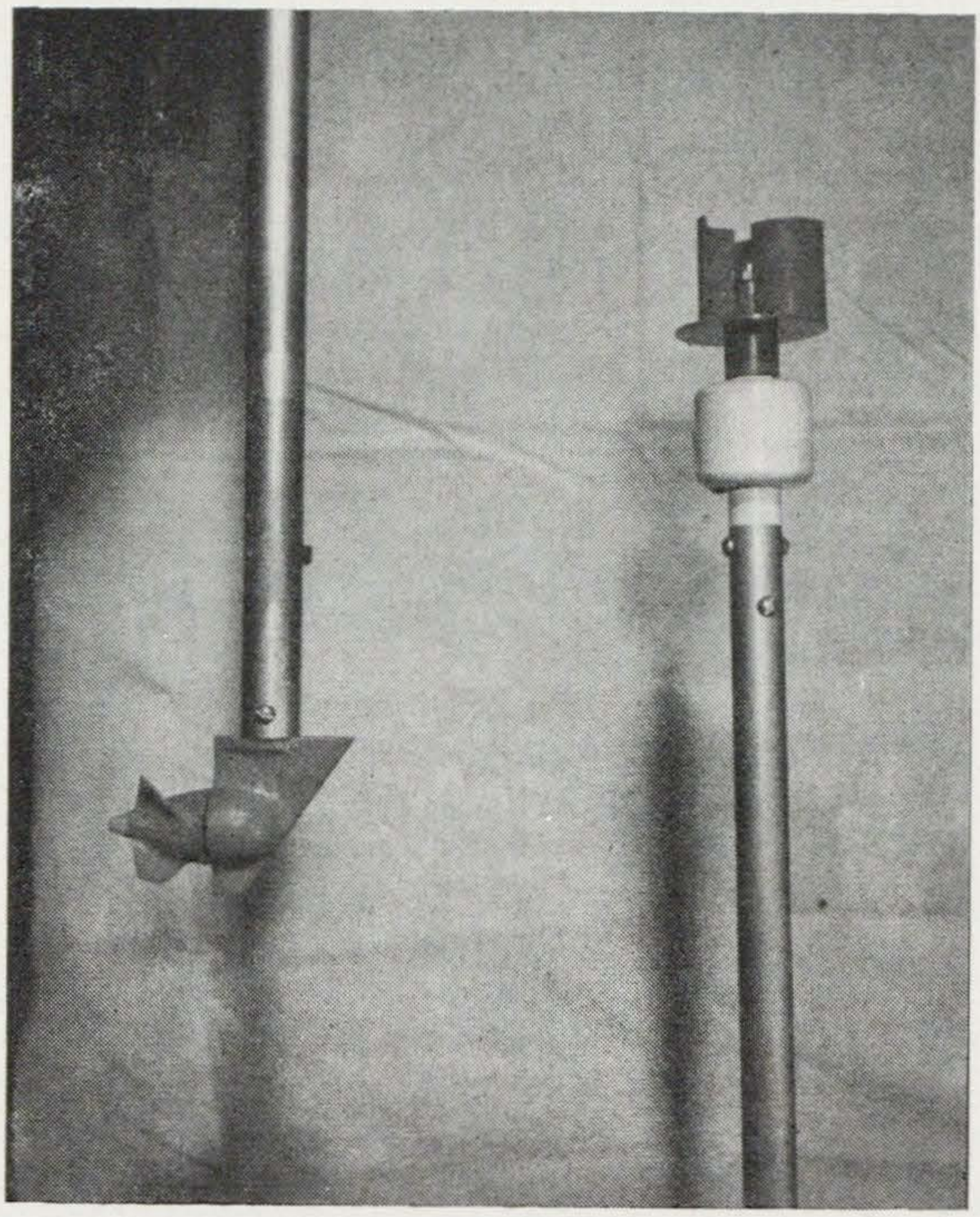


Fig. 2

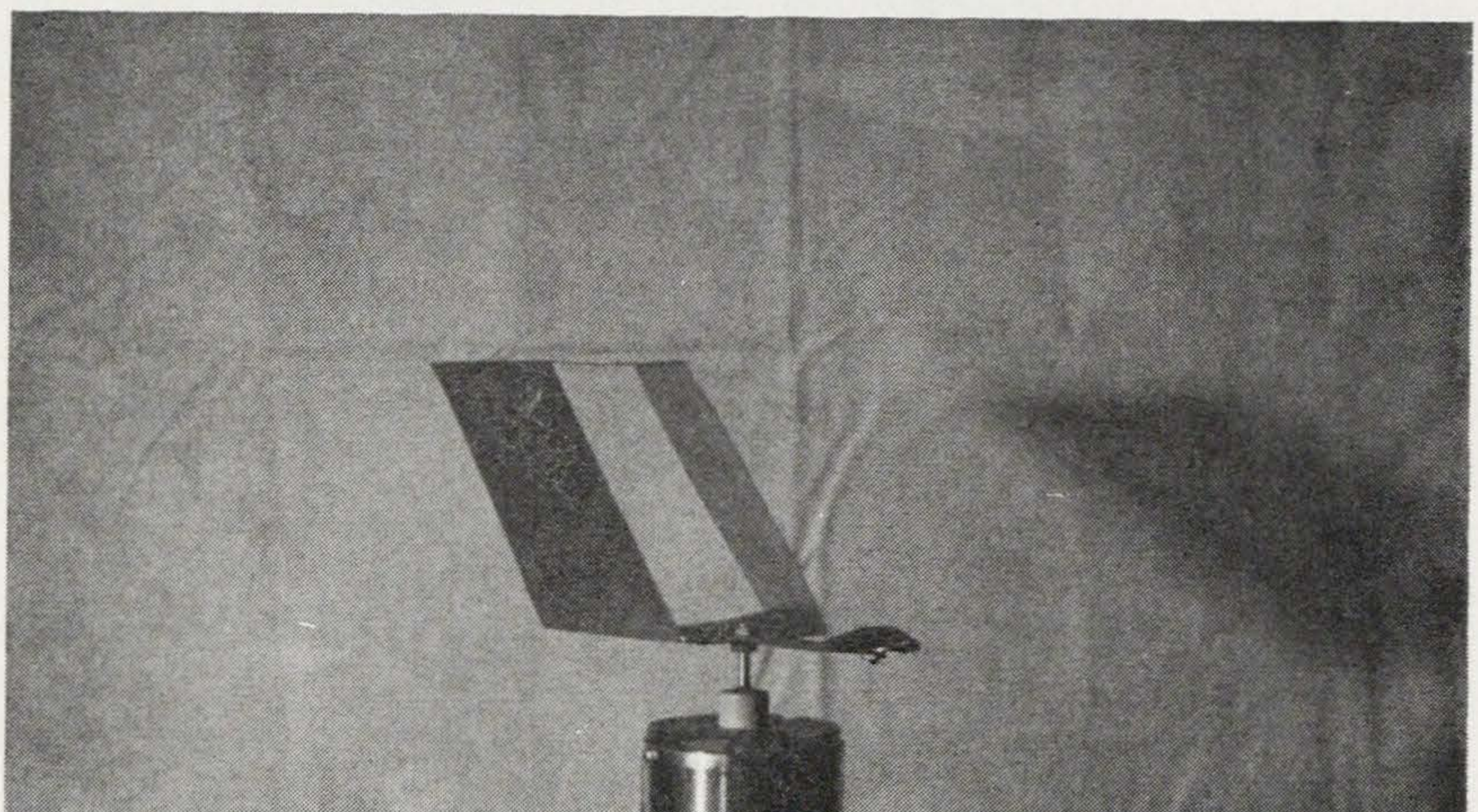


Fig. 3

plate, air-condenser. Its plate structure corresponds to tuning condensers found in radio receivers. The electronic circuits employed with this wind-vane are shown in Appendix D. Again they employ operational amplifiers.

The box-shape foils of the wind-vane, shown in Fig. 3, accomplish several things. It is a strong structure that can take a beating from the weather without distortion. Being boxed in, the usual tip vortices of air from the foils are eliminated. This is equivalent to a high aspect ratio; thus the foil forces are powerful. The two vertical sides of the box are each angled 15 degrees but oppositely from a centre-line to produce powerful but balanced forces at zero degrees to the wind. Tests in the wind-tunnel described in Chapter XI showed that all adjustable angular settings can be repeatedly indicated to a fraction of one degree even in very light air. I have not seen this high accuracy of angle indication in any other wind-vane.

PART FOUR

HULL MODELS

CHAPTER XIX

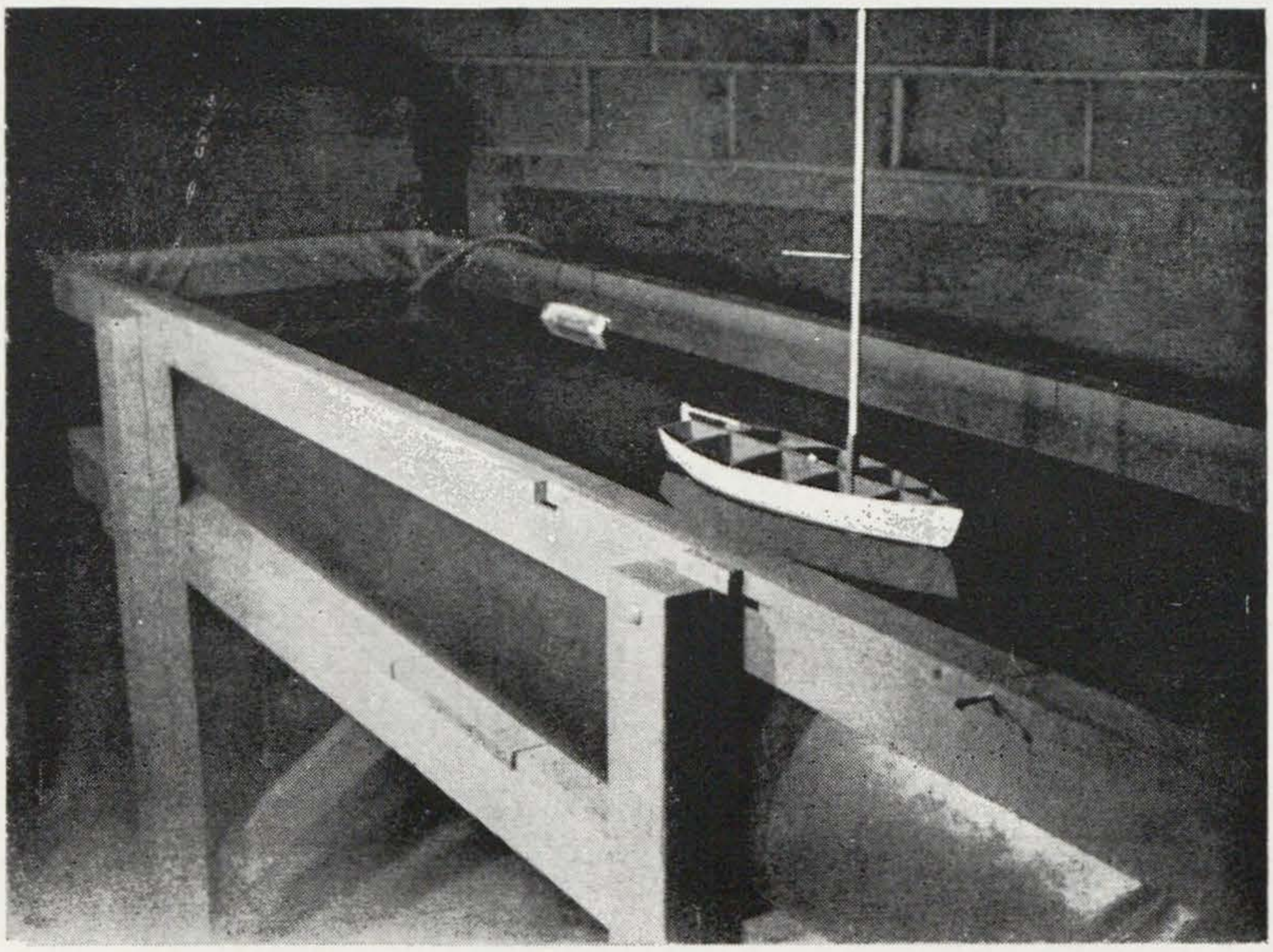
THE BRUCE TANK

Reprinted from AYRS 30, April 1960

by Edmond Bruce

Introduction

This article describes a test tank which is only 10 ft long, 2 ft wide and 1 ft deep which has been used for 15 years to test over 200 model hulls. Where it has been possible to check the figures produced by the tank against full size craft, they have been found to be accurate and useful to yacht designers.



The Bruce Tank

The basic principles behind the testing of models of larger craft in a tank and of finding out the resistances which may be expected at full scale have been dealt with in AYRS No. 24 but they will again be stated here in a summarised form.

The total resistance of a hull is composed of two factors, skin friction and "pressure resistance" (made up of wave-making resistance and "form" resistance). These two resistances were shown by Froude to be apparently quite separate from each other. In a model in the tank, therefore, the objective is to find out these two factors separately, enlarge them separately and again add them to find out the full scale resistance.

In the conventional tank, the same Froude number is used both for the model and the full scale craft so that the "pressure resistance" of the full scale craft will be that of the model multiplied by the cube of the "scale factor". Skin friction, on the other hand, cannot be scaled up in the same way, though there is an approximate correspondence to Reynolds' number. In fact, the skin of the model is measured in effective length and area and its resistance is calculated. Then, by scaling up by Reynolds' number and using the empirically derived Schoenherr curve, the full scale skin friction can be calculated. Both the model and full scale skin resistances will lie along the Schoenherr curve if they are both turbulent. Now, the full scale craft will have turbulent boundary layer flow but a small model will have a large area near the bow which is in "laminar" flow and this will make the skin resistance different from the Schoenherr curve. It is therefore the practice to cause the boundary layer of the model to become turbulent by adding trip wires, studs or sandpaper to the bow or by other means.

Now, it has never been questioned that Froude's law of comparison holds truly for the smallest models and, if the "pressure resistance" could be found for them by an accurate discovery of the skin friction, the pressure resistance of the full scale craft could be found. The skin friction of the larger craft can then be calculated from the effective length and area of the wetted surface and thus the total resistance produced.

The theory on which the tank which is being described here is founded is that the models are so small that they are entirely in a state of "laminar flow" in their boundary layers which is a stable condition. As the models (or the Reynolds' numbers) get larger, turbulent flow begins to appear at the sterns and this is rather unstable in its resistance so the models must be small enough to prevent turbulent flow altogether. Firstly the model is towed in the tank and its resistance found. Then, a plastic "skin" of the shape and area of the wetted surface of the model is towed and the resistance found. The difference between these two resistances gives the "pressure resistance" of the model.

The Tank's Background

The late Professor Davidson, of the Stevens Tank, was a class mate of mine years ago and, more recently, I have had helpful arguments with him about basic methods. In fact, these arguments and my convictions founded my hobby for me.

The consequences of an inexpensive tank method could be frightening to professional tank people and there is a controversial aspect to all ship model testing no matter where or by what method it is done but it is felt that adequate evidence will be given here to show that a small tank which tests models in laminar flow can give accurate results.

Davidson was well aware of my private tests and, in return for supplying me with copies of many Stevens reports on sailing hulls, he requested that I not publish my views. He felt that, if small tanks sprang up everywhere, his life would become miserable combating misinformation from unskilled experimenters. Since his recent passing, I no longer feel bound by this undertaking and I never agreed with Davidson's viewpoint on the ills of widespread tank experiments.

With my tank, I have been quietly helping certain naval architects for years with a few of their problems where they interest me and I am proud to say that every effort so far has been successful at full size. To give just one example, I was able to show Mr. Henry A. Scheel that a marked improvement could be obtained in pointing, footing and balance with multiple adjustable centreboards in addition to a fixed keel. The higher lateral lift-drag ratio is largely responsible for the racing successes of the boat he had built and which he described in an article in the September 1958 "Rudder" where he acknowledges the help given to him by the tank.

The Wave Resistances

In this tank, the total resistances of models, when reduced by their skin resistances (found separately), at the same speed, produce pressure resistance values which check Froude's "similitude" law very well. This was determined by tests on three sizes of models which were similar in shape and had their weights proportionately scaled. This is substantial encouragement for the worth of the method and is the type of experiment I would recommend to those just starting in tank testing.

The Skin Resistances

It is on the method of measurement of the skin resistances of the model hulls tested that this method differs from the orthodox. In short, the skin friction of the model hulls is tested by cutting out a sheet of polyethylene film 0·012 in thick to the shape of the skin of the hull, including all small appendages to scale such as rudders, keel etc., so that their low Reynolds numbers compared to that of the main hull are properly accounted for. This floats on water horizontally and is towed down the tank by a string attached to its upper forward surface.

The centreline of the skin can represent the waterline on the two sides of the hull but joined together. Further out on each side is the reproduction of the side surface of the keel with the rudder similarly produced aft.

The laminar *theoretical* work by Blasius indicates a resistance coefficient versus Reynolds' number which is precisely parallel to my *experimental* data, even throughout a range of water temperatures, when plotted on log-log scales. This slope or exponent is my indication of laminar flow. The transition and turbulent regions have slopes which are quite different. My proportionality factor is slightly higher than Blasius but so are data I have obtained from the U.S. Model Testing Basin.

Theoretical Skin Friction

It is usual to plot the coefficients of skin friction against Reynolds' numbers, the reason for this being given in many text books. It gives the skin resistance in a straight line on a log-log plot. Its slope therefore indicates the exponent and its base intercept, the proportionality.

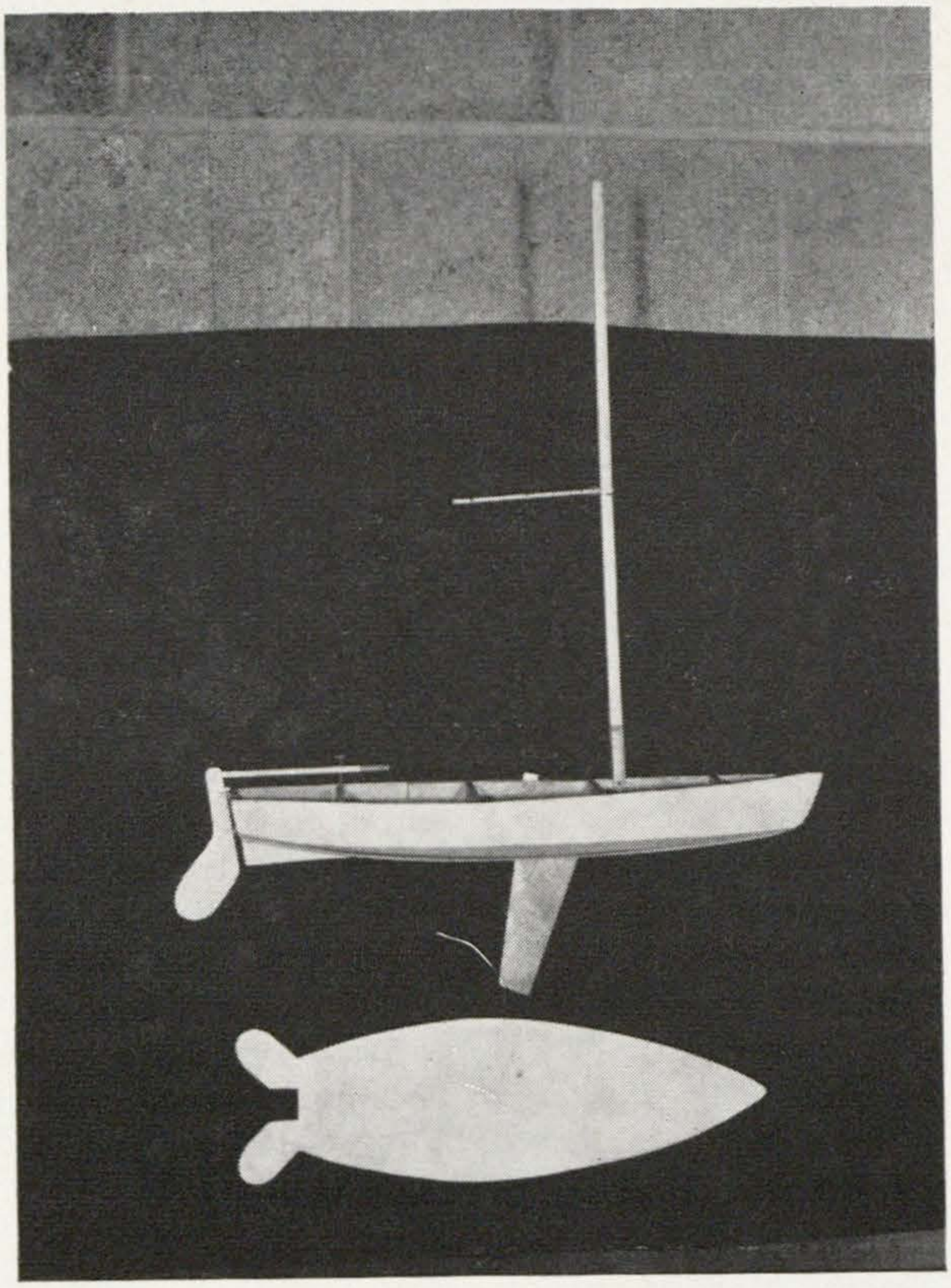


Fig. 1. Model and "Skin"

The coefficient is represented by:

$$C_F = \frac{R_F}{(\rho/2)\ A_W\ v^2}$$

where R_F is the total frictional resistance in pounds.
A_W is the wetted surface in square feet.
v is the velocity in feet per second.
ρ is the fluid density in pounds per cubic foot divided by the acceleration of gravity in feet per second per second.

The Reynolds' number is written:

$$R_e = \frac{vL}{\mu/\rho}$$

where L is the effective length in feet in the direction of motion.

μ/ρ is the kinematic viscosity of water allowing for temperature and type of water.

In Fig. 2, the line on the right is a reproduction of the well-known Schoenherr curve for the region of complete turbulence. Schoenherr assembled experimental data from many sources and plotted them all. His line is the mean drawn through them. It is reported to be nearly completely turbulent from $R_e = 2 \times 10^6$ upward. Below this and down to about $2{\cdot}5 \times 10^5$, added stimulation is usually needed to force the water to full turbulence. Still lower, full turbulence is not possible.

The line on the left is the Blasius theoretical laminar curve but with E. H. Lewitt's slightly modified proportionality factor. It is written:

$$C_F = \frac{1{\cdot}369}{\sqrt{R_e}}$$

In the figure and above Blasius' curve are some of my early data. These were obtained from two "tear-drop" shapes of polyethylene of similar shape but 12 and 15 in long respectively. The Reynolds' number implies that they will have the same coefficient of resistance if vL is the same and the correspondence is quite satisfactory. However, when these skins were reversed and towed blunt end first, instead of the fine end first as was done for the figures in the graph, the resistance coefficient increased by 16 per cent, although the slope was the same. This was due to the blunt forward shape extending beyond the "Mach angle" of the water's advance ripple pattern. Few hulls are this blunt, but this circumstance should be avoided.

The Skin Testing Method

Whereas large tanks usually make measurements of skin friction from planks on edge suspended from an overhead carriage there are problems of the finite thickness of the planks and of longitudinal flutter in thin planks. For this reason, I abandoned this approach in favour of thin polyethylene films positioned horizontally on the water's surface. Support is obtained both from the material's buoyancy and from the surface tension of the water. Tests of ribbon-like surfaces were abandoned also in favour of the model hull's actual wetted surface area laid out on a flat film by transference of adjusted girth measurements at various station locations. For accurate testing of skins, it is essential to keep the towing cord out of the water. For this reason the cord is given a 10° rise but only the horizontal component is used for calculations.

It has been interesting to discover that films 0·002 in thick measure the same as films of identical size and shape but 0·012 in thick. Vinylite and cellulose-acetate give the same results as polyethylene. Waxing or oiling the surface produces no measurable changes. The only thing which seems to alter the resistance is silicone grease which makes it greater. However, exposure of the tank water to daylight for three days or more grows algae and this increases frictional resistance which makes a change of water and tank

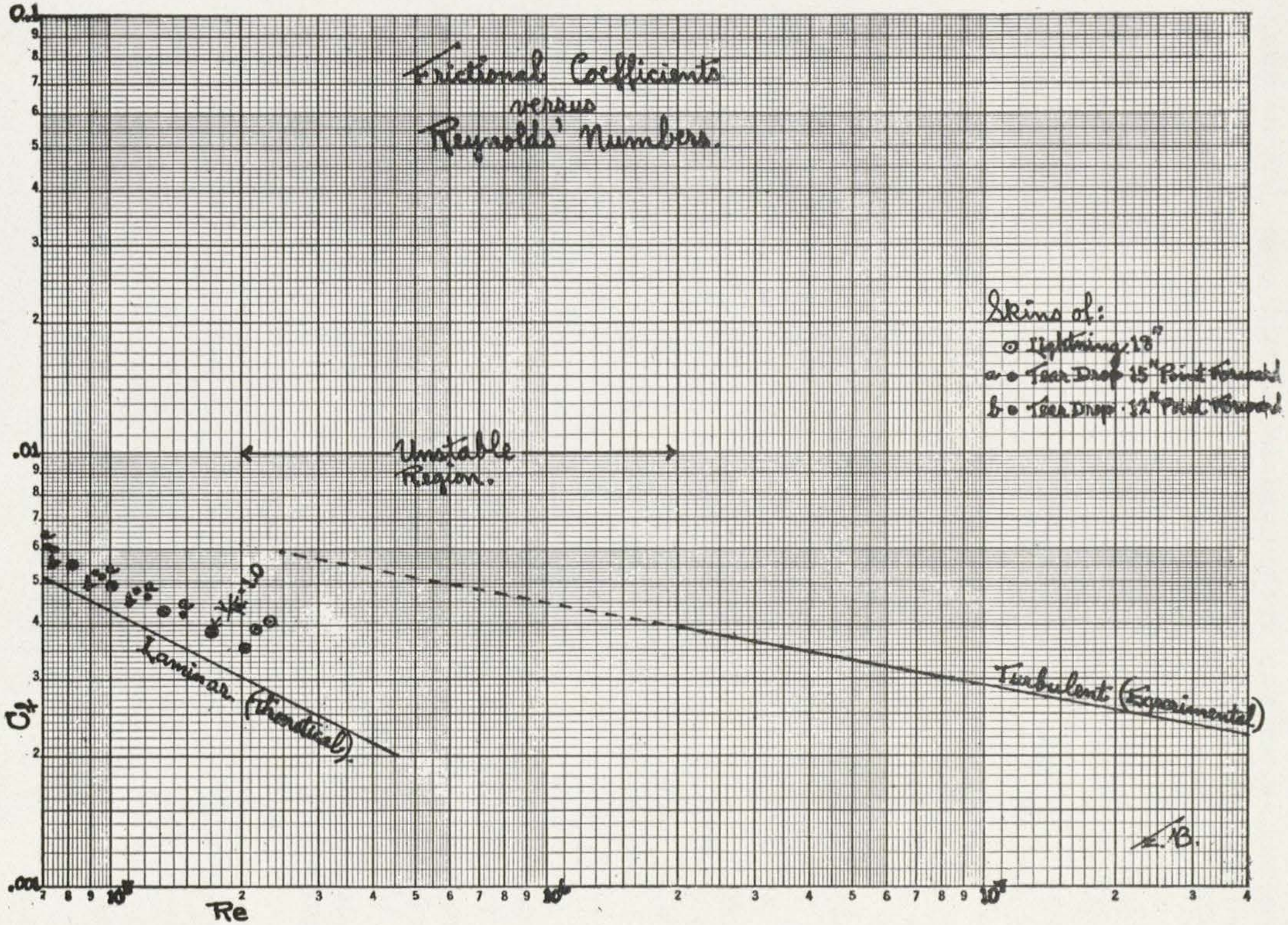


Fig. 2. Frictional Coefficient vs. Reynolds' Number. Blasius's and Schoenherr's curves and experimental plot for 18″ Lightning (circles), 15″ Tear Drop with point forward (crosses), and 12″ Tear Drop with point aft (triangles).

cleaning important. This is an additional argument for a small tank as it is an annoying chore. Covering the tank with a light-proof cover is helpful, as are anti-algae preparations used in swimming pools.

The earliest model tested was a *Lightning* class sailboat. By chance, the skin representing the model's wetted surface was 18 in in total length. The measured data for this skin, at the usual displacement speed-length ratios, is plotted on the attached curve sheet. They show that the model is slightly too large for the top speeds. Up to a Reynolds' number of 2×10^5, the experimental slope is the same as the theoretical laminar curve and therefore considered stable. Instability sets in beyond this which sometimes cannot be repeated in successive runs. I no longer use models as large as this.

Experience has taught me that the average length, rather than total length, must be used for Reynolds' numbers. This is obtained by dividing the area by the extreme width of the skin. This pulls most data, with a few exceptions, to the same line, which would otherwise appear scattered. This means that the shape of the skin is important.

Water temperature is extremely important. If the proper viscosity values are used in the Reynolds' number, the alignment of data will be quite satisfactory. Several tests with progressive temperatures, obtained by heating the water electrically, confirm this. An electrical heating cable is placed in spiral fashion on the bottom of the tank to adjust the temperature.

Every model I test has a separate skin test to determine the component of frictional resistance versus speed. Displacement types have nearly constant wetted areas as their speeds are varied. Planing types, on the other hand, have areas which vary with speed and they need special consideration. The laminar curve illustrated with a plotting of points is used only to check that the frictional coefficients have not strayed from the purely laminar region. However, even if the skin departs from the laminar state, the pressure resistance can still be determined correctly provided the hull surface and the separate skin behave in the same manner.

The Calculations

For a given speed, one first finds the total resistance of the model hull and the resistance of the skin separately. The difference between these two figures gives the pressure resistance. The pressure resistance is scaled up to full size by Froude's "similitude" law. The effective skin length of the model is found by dividing the area of skin by the greatest width. For the same speed, one can then calculate from Schoenherr's curve the full sized frictional resistance precisely as the commercial tanks do and add it to the pressure resistance transferred to full size by the Froude ratio. This gives the expected total resistance of the full sized craft.

The Tank

Commercial tanks provide enough tank length for the acceleration and deceleration of their heavy overhead carriages which support the models. We do not have this problem since floating models towed by a fine cord are used. Continuous photo-electric, automatic recording of travel time in units of 1/100th second for every 2 in of the tank length permits not only the measurement of speed but also of acceleration.

The horizontal towing force of the cord is derived from a falling weight via a low friction pulley. This force has two additive parts. One overcomes the model resistance in the water at the momentary speed and the other accelerates the model. If we wait long enough so that the acceleration is zero, the falling weight will represent the water resistance alone. For the size of models we must employ to remain in the region of laminar flow, acceleration to maximum speed can be accomplished in about 8 ft or less. However, if the ultimate speed is not obtained for any reason the acceleration remaining times the mass of the model with pulley correction indicates the force which should be subtracted from the falling weight to give the model resistance for the speed developed. Ideally, one run from a standing start is all that is needed for a range of resistances versus speeds but actually a series of weights is used to give greater accuracy.

Tank experts tell us that to avoid appreciable wall effects, the cross-section of the tank should be more than 100 times the cross-section of the underwater body of the model. This means that for our size of models, a tank 2 ft wide by 1 ft deep is ample. To accommodate the length of the model plus the travel distance, therefore, the tank need be only 10 ft long if an arrestor cord is used at the terminal. This is an astonishingly small tank by prevailing standards, but we cannot beneficially employ a larger one with our laminar method.

Accuracy in a tank test usually requires still water. Waiting for waves and ripples to die down is time consuming with a tank having hard walls. In an attempt to damp down the wave motion somewhat more rapidly, my tank is made of flexible Vinylite only 0·012 in thick. It is mounted on a skeleton frame and the bottom rests on a platform. This supports the weight of water and relieves heavy cumulative strains through the Vinylite. A friend of mine slapped a bulging side and remarked that it reminded him of spanking the baby.

The Vinylite has a surface which is slightly rough optically which makes it translucent. When this surface is in contact with water on the inside and a smear of Canada balsam is put on the outside, a satisfactory window is provided which permits looking at the underside of a hull to examine the water action. If powdered rosin or aluminium powder is sparingly mixed in the water, it makes possible the observation of water adjacent to the hull surface in search of harmful eddies.

Mechanically pulsing one flexible end of the tank gently generates waves which are useful for visual observation of rough water performance. Accurate measurements under these conditions are, however, not easy.

A tank at ground level is an abomination. Frequent stooping to adjust a model is a back-breaking thing and if the tank is raised so that the water surface is breast-high, the experimenter is much happier.

Since we will make tests of sailing hulls, among others, running, reaching and windward courses must be studied. These require that the towing force,

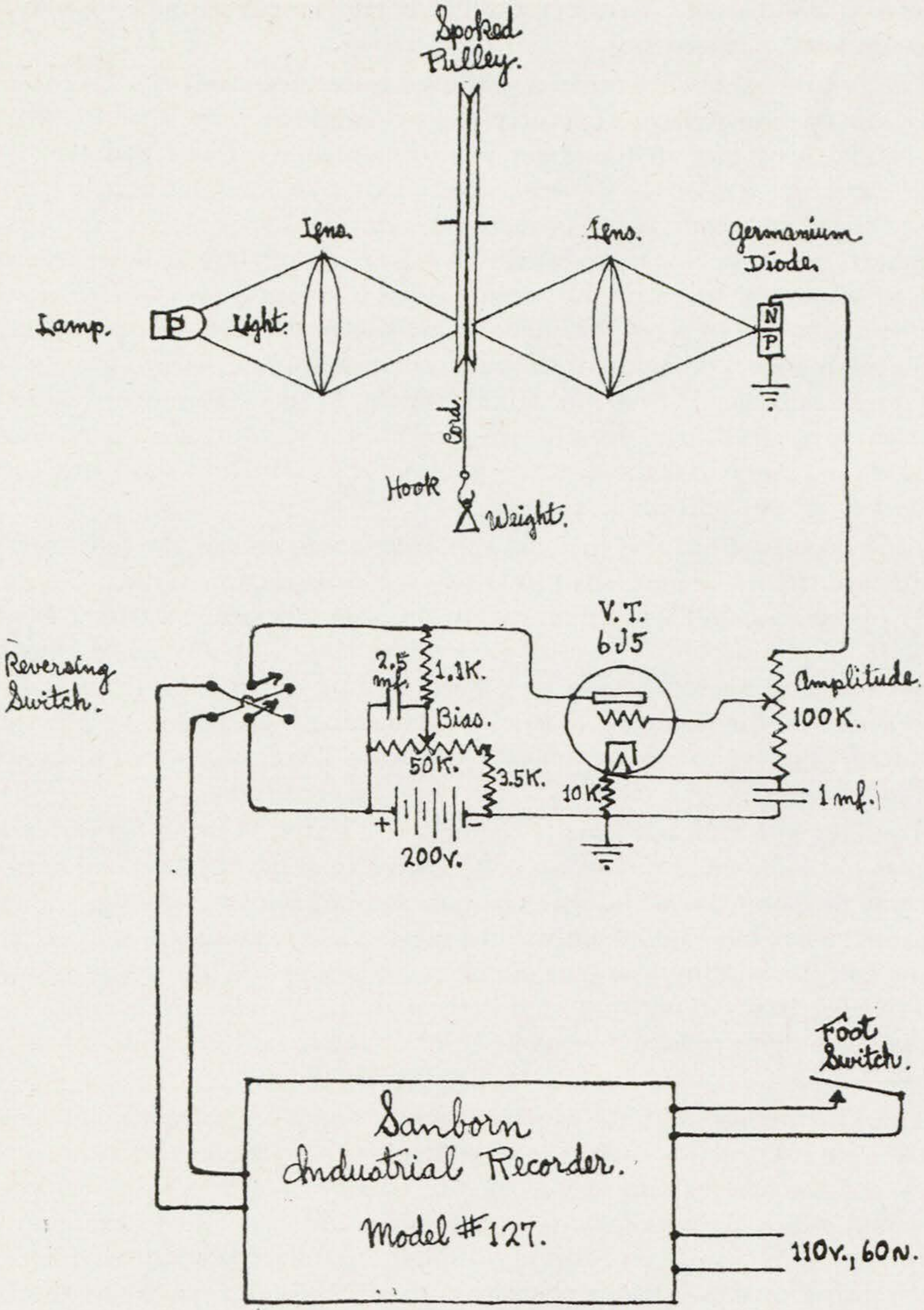


Fig. 3. Timing mechanism.

which simulates the direction of the sail force, must be in various directions. To take care of this, my tank is rotatable horizontally. This permits a fixed location for the towing and recording equipment. It is not wise to turn a full tank when it contains 1,250 lbs of slopping water but, when partially full, clusters of three small castors under each of the six legs make it easy on the concrete floor. Filling with water is via a hose which is also used for emptying by siphon action to a floor drain.

Thus, the tank proper is simplicity itself and quite inexpensive. It has served for 12 years without repair.

The Towing and Timing Mechanism

Timing the events with a hand stop watch is much too crude. One needs an accuracy of 1/100th second rather than 1/5th second. With such precision in timing, no personal reaction time must be involved in determining the time between departure and arrival. The answer to all this is photo-electric time and distance measurements. The sketch shows how this was done in a simple manner.

A 9 ft drop is provided for the falling weights. These weights vary from about 1 per cent to 25 per cent of the model weight which may be 100 to

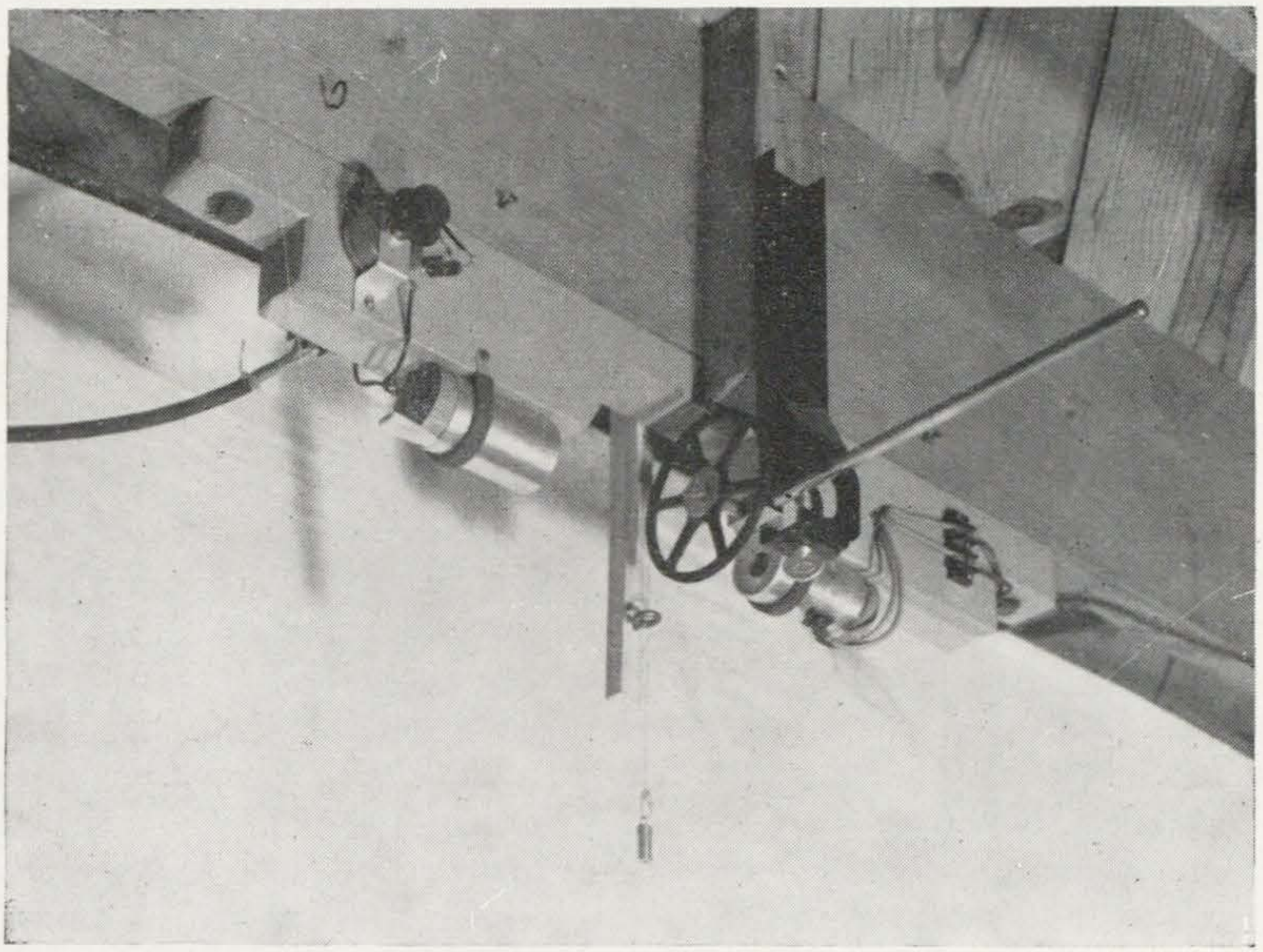


Fig. 4. Photograph of pulley and photoelectric units.

150 grammes in usual cases. A pulley was made having a low mass wheel and a circumference in its groove of almost exactly 1 ft. Since six accurately spaced spokes are used, a light beam shining through them is interrupted once in every 2 in of travel of the towing cord. Tiny instrument ball-bearings were used. These were selected as being much more rugged in withstanding heavy bearing loads and abuse rather than needle bearings which were measured to have less rolling resistance. The rolling resistance of the ball-bearings was measured for a range of bearing loads, and proved to be far less than 1 per cent of the weight used in all cases.

The linear filament of a small lamp is focused on a spoke of the pulley by means of a simple lens. Beyond the pulley, another lens refocuses the unobstructed image on a germanium (or silicon) P-N junction.

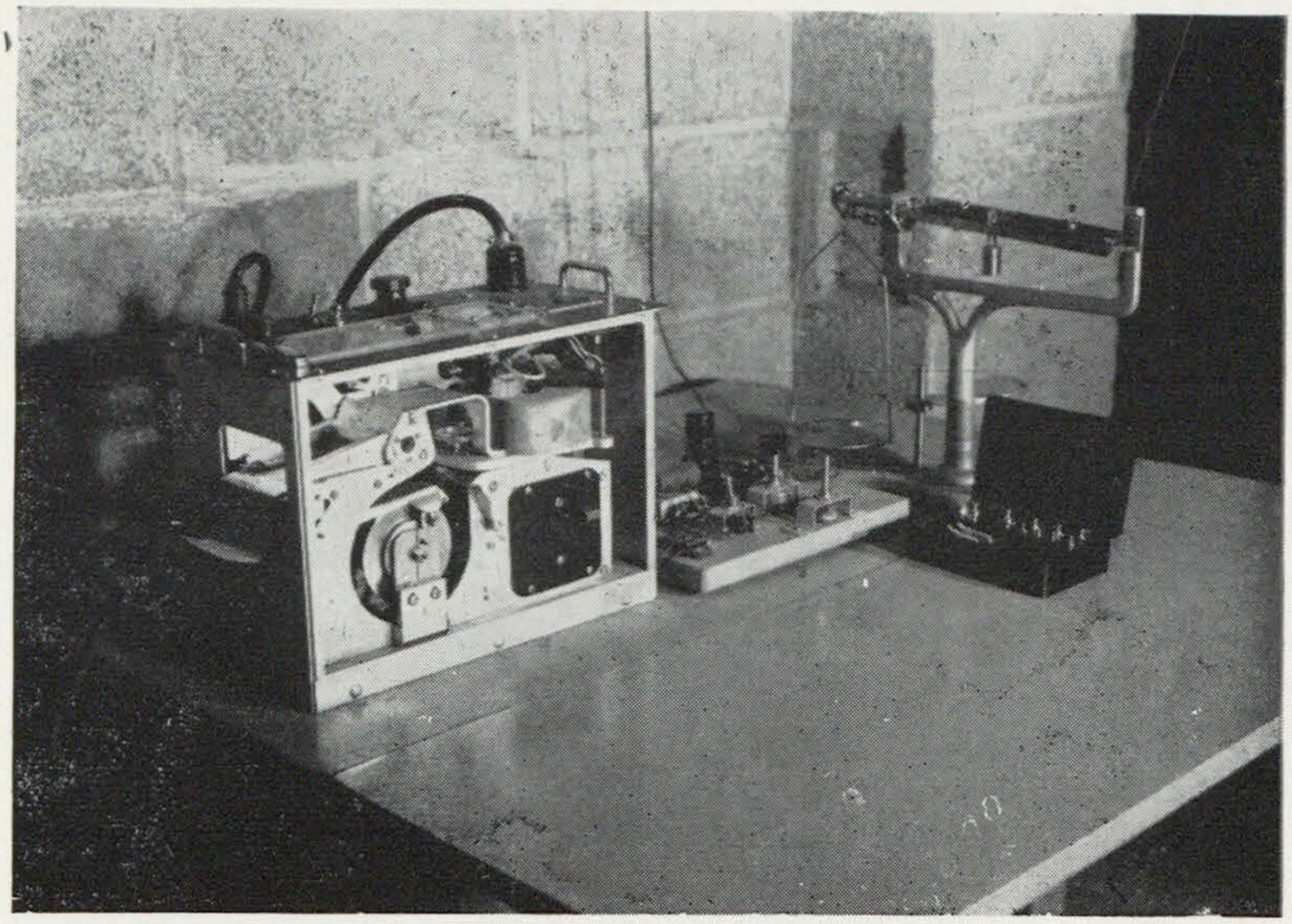


Fig. 5. Timing recorder.

The normal high electrical impedance of the reversed bias, solid-state junction is greatly reduced every time light impinges on it. The voltage variation across an adjustable potentiometer in the circuit is fed to a vacuum tube (valve). This, in turn, amplifies the current so that it will actuate the stylus of a Sanborn industrial automatic recorder, Model 127, having an accurately timed graph-paper feed. Full scale deflection of this recorder, each side of centre, requires 25 milliamperes. A variable bias and reversing switch is shown so that the recording stylus can be adjusted to any part of the width of the paper. By doing this, as many as 10 runs can be indicated in parallel on a short strip of the recording paper for comparison and economy reasons. The recorder paper-drive is started and stopped by a foot-actuated switch at the model's starting location.

Since timing can be measured to an accuracy of about 1 per cent for a one second interval, the overall accuracy can be expected to be within experimental errors.

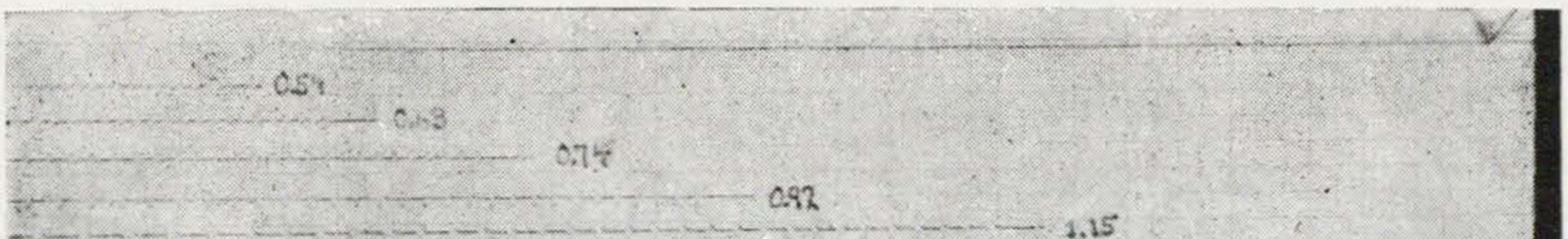


Fig. 6. Timing record, six runs.

Test Results

With No Leeway

Tests on power boat models should have the towing cord attachment aligned with the propellor shaft. For tests of sailing models, a stub mast supporting an elevated horizontal rod is used and so arranged as to permit cord attachment at a point which corresponds to the exact force centre of sail effort. The examples given here will be from tests of models of the *Lightning* class which is an old and well-known class boat with numbers approaching 10,000.

When a *Lightning* is on a running course, a mainsail and boomed out jib

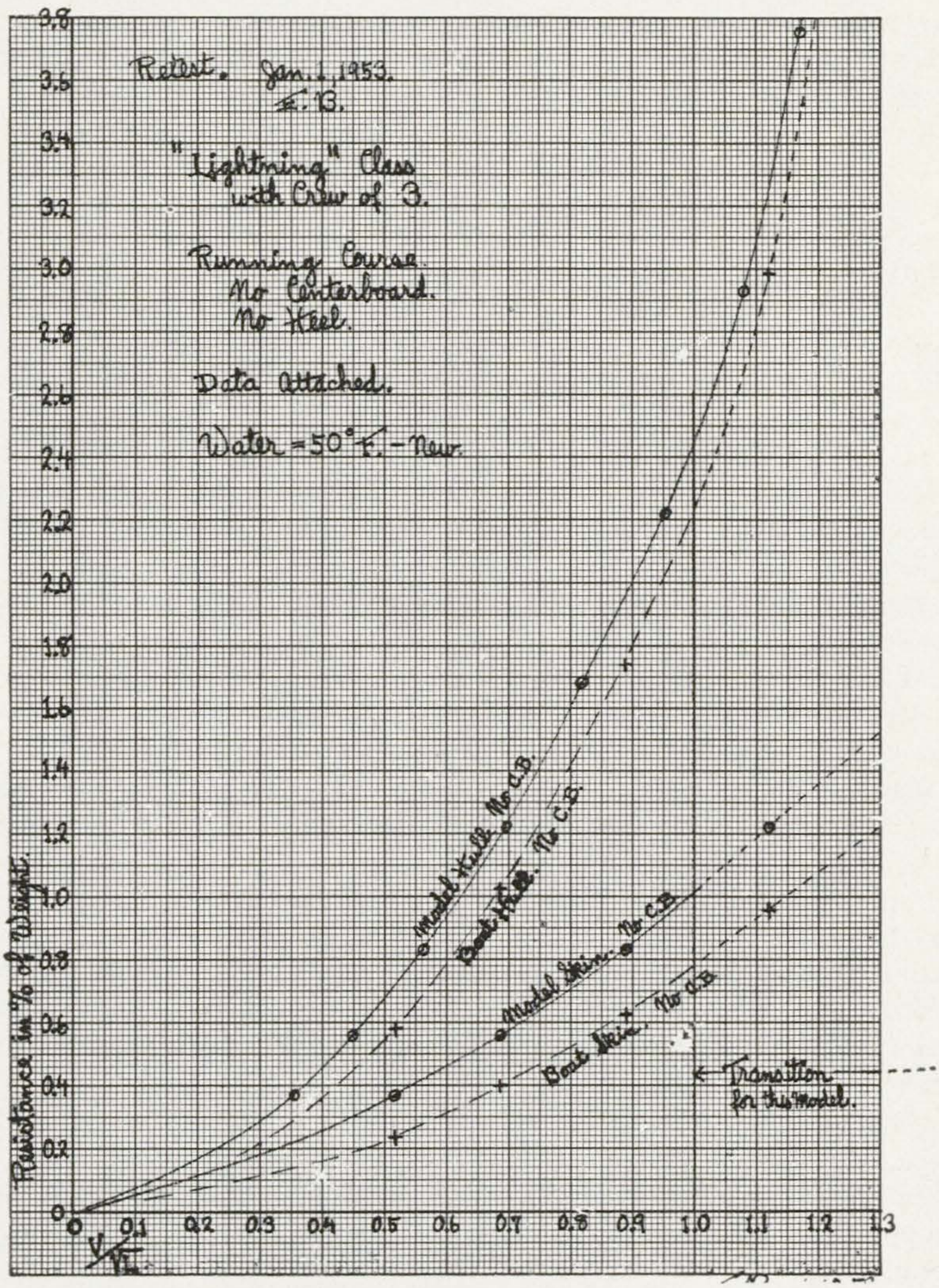


Fig. 7. "Lightning" model results with estimated full sized resistances.

would be slightly unbalanced. For simplicity, however, let us consider the more balanced case which can be achieved when the spinnaker is used. The graphs and figures show the actual data of such a test on a model *Lightning* with a crew of three so placed as to have no heel. A centred helm is used with no centreboard lowered. The skin test for this model was not stable much beyond $\frac{V_B}{\sqrt{L}} = 1{\cdot}1$, a point which was discussed previously. However, resulting errors may be overshadowed by the high pressure resistances encountered at these speeds.

The data sheets give an opportunity for a detailed study of the method and are better than a lengthy word description. I should comment, however, that the *Lightning* is a notoriously slow runner although, when beating to windward, it is a reasonably good boat due to a centreboard having a high aspect ratio. Its hull is beamy and has a hard chine with a large amount of wetted surface for its displacement. Considerably less running resistance has been observed in the tests of a number of models of other boats.

With Leeway Simulating Close Hauled Courses

If we consider a well balanced and properly trimmed sailboat hard on the wind, the close windedness of the boat to the apparent wind will depend, disregarding speed, only on the magnitudes of the lateral lift-drag ratios of both sails and hull. This can be calculated readily from a sailing action and reaction force diagram, if desired. Such calculations emphasise the importance of hull research for windward situations since they have fallen so far behind sails in merit. Since we are presently discussing hulls, rather than sails, we may wish to know what is the highest lateral lift-drag ratio a particular hull can achieve, this ratio being that of the forces at right angles to and in line with the course made good.

The flyers of kites, who are familiar with the scientific theories, are well aware that the more nearly vertical the cord to the kite, the better is the kite. In other words, the higher is its lift-drag ratio, which is defined by the tangent of the cord angle to the horizontal. The same technique can be used to "fly" the sailing hull laterally.

The more nearly the cord pull can approach being perpendicular to the course made good by the hull (not to the heading which is greater by the angle of attack), the higher is its lateral lift-drag ratio. This angular limit can be measured. Since it is so close to the type of stalling called "in irons", the measurement of speed is rather meaningless. Speed can be measured later at a lesser cord angle to promote greater stability in comparative measurements.

The place of cord attachment to the model, for windward tests, is elevated to a height which corresponds to that of the force centre of sail effort. Also, it must be carefully adjusted fore and aft along a horizontal rod which is supported at this height by a stub mast. This rod is aligned parallel with the centreline of the hull for the test.

Hull balance is achieved when the attachment is vertically above the centre

January 1, 1953. Retest (Copy). E.B. 6-10-59. *Lightning* Class with Crew of Three. Running Course: No Centreboard. No Heel. Scale: 12:1.

Water: Clean, 50°F $\dfrac{\mu}{\rho} = 1{\cdot}41 \times 10^{-5}$

	Boat	Model	Comment:
Lightning Wt	820 lbs	215 grams	Retest for
Crew Wt	450 lbs	118 grams	confirmation
Total Wt	1,270 lbs	333 grams	of 1945 data
LWL	16·0 ft	1·33 ft	
Skin L_{av}. with Rudder	13·3 ft	1·11 ft	
Skin Area with Rudder	72·0 sq ft	0·50 sq ft	

Model R and R_F								
Pull wt No.	2	4	7	11	16	22	29	38
Pull grams	1·22	1·88	2·79	4·08	5·63	7·48	9·83	12·63
$\dfrac{\text{Resistance}}{\text{Weight}}$ in %	0·363	0·560	0·831	1·22	1·68	2·22	2·93	3·76
Model Hull Tests								
Secs./ft	1·46	1·15	0·92	0·74	0·63	0·54	0·48	0·44
v in ft/sec	0·686	0·870	1·09	1·35	1·59	1·85	2·09	2·27
V in knots	0·406	0·515	0·645	0·799	0·941	1·095	1·24	1·34
$V_B/\sqrt{L}$	0·353	0·448	0·561	0·695	0·818	0·953	1·08	1·17
Model Skin Tests								
Secs/ft	1·00	0·75	0·58	0·46				
v in ft/sec	1·00	1·33	1·72	2·17				
V in knots	0·593	0·787	1·02	1·29				
$V_B/\sqrt{L}$	0·516	0·684	0·887	1·12				
Full Size Skin Calculation								
Equiv v in ft/sec	3·47	4·61	5·95	7·52				
v × L_{av}	46·2	61·3	79·1	100				
Reyn. No. = × 10^6	3·27	4·35	5·61	7·10				
Schnhr. C_F	0·00036	0·0034	0·0032	0·0031				
R_F in lbs	3·02	5·03	7·89	12·2				
$\dfrac{\text{Resistance}}{\text{Weight}}$ in %	0·238	0·396	0·622	0·956				
$\dfrac{R}{W} - \dfrac{R_F}{W}$ in %	0·125	0·164	0·209	0·266				
Correction Reqd.								

Notes:

$$R_F = C_F \cdot \frac{\rho}{2} \cdot A_W \cdot v^2$$

$$Re = \frac{v\,L_{av}}{\mu/\rho}$$

Froude Law of Comparison:

$$\frac{V_B}{\sqrt{L}} = k\,\frac{R_P}{W}$$

$$R_P = R - R_F.$$

of lateral resistance of the hull when optimum speed has been reached. In this position, the hull will travel in a straight line. It will assume an angle of heel, of yaw and of pitch precisely like the full size boat under the same conditions. When the attachment is improperly adjusted, the hull will turn either high or low of the course.

In this tank, the towing mechanism will provide horizontal pull via a long, fine nylon thread, 40 ft long, this length being used to minimise the change in angle of the course to the towing cord as shown in the attached sketch. Its attachment point will be indicated by the percentage of waterline length measured from the bow. With the hull balanced, this pull will be adjusted in a direction as nearly perpendicular to the course as we can make it without stalling the model's progress. An optimum positioning of both the centreboard and the helm will contribute towards our success.

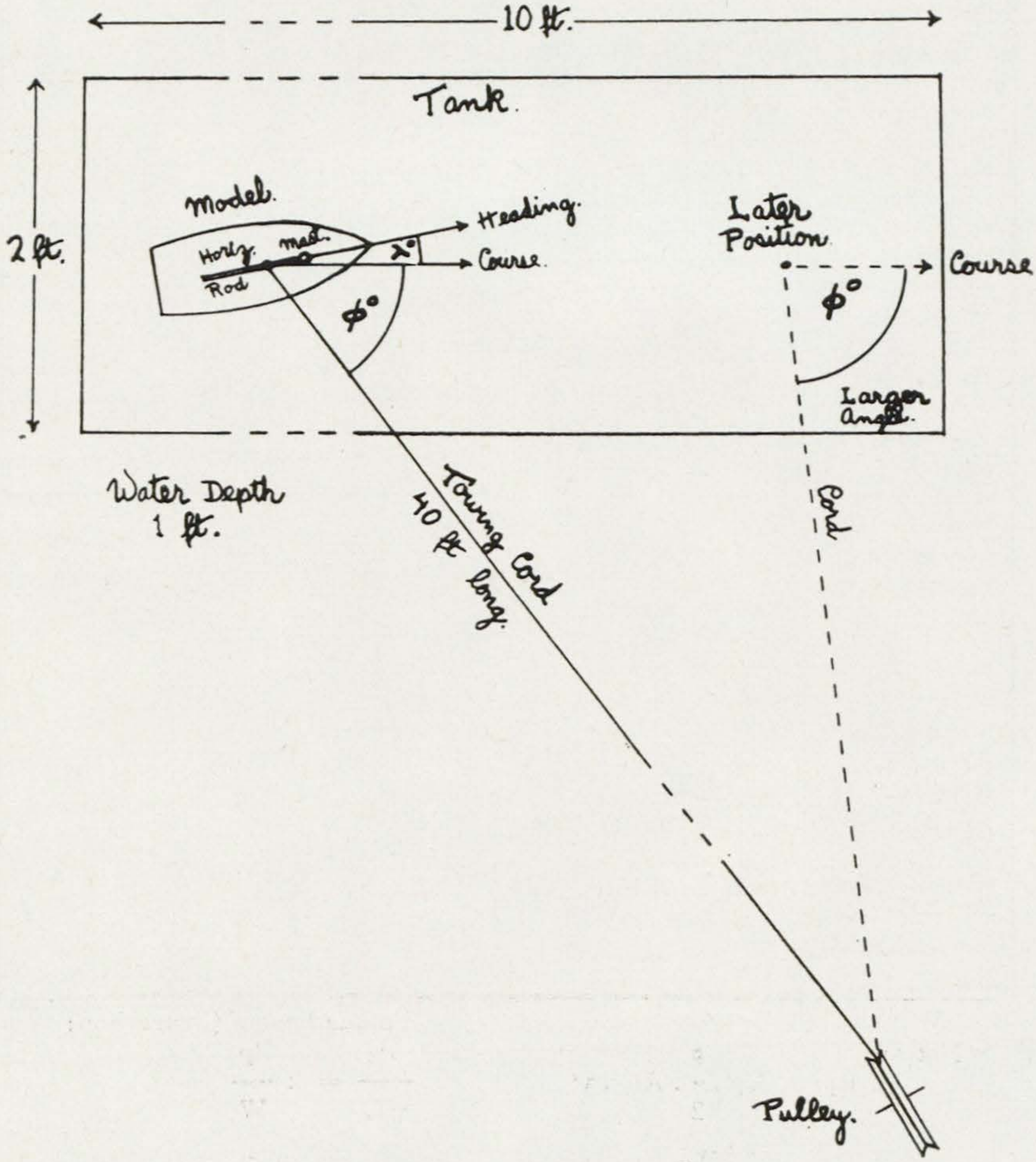


Fig. 8. Method of close-hauled testing.

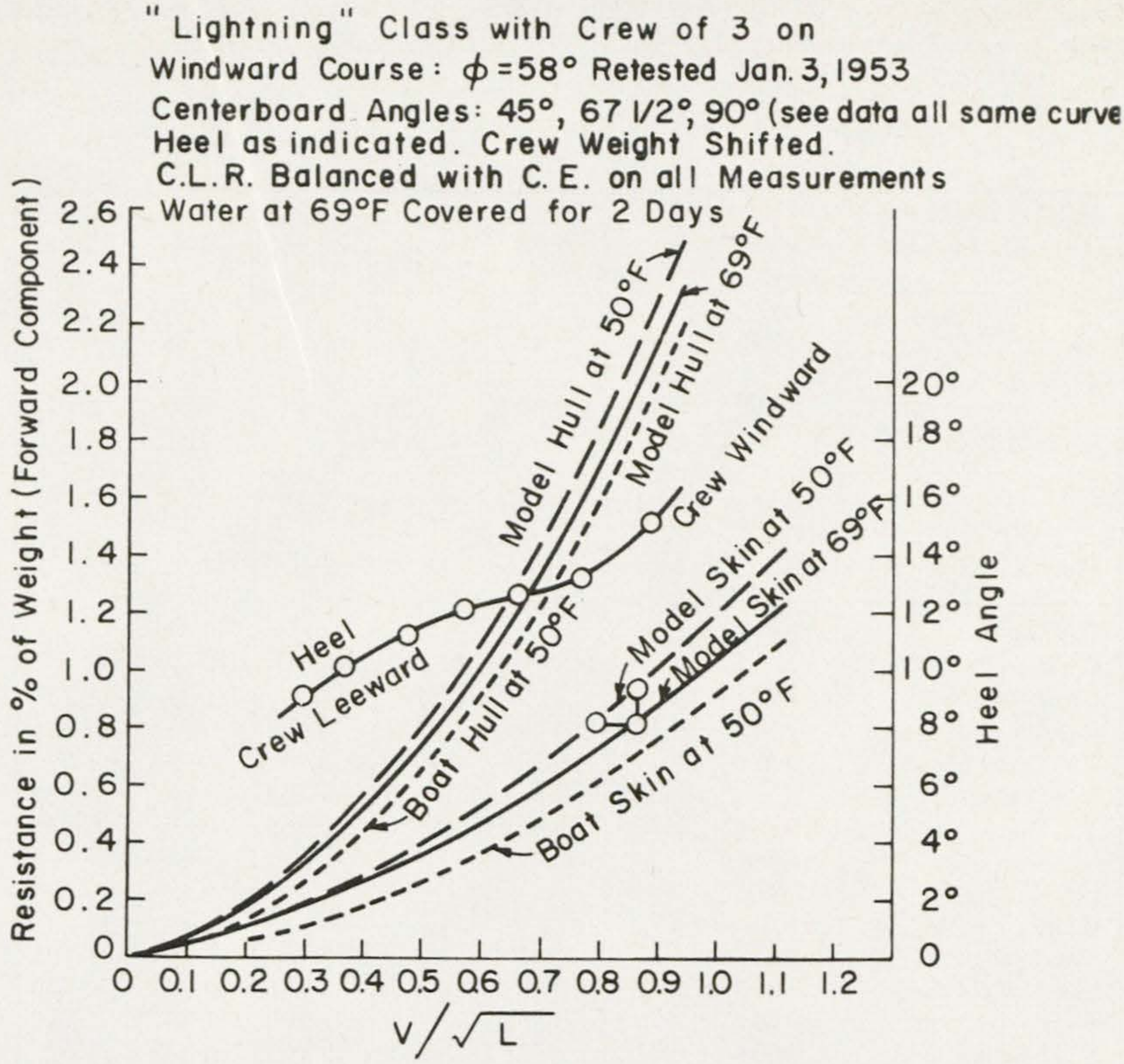


Fig. 9. Model and full size resistances adjusted for temperature.

Such tests were made on our *Lightning* model with the leading edge of its centreboard fixed at $67\frac{1}{2}°$ from the waterline and the helm fixed amidships. The resulting measurements will be found in the data sheet overleaf. The range of towing force appears at the top of this sheet and the maximum cord angles and lift-drag ratios at the bottom. A curve of this data is drawn on the graph. It is seen that the optimum lateral lift-drag ratio, for these adjustments, varies between 4·0 and 4·7 for the range of forces.

Except for the effects of skin friction, ideally the lift-drag ratio is independent of speed. It is often the case, however, that the lift-drag ratio falls off at the higher forces due to heeling and hull speed limits. In the present case, the crew ballast was moved to windward to avoid heeling as is good dinghy practice.

The *Lightning* has a good high aspect ratio centreboard which contributes to its windward performance. Certain other models, with poorer shaped centreboard, or fixed keels, do not do as well as this. Also, heeling usually cannot be prevented on large boats.

Next, we will examine the windward speeds at a lesser cord angle to get a

Bruce Tank. Tests of Model *Lightning* to Windward with Crew of 3, using Centred Helm $\phi = 58°$. See Running, January 1, 1953 for Dimensions. Retested: January 3, 1953.

Water: 69°F — 3 days covered. $\frac{\mu}{\rho} = 1{\cdot}07 \times 10^{-5}$

Pull wt No.	4	7	11	16	22	29	38
Total pull grams	1·88	2·79	4·08	5·63	7·48	9·83	12·63
58° forwd pull grams	0·996	1·48	2·16	2·99	3·97	5·21	6·70
$\frac{\text{58° Fwd res}}{\text{Weight}}$ in %	0·299	0·444	0·649	0·898	1·19	1·56	2·01
$\frac{\text{Total res}}{\text{Weight}}$ in %	0·565	0·838	1·23	—	2·25	—	3·79
Heel angle	*9°	10°	11°	12°	12½°	†13°	†15°
CB = 90°							
CLR in % LWL	49	49	48	47	46	45	42
Cord secs/ft	3·31	2·66	2·02	1·75	1·46	1·27	1·13
Cord v in ft/sec	0·302	0·376	0·495	0·571	0·685	0·788	0·885
Fwd v in ft/sec	0·571	0·711	0·936	1·08	1·30	1·49	1·67
V in knots	0·338	0·421	0·554	0·639	0·769	0·882	0·988
$V_B/\sqrt{L}$	‡0·294	0·366	‡0·482	0·556	‡0·669	0·767	0·858
CB = 67½°							
CLR in % LWL	54	52	52	51	50	49	47
Cord secs/ft	3·33	2·67	2·12	1·72	1·47	1·26	1·10
Cord v in ft/sec	0·300	0·375	0·472	0·582	0·681	0·794	0·909
Fwd v in ft/sec	0·567	0·709	0·892	1·10	1·29	1·50	1·72
V in Knots	0·336	0·420	0·528	0·651	0·763	0·888	1·02
$V_B/\sqrt{L}$	0·292	0·365	0·459	‡0·567	0·665	‡0·772	‡0·887
CB = 45°							
CLR in % LWL	57	56	56	55	55	54	52
Cord secs/ft	3·40	2·64	2·05	1·77	1·49	1·29	1·11
Cord v in ft/sec	0·294	0·379	0·488	0·565	0·672	0·776	0·902
Fwd v in ft/sec	0·556	0·716	0·923	1·07	1·27	1·47	1·71
V in knots	0·329	0·424	0·547	0·633	0·751	0·870	1·01
$V_B/\sqrt{L}$	0·286	‡0·369	0·476	0·551	0·653	0·757	0·878
Maximum Possible Cord Angle ϕ° with Centreboard fixed at 67½°							
ϕ°	76°	77°	77½°	—	78°	—	78°
CLR in % LWL	58	58	58	—	58	—	58
Max. lateral Lift/Drag	4·0	4·3	4·5	—	4·7	—	4·7

Wetted Areas:	Model	Boat
Hull and Rudder sq ft	0·50	72·0
67½° Centreboard sq ft	0·079	11·3

Model Hull — 50°F

Running — R/W = 1·68%	$V_B/\sqrt{L}$	
No CB	0·818	Copy EB
67½° CB	0·795	October 28, 1959

From Running Hull Curve: $\triangle$R/W = 0·11% CB Effect.

*Crew to Leeward. †Crew to Windward. ‡Highest.

more stable speed performance. Due to a gradually increasing cord angle $\phi°$ as the model progresses, in a windward test, maximum speed on the automatic record is usually reached slightly before the end of the tank, after which the model slows down. This is a point of no acceleration or deceleration and makes an excellent data point if hull balance was achieved. At all speeds, the angle of the course to the cord was 58°, when measured at this point. To determine the course, the stub mast is made to travel parallel and close to a fixed cord stretched lengthwise over the tank. Lesser angles for ϕ can be used for measuring various reaching courses but the procedure is similar.

The centreboard of a *Lightning* has a stop which prevents the board from being lowered to more than 67½° from the horizontal. However, the tests were made with centreboard angles at 45°, 67½° and 90° to investigate all possibilities. At centreboard angles less than 45°, the area of the board becomes so reduced that the tests have little interest due to excessive side slip.

For every test run, the CLR balance point for optimum speed is indicated on the data sheet; also its speed-length ratio $V_B/\sqrt{L}$ and the course component of resistance in percentage of weight of the model.

Examining the curves, which are plots of these data, we find that for each of the three centreboard positions, the centre of lateral resistance of the hull moves forward with an increase of speed. Since the centre of force effort of properly trimmed sails will vary only a little with varying wind strengths, we must maintain our point of balance principally by adjustment of the centreboard.

The positions for the centre of sail effort are examined on the plot. Remembering that we cannot lower the board beyond 67½°, we find a better range of centreboard adjustment when the centre of effort is 54 per cent of the waterline length rather than 52 per cent. At 52 per cent, we would be plagued with an excessive lee helm in light airs. Thus 54 per cent of the waterline length for the centre of effort appears to be a good tuning position for the sails on a *Lightning*. The centreboard angle required for various speeds, to obtain balance, is plotted on the accompanying graph sheet. This general type of test has been a favourite of designer friends for larger boats. They laid out their sail plans accordingly and have obtained balances, without risk, which delighted them.

Within the range of centreboard adjustment of 45°, 67½° and 90°, the data sheet indicates no significant hull speed advantages for any of these positions, provided balance is maintained. Below 45°, as mentioned before, the performance drops off rapidly.

The skin resistances, for the windward tests, are shown slightly higher than those of the running tests because of the added presence of the centreboard. The centreboard resistance versus speed was obtained by the differential resistance on the model hull, on a running course, with the centreboard raised and lowered. No appreciable differences were found with the board at 45°, 67½° or 90°, probably because the change in area is so small.

Looking back at this old data, I now regret having assigned the centreboard drag entirely to the skin resistance, as eddies were undoubtedly present. This worry, however, is more theoretical than numerical since eddies would be a small proportion of a small "scaling" correction. Ideally, a separate windward skin, including the centreboard, should have been used.

Our previous running tests were made with water at a temperature of 50°F whereas these windward tests were at 69°. Corrections are applied to this later data to give the results at 50° for comparison with the running tests.

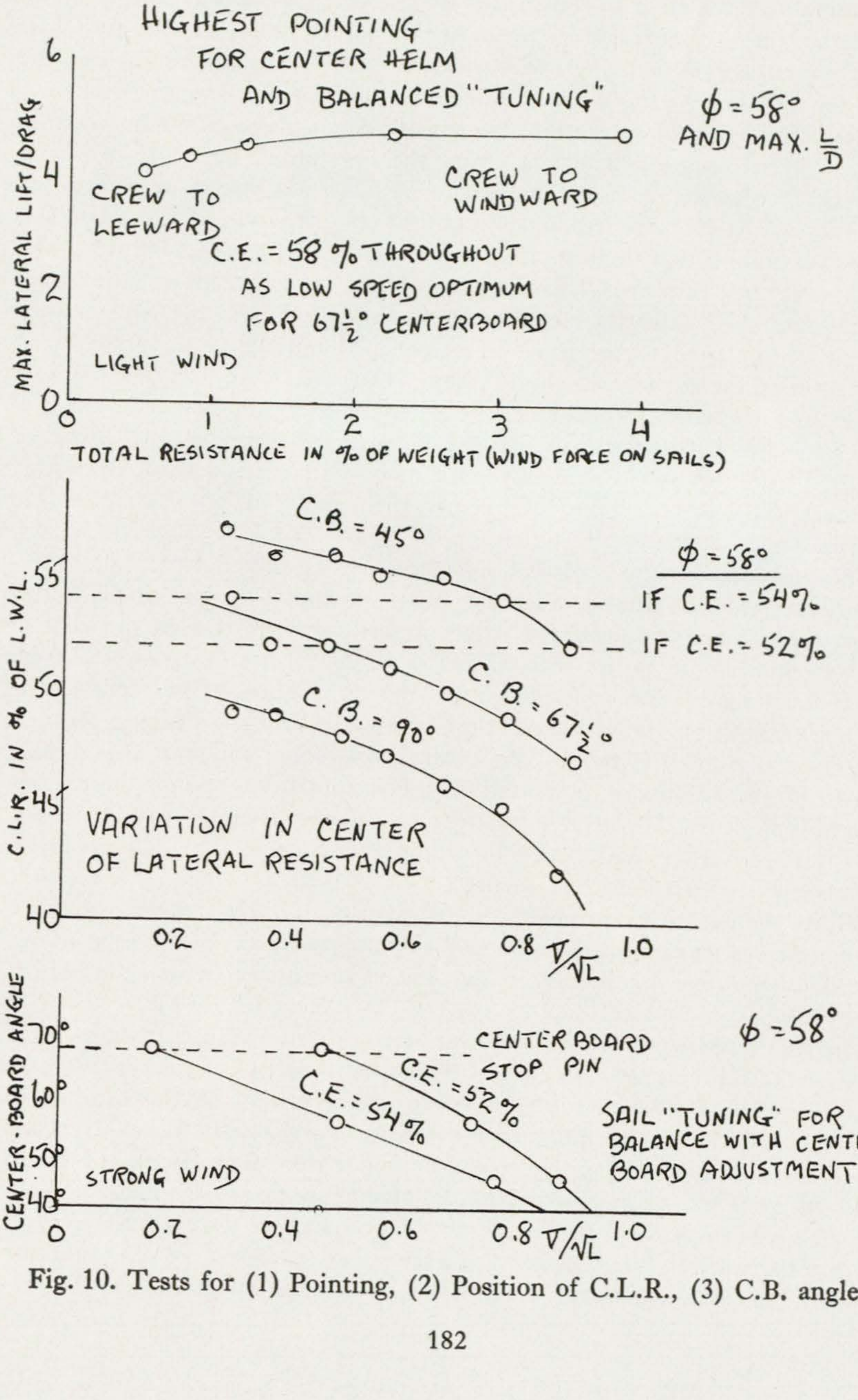


Fig. 10. Tests for (1) Pointing, (2) Position of C.L.R., (3) C.B. angle.

Study of these curves reveals that heating the water can be a tool for minimising "scale effect". Water at about 100°F would do reasonably well, in the present case, for it is near elimination. As alternatives, this adjustment usually can be made by a proper selection of model length or water temperature or both. The region of transition to turbulence should be avoided.

In this short account, I have not revealed the grand windward speed optimum obtained from inter related adjustments of helm, centreboard, trim and CE. If any tank builder finds this out, I will be glad to compare data. In my case, this tank work contributed 18 *Lightning* trophies to my trophy cabinet.

Some General Results

I have found in running tests that short, fat hulls with their maximum cross section forward of amidships are best at very low speeds. At somewhat higher speeds, the maximum sectional area must be reduced and its location placed further aft. Catamarans with narrow semi-circular sections and low prismatic coefficients excel in running resistances in the range of about $V_B/\sqrt{L} =$ 1 to 3. Where, in this range, each excels depends on their L/B ratio. A single hull with outriggers, barely immersed is faster than similarly shaped, optimally spaced twin hulls when the two craft are equal in weight and sail area. To be exactly similar in shape, and equal in weight, twin hulls would be about 79 per cent of the length of the single hull. However, if comparison is made on a speed basis of $V_B/\sqrt{L}$, there is little to choose between them since this ratio handicaps length. Beyond $V_B/\sqrt{L} = 3$, the good planers take over in minimum running resistance. First the soft chine planers excel, followed by the hard chine planers at greater speeds. At very high speeds, the stepped planers and three pointers run neck and neck. I am having trouble making hydrofoils perform near the water surface, though at depth they are fine. My enthusiasm is greatest for the performance of submarines with zero buoyancy. I must again stress that the preceding applies only to running resistances. For windward work, totally different rules may apply.

It is my present belief that, for both displacement and planing hulls, minimum running resistances can be obtained at only one definite speed. When I examine my best model in each speed range, I invariably find that the positive rate of change of frictional resistance just equals the negative rate of change of the combined pressure resistances as certain parameters are varied. It may be a hydro-dynamic law.

NOTE ON SIZE OF MODELS

Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 45, Oct. 1963

Dear John,

A more precise reasoning about appropriate model sizes is as follows:

For the upper limit of the stable laminar region, the Reynolds number,

$$\frac{v \times L_{av}}{\mu/\rho} = 200{,}000$$

where v is in ft/sec
L_{av} is in ft

If fresh water at 60°F is used,

$\mu/\rho = 1{\cdot}21 \times 10^{-5}$.

Thus the limiting $v \times L_{av} = 2{\cdot}42$.

Table of Model Sizes

L_{av}	v ft/sec	V knots	$V/\sqrt{L_{av}}$	$V/\sqrt{LWL}$
15 in	1·93	1·14	1·02	Slightly smaller
12 in	2·42	1·43	1·43	
9 in	3·23	1·91	2·21	
8 in	3·61	2·14	2·62	
6 in	4·84	2·87	4·07	

Actually, a model less than 8 in seems extremely small for accuracy. During the past year, I have been experimenting with tank water that is ultrasonically excited. It does nothing to the laminar region but stabilises the transition range to its uppermost resistance. Provided one tows both hull and skin in this region, the difference still gives the correct pressure or residual resistance. I want more experience before I recommend this.

EDMOND BRUCE

CHAPTER XX

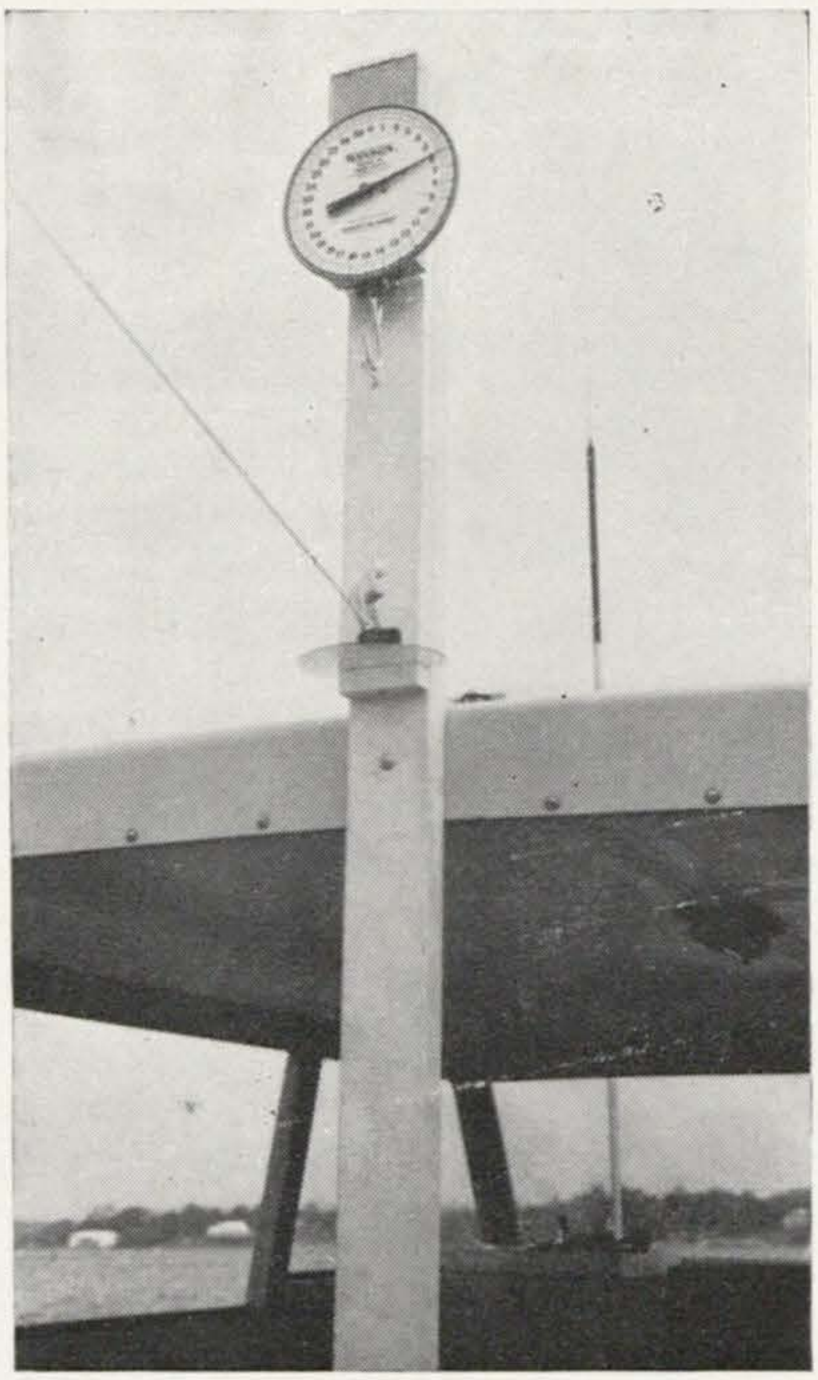
CONFIRMATION AT FULL SIZE

Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 37, Oct. 1961

Dear John,

I have received letters from universities, designers, a boating magazine and amateurs regarding my towing-tank article. (See previous chapter.) There have been no technical criticisms except the wish for details of full size confirmation.

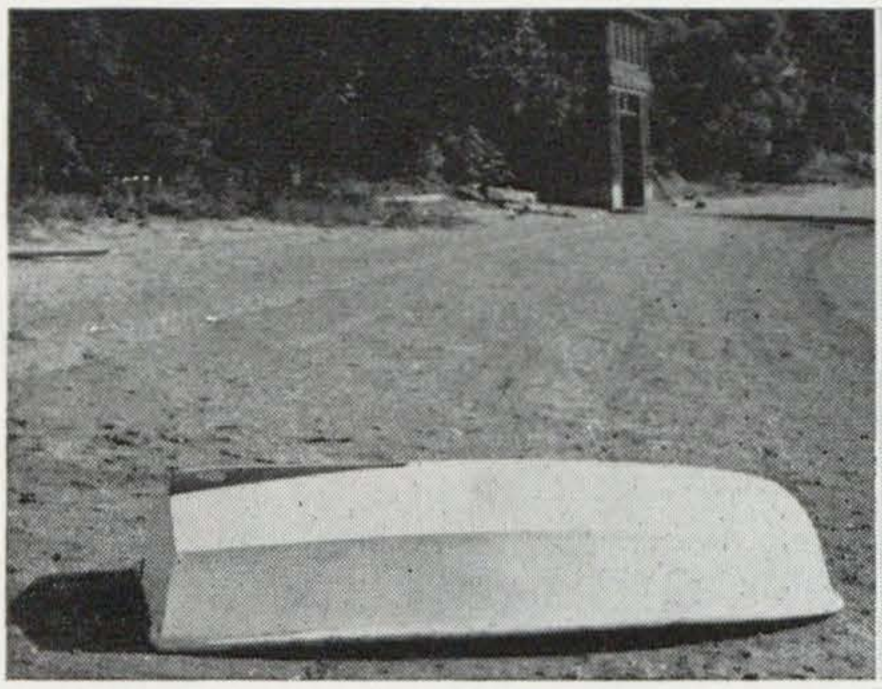


Towing attachment

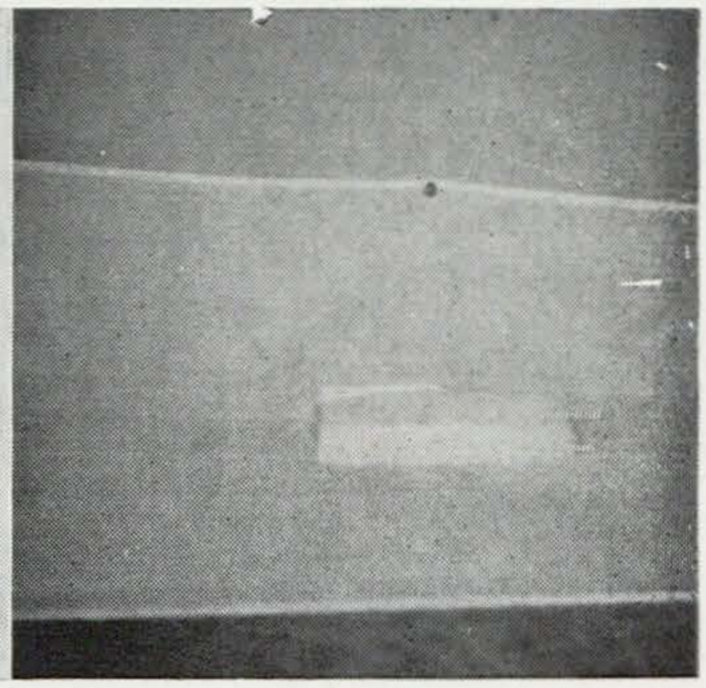
Most of my full size confirmations have been in the field of fast power boats and in the form of predicted speeds for various horse-powers and propellor efficiencies. These agreements have been excellent but I considered them not quite appropriate in a discussion of sailing tests.

Some time back, I tried towing my dinghy, with one passenger, from my deep draft sailing auxiliary but found that the dinghy speed relative to the water was disturbed by the deep draft wake. A good check at a single speed was obtained by towing from the end of the main boom which was swung out abeam and supported by a topping lift. The turning moment on the towing boat was so great that a hard-over rudder compensation was necessary. The auxiliary's power was so low that only one speed was practical in this test.

I have now acquired a shallow draft body but amply keeled power boat which is equipped as a full size test vehicle as shown in an attached photograph. It measures towing force and horizontal angle, therefore windward tests of actual sailing craft, similar to the corresponding tank tests, are being



Dyer Dhow



Model

accumulated. Using this equipment on the previously mentioned dinghy, measurements were obtained as indicated on the attached curves for the boat and its model. Photographs of this dinghy and its plastic model are also attached.

To obtain sufficient accuracy in the speed determination, two-way towing and timing over a measured nautical mile were employed.

The results of these tests are in the curves shown of the Dyer Dhow. The upper dotted curve shows the total resistance of the model, as tested in a laminar flow tank, multiplied by 12^3. 12 is the scale factor of linear dimensions of boat to model. The water for this test was 50°F and fresh. The speed in this curve is the tank speed multiplied by $\sqrt{12}$.

The lower dotted curve is of the same type but it is for tests of the skin alone when in the same water conditions as the model test.

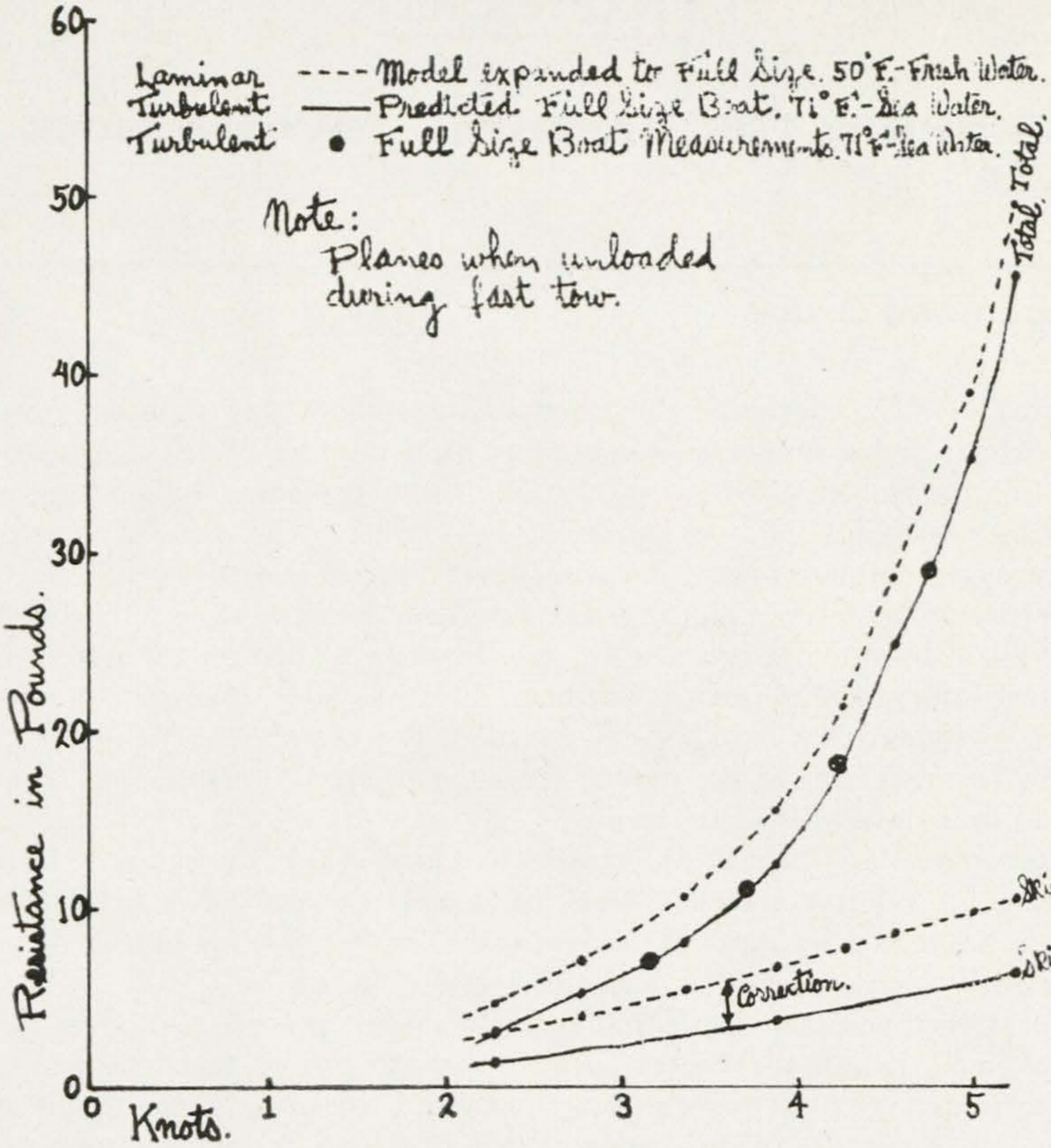
The full size boat had been towed for testing in water conditions which were:

a Turbulent rather than laminar.

b At 71°F rather than 50°F.

c Sea water weighing 64·0 lbs/cu ft instead of fresh water at 62·4 lbs/cu ft.

To enable comparison, these same values were used for determining the predicted full size curve.



All three of these corrections must be applied to the frictional resistance. Temperature and density are taken care of in the standard tables of kinematic viscosity. This kinematic viscosity is used in the determination of the Reynold's Number. Using this, the frictional coefficient is determined from the Schoenherr curve for turbulent flow. The predicted full size skin resistance can now be calculated for various speeds since we know the Schoenherr coefficient, density of sea water and the full size wetted area as per equation in the previous Chapter. The lower solid curve is a plot of these calculated skin frictions versus speed for the full size boat.

The differences between the two model dotted curves at each speed are the expanded model resistances in fresh water. When these are multiplied by 64·0/62·4, which is the weight ratio of sea water to fresh water, we get the final full size pressure resistances. Adding these to the corresponding full size skin resistances gives the upper solid curve which is the predicted full size, turbulent, total resistance in 71° sea water. The four circled dots are measurements made on the full size boat when towed in these water conditions.

Sincerely,

EDMOND BRUCE

CHAPTER XXI

TECHNIQUES FOR HANDLING TOWING TANK DATA

Reprinted from AYRS 36, July 1961

by Edmond Bruce

In Chapter XIX, the writer described a laminar flow type of model testing tank which he has employed successfully for a number of years. Measured data for the model, used as an example, were presented by plotting the resistance-to-weight ratio in per cent, R/W, versus the ratio of speed in knots over the square root of the water-line length in feet, $V_B/\sqrt{L}$.

The described form of plotting data is the time-honoured method proposed by William Froude nearly a century ago. It was intended for the purpose of "scaling" the model to the full size boat. This was done, for pressure resistances, by holding the ratio $V_B/\sqrt{L}$ constant. For example, if the boat had a length 16 times that of the model, the appropriate "corresponding speed" should be 4 times that of the model.

Since model and boat are identical in relative shape, the ratios Velocity/$\sqrt{}$Beam or Velocity/$\sqrt{}$Draft would be equally correct for scaling. Since length, beam and draft are all proportional to $\sqrt[3]{\text{Weight}}$, for similar shapes, the ratio Velocity/$\sqrt[6]{\text{Weight}}$ is also correct for scaling.

One sometimes sees data for differently shaped models plotted as R/W versus $V_B/\sqrt{L}$ and the curves used as comparisons of their merit. Such comparisons may be positively dangerous and misleading in the opinion of the writer. I wish to warn the membership of AYRS against this procedure by a demonstration of examples. I will also propose a method which is believed to be more accurate, for comparisons, and yet simple.

Between two differently shaped models of identical weight and having the same driving force, certainly the faster model is the better, under these conditions, regardless of the linear dimensions. Use of the ratio $V_B/\sqrt{L}$ appreciably penalises length as will be demonstrated later. For a given design, there is always an optimum length for a stated speed.

The ratio $V_B/\sqrt{B}$ has been proposed for "buried chine" planing boats but it is not attractive for other planing types and in all cases it unjustly penalises beam. $V_B/\sqrt{D}$ likewise penalises draft. None of these penalties is desirable. Among the scaling ratios mentioned, the use of $V_B/\sqrt[6]{W}$ would be the best for model comparisons. For extreme accuracy, this ratio with equal weight models would be perfection.

Undoubtedly, Froude selected $V/\sqrt{L}$ as his scaling factor because full-bodied displacement hulls encounter a resistance barrier when the water-line length of the hull equals the length of the surface wave generated in the water. This occurs when $V/\sqrt{L} = 1{\cdot}34$. This no longer concerns us at the higher speeds of catamarans, of planers, etc., or at the very low speeds of any hull. It is my recommendation that the speed-weight ratio $V_B/\sqrt[6]{W}$ be used for comparisons and for scaling. It is particularly advantageous for planers where the wetted dimensions can change rapidly with speed.

I will illustrate the above contentions by test data on two totally submerged, cigar-shaped models which were internally ballasted so as to just neutralise their buoyancy. These models were equipped with tail horizontal and vertical stabilising planes to avoid the type of flutter seen in flags. These examples were chosen to emphasise my point. It becomes more apparent since masking by surface wave formation is avoided through submersion. However, frictional resistances of submerged models are somewhat greater than good forms, of equal weight, operating at the water surface.

The submarines, under discussion, have equal volumes and ballast. Model A is short and fat with a length-to-beam ratio of 3·0. Model D is much longer and more slender with a length-to-beam ratio of 13·7. Both have nearly equal frictional resistances at all speeds since the increase in wetted surface with length is nearly compensated for by the decrease in the laminar frictional coefficient with length. Therefore, the variation in model total resistance at various speeds is due almost entirely to pressure resistance variations.

Let us examine the attached sketches. Fig. 1 shows the speed in ft per second of these two models of equal weight versus R/W in per cent. Model D is definitely faster than Model A, boat against boat.

Fig. 2 is a corresponding plot but speed is now indicated by $V_B/\sqrt{L}$ which is proper for scaling but is a handicap to length. Now we find the comparative situation completely reversed. Model A appears to be faster.

In Fig. 3, the data is plotted as a function of the speed-displacement ratio $V_B/\sqrt[6]{W}$ and is the form preferred by the writer. These curves are completely correct for pressure resistance scaling and also are quite accurate for comparison of performance where the weight difference between models is not too great. As mentioned previously, equal weight models will result in perfect comparison.

Towing tank workers sometimes prefer having data in the form of "dimensionless coefficients". The advantages of this are greater sensitivity and numerical comparisons. Let us examine some of these possibilities.

The curves in Fig. 1, 2 and 3 are approximately square law with speed. These agree with Newton's equation of fluid resistance. The rising steepness of such curves washes out the detail of small variations which may be of interest. The basic equation,

$$R = C \cdot \frac{\rho}{2} \cdot A_W \cdot V^2$$

Submarine Models with Tail Stabilizers and No Buoyancy.

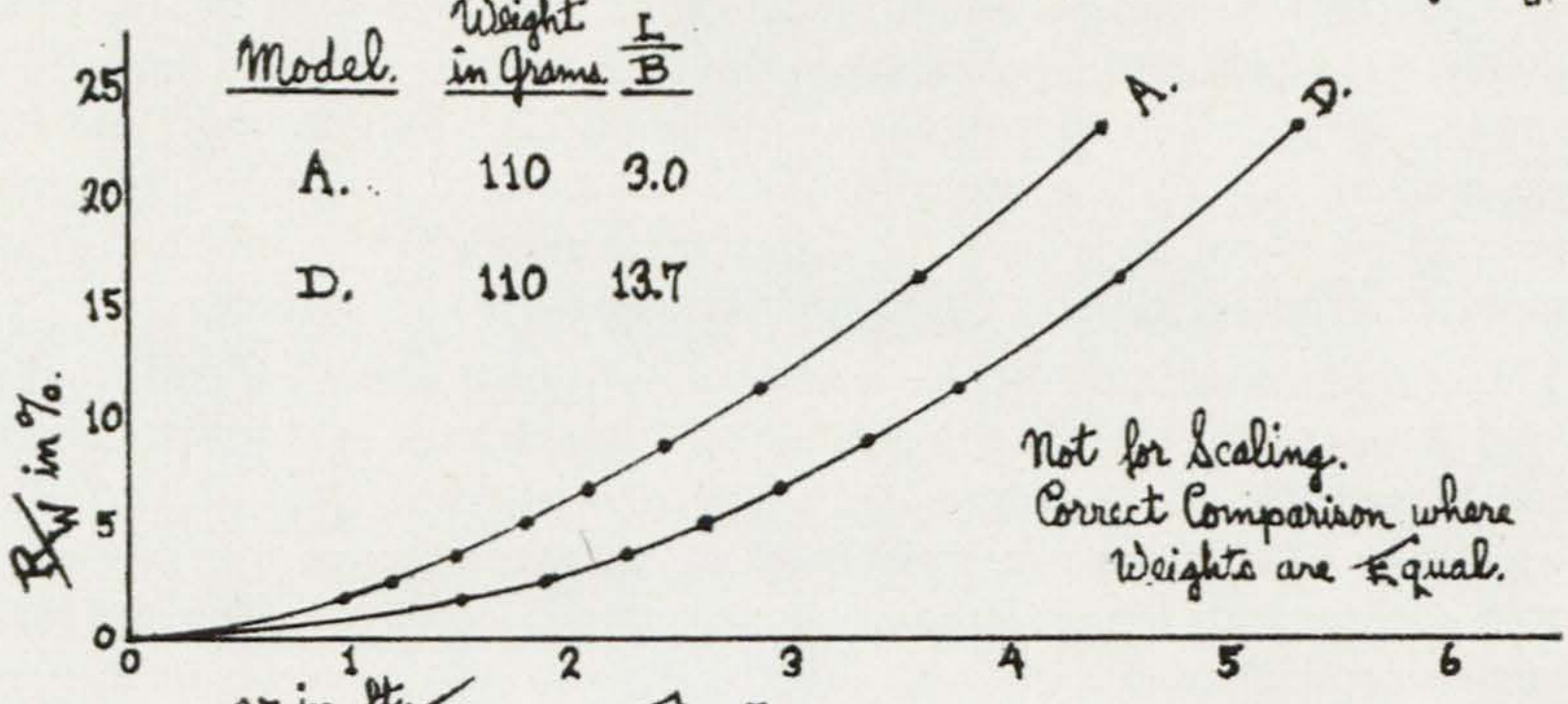


Fig. I.

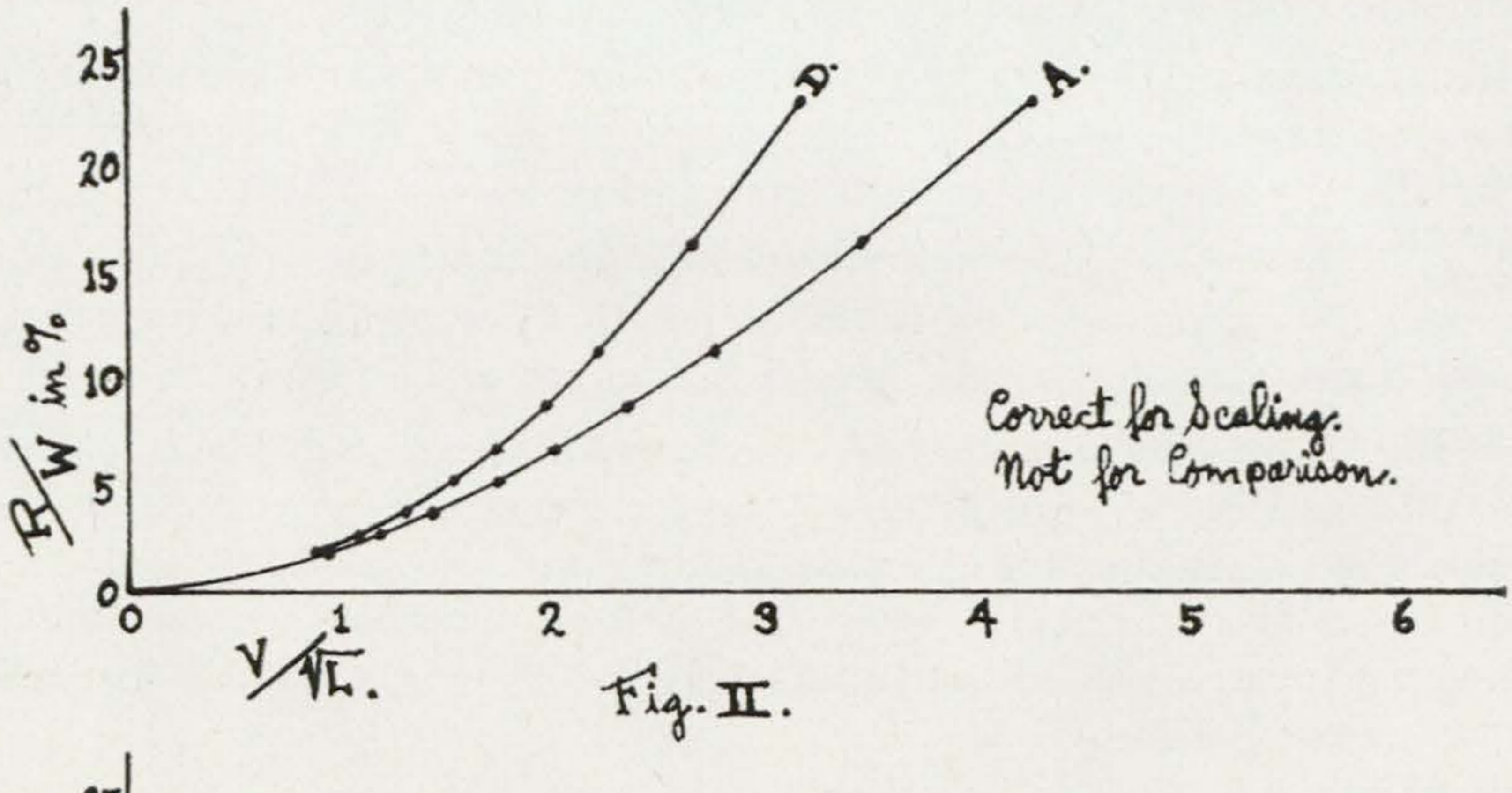


Fig. II.

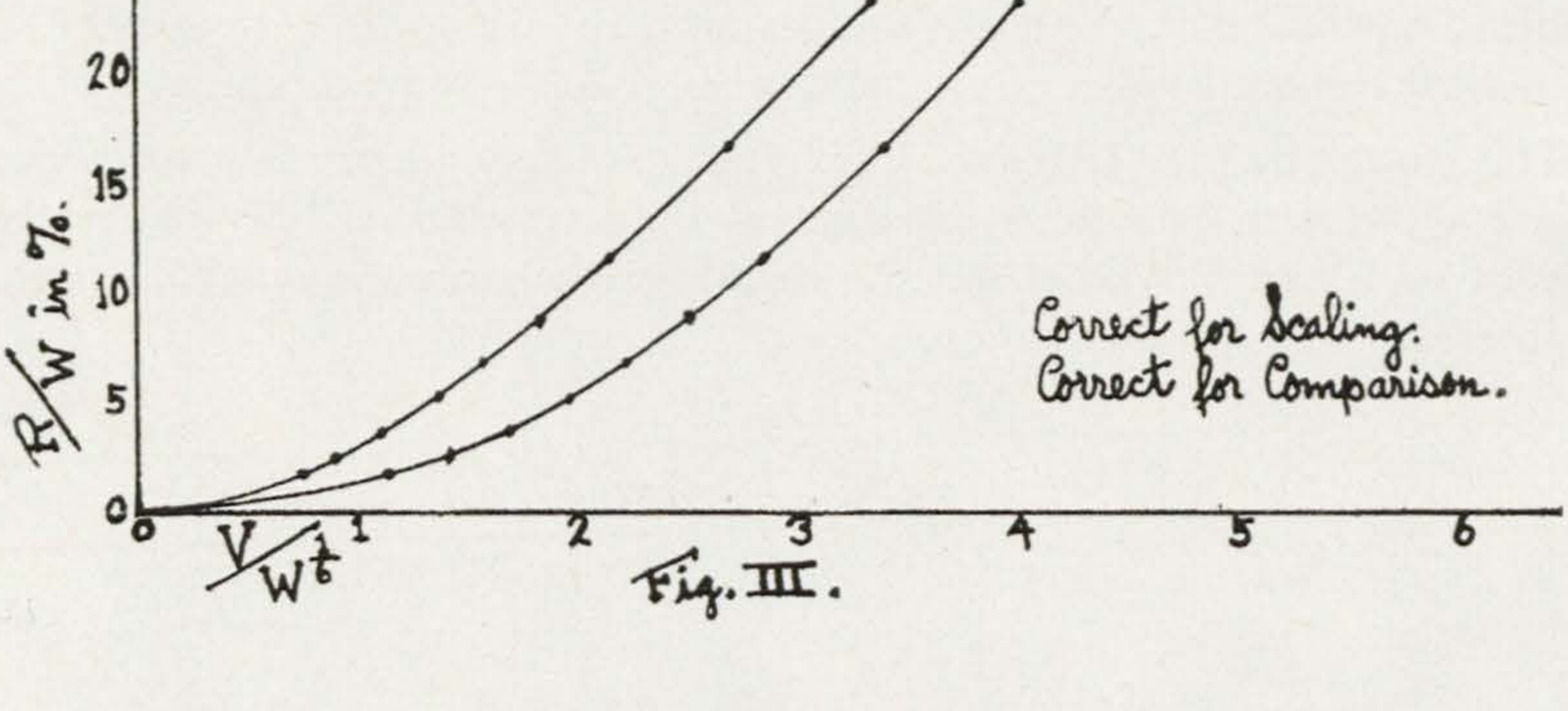


Fig. III.

can represent our data if C is not a constant but a coefficient which is sensitive to variations which we may wish to analyse. Thus,

$$C = \frac{R}{\frac{\rho}{2} \cdot A_W \cdot V^2}$$

is used quite often. In this equation,

- R is the resistance in pounds.
- A_W is the wetted surface in square feet.
- v is the velocity in feet per second.
- ρ is the fluid density in slugs per cubic foot.

The previous equation is not satisfactory for fast planers since the dynamic wetted area becomes very small and the static wetted area is meaningless. Also weight, which is equivalent to displacement volume, at low speeds, is not mentioned. Coefficient comparisons for fast boats can be made much better on the basis of weight. Fortunately, the surface area A_W is proportional to $W^{2/3}$ so we can write,

$$K = k \frac{R}{W^{2/3} \cdot V^2} \text{ where V is in knots}$$

(We use K instead of C when it applies to a hull with weight expressed in pounds and speed in knots.) This can become:

$$K_H = K_{HP} + K_{HF} = \frac{(R_T/W) \text{ in } \%}{(V/W^{1/6})^2}$$

Thus the numerator and denominator include the coordinates used in Fig. 3 and can be calculated from those data.

The total resistance coefficient K_H versus $V/W^{1/6}$ is plotted in Fig. 4 for models A and D. K_{HF}, the frictional resistance coefficient, and K_{HP}, the pressure resistance coefficient, are shown also. These were obtained from separate skin tests.

The pressure coefficient for model A is much greater than its friction coefficient which indicates less cross-section and more length is advisable. The falling pressure coefficient with speed, for model A, is present because some models at speed tend to carry wedges of water fore and aft which improve their stream-line shape. This can be seen by sparingly placing powdered rosin in the water and mixing well.

The curves for model D are of great interest. Note that its total coefficient is at a minimum at a speed-displacement ratio of about 1·5. This is undoubtedly this model's optimum speed. Also note that the negative rate of change

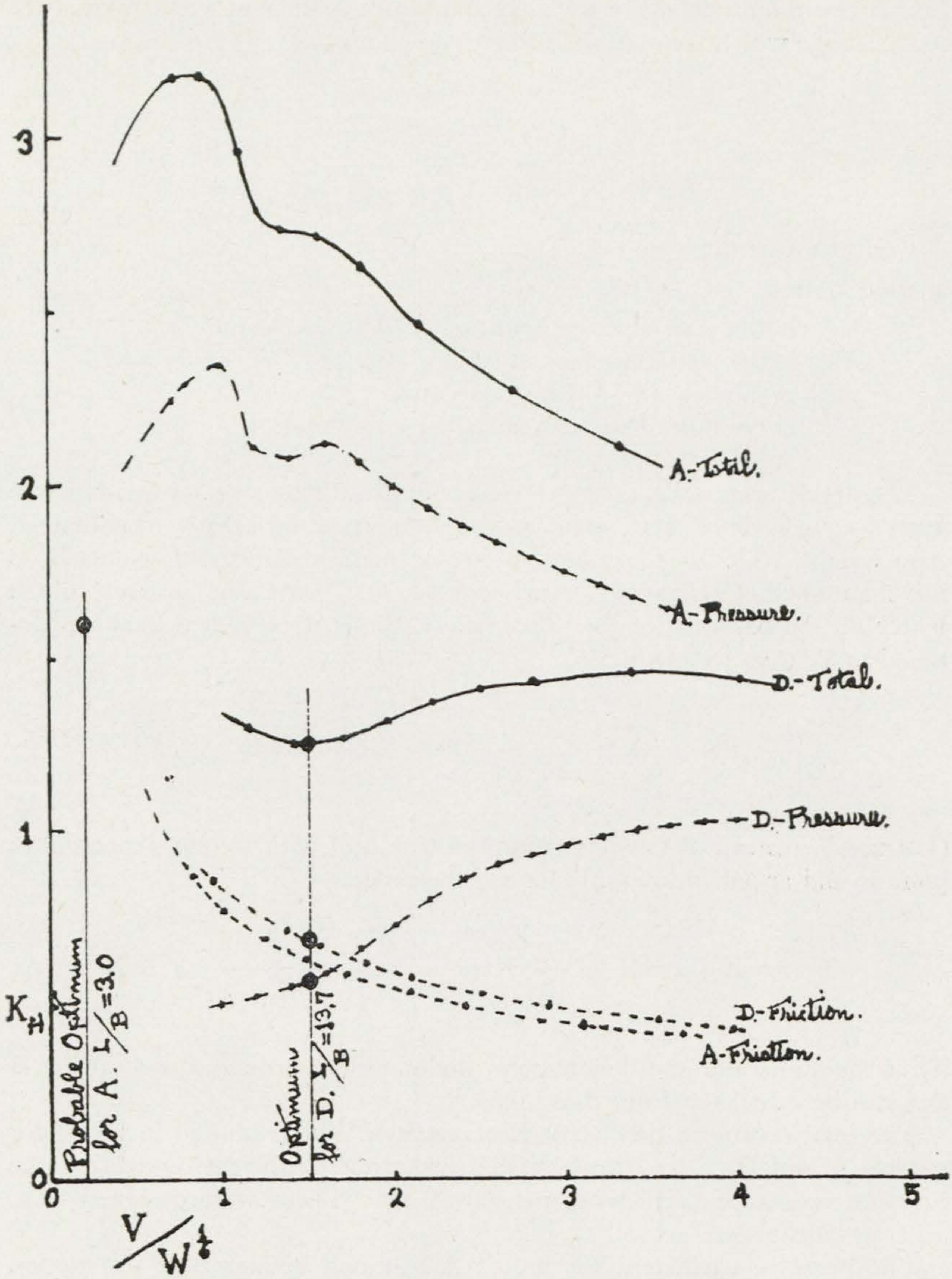


Fig. 4

of the frictional coefficient is just equal to the positive rate of change of the pressure coefficient at this speed. While the coefficients are nearly equal, I believe it is these complementary rates of change that are the criterion. This probably occurs also for model A at lower speed than was measured, an estimate of which is marked in Fig. 4.

These related conditions exist in all my best models whether they are displacement types, planers, or any other type. It is the best method of boat data analysis of which I am aware. Such an intimate insight is lost if one deals only with the steep curves of the type shown in Fig. 3.

Again I wish to emphasise that the determination of the lateral lift-drag ratio in windward tests of sailing craft is highly important. This was explained and discussed in my article in Chapter XIX. I consider this to be the field in which the greatest advances in sailing craft may come in the near future. "America Cup" designers take notice!

Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 36, July 1961

Dear John,

Your letter of 11.4.60 poses questions that have interested me for some time. I try constantly to make step-by-step experimental checks as guides to my theoretical endeavours to avoid bad assumptions. The worst "scientific" assumption I ever heard of was that of an "ideal" fluid without viscosity on which so much classical hydrodynamics is based. It wasted years of effort of many able mathematicians who were not experimenters.

I once assumed that, for a fixed displacement, a hemisphere might have least frictional resistance at low speed. I could not check this experimentally. I finally obtained agreement between theory and experiment on the following basis:

As one stretches a hemispherical shape into a hemi-ellipsoid, holding the displacement constant, the rate of increase in surface area is less than the decrease in the frictional coefficient with increasing length within the initial range. Thus a slightly elongated form has minimum frictional resistance. The need for stream-lining comes from pressures.

For a given speed, an optimum cross-section balances the pressure resistance against the frictional resistance and minimises their total. I have written up separately in an attached section how this was measured in case it is worthy of publication. You may decide it is unorthodox and too technical although I have attempted to minimise the mathematics even though it is elementary.

Incidentally, pressure resistance is normal to an elementary surface area and frictional resistance is tangential. This is all one requires.

As to "Mach" angles, if a stick is placed vertically in water and moved slowly horizontally, ripples appear always ahead of the disturbance. Gravity waves always follow the disturbance. They obey very different laws. Ripples have an almost constant speed of propagation, therefore the classical "Mach" angles and velocities appear. The angle becomes smaller with speed. Individual gravity waves advance at the speed of disturbance with a pattern which is due to wave interference and "Mach" angles, as ordinarily defined, do not appear.

Empirically, the fore-and-aft location of the maximum beam seems best in my models when adjacent to the first depression in the gravity waves alongside. Without other evidence, I am of the opinion that it is the "constant cross-sectional area rule" of super-sonic aerodynamics trying to work.

Submarines and fish always require their maximum beam forward of amidships because there are no gravity waves which only appear on the water's surface. It is these surface waves which force departures from the true streamline shape. For surface vessels I believe the following:

At low speeds, buoyancy produces marvellous lift-drag ratios or in other words weight-resistance ratios. These ratios drop off with increasing speed. Planing can never help us until this ratio drops to at most 10. When a catamaran or any other displacement craft falls much below this ratio, it had better convert to planing to improve performance. This may be the reason for the desirability of flattening aft at high speed. First the rounded chine is best since it makes less fuss struggling through the transition range to full planing, where the sharp chine boat is miserable. Full dynamic planing without appreciable buoyancy is necessary to make the sharp chine boat desirable.

Upward curvatures aft cause suction. This can be detected in displacement models at low speed since their centre of buoyancy is not vertically aligned with their centre of gravity. Making the sum of the moments equal zero also reveals the location of the suction. Even slow displacement boats benefit by straight "runs" aft. Squatting often adds wetted area aft but reduces it forward resulting in little change in area where dynamic lift is absent. Compensation also seems to occur between the crests and hollows of the waves alongside. My opinion was formed through the fact that the MIT tank uses change in wetted area obtained through analyses of photographs to determine where the inception of dynamic lift sets in.

I hesitate to be specific about the speed ranges where the various transitions take place in my models. Such things as a means of reducing friction per unit area could upset the entire spectrum. Also, I do not have faith in expressing this in terms of Froude's scaling ratio although I resorted to this in my AYRS article to avoid complicated explanations. Possibly the resistance-to-weight ratio would be better once one got used to it. Such a ratio reveals that a full-bodied boat should resort to planing at lower speeds than would be desirable in catamarans. Other examples could be cited.

EDMOND BRUCE

CHAPTER XXII

RUNNING RESISTANCE VERSUS SPEED OF SAILING MULTI-HULLS

Reprinted from AYRS 45, Oct. 1963
and AYRS 78, 1972

by Edmond Bruce

Introduction

Now that AYRS has a laminar towing tank of its own, near headquarters, it seems appropriate that data on measurements should be presented for some easy to duplicate models which will permit the various similar tanks to compare and equalise results. These data also should be of considerable interest to designers of multi-hulls. With this in mind, I am providing data from my N.J., U.S.A., tank on what one might call a "multi-hull reference series". In addition, several variations from these reference forms will be studied.

There are at least two optional systems of employing models to obtain predictions of the performance of full size hulls. In the writer's article in Chapter XIX, a laminar variation of the "absolute" or quantitative system was described. This system was devised by William Froude who first proposed separating a *single* model's frictional and pressure components of resistance and separately scaling them to full size, where they were recombined.

In the above process, Froude used the frictional resistances of flat surfaces to represent those of rounded three-dimensional surfaces of equal area. He also treated frictional and pressure resistances as if they were directly additive without mutual relationships. These last two devices have caused some controversy among the theoreticians, but they have survived, since experimentally this works quite well, even if over-simplified in concept.

Practical experimenters have on occasion used a second "comparative" or qualitative system. Here, *two or more* different models of the same weight are compared as to total resistance. No separations of component resistances are attempted. The assumption is made that the better model hull would also be qualitatively better at full scale. Theoretically, this seems reasonable with a possible reservation of judgement when the total resistances are nearly equal. If the wetted areas should be the same, no doubt exists. Usually a designer is satisfied to know definitely that one shape is better than another even if the degree is approximate.

In the following discussions, the comparative system is being presented as a demonstration of the method. It is simple and effective. It may become popular for this reason. However, if one desires more accurate quantitative answers, the model's wetted areas will be stated so that one can transform the results of a final selection to full size resistance magnitudes by the skin or frictional resistance corrections described in the writer's article in Chapter XIX. As the model speeds will extend into the transitional range, above Reynolds' Numbers of 3×10^5, the frictional coefficient may be considered constant in this range. However, it does not matter greatly since the pressure resistances dominate at these high model speeds.

Whereas mono-hull sailing craft are restricted to hull designs which provide good lateral stabilities, by virtue of geometric form or by low centres of gravity, multi-hull sailing craft do not have these restrictions. For their ability to carry sail to windward, multi-hull craft rely on combinations of spaced hulls to give the necessary lateral stabilities.

This article will discuss model measurements made in the laminar flow towing tank of total running resistances without leeway. These will be stated as a function of speed, for various shapes of an individual hull, of a multi-hull configuration, without regard to its lateral stability.

The writer has a "reference series" of models of low lateral stability. This series does not necessarily possess the best shapes possible. It is intended to provide easily constructed comparison forms which are not only low in resistance but are of such a simple shape that their displacements, wetted areas, prismatic coefficients, etc., can be calculated readily from their dimensions. These models can be turned in a lathe with the aid of a profile template. If a proposed form is not at least as good as its equivalent reference form, in resistance characteristics, the wisdom of its construction at full size is doubtful.

Reference Series

The well known "Taylor Standard Series" of models is of little interest to the designer of multi-hulls. Taylor used mid-sections which were more or less rectangular with slight rounding at the lower corners or bilges. This shape was essential to give lateral stability during broadside gun-fire on naval ships. They also provide usefully shaped cargo spaces in merchant ships.

The multi-hull designer need not worry about lateral stabilities of the individual hulls. For this reason, he can achieve less wetted surface and the resulting lower friction by discarding lateral stability. This leads to the semi-circular cross-sections, below the water-line, which are so much in vogue. This shape encloses within its plane, the greatest buoyancy area for any given wetted perimeter. Because of this, the reference series uses semi-circular wetted sections throughout its length.

The reference series also uses submerged profiles which are portions of a circle. In fact, if a segment of a circle is rotated by a half-revolution about its chord, as an axis, the under-water reference form is generated. Various models in the series differ only in their water-line length-to-beam ratios. All reference models are of such a size that their displaced volumes and total weights are equal. All have good prismatic coefficients. All have beam-to-draft ratios equal to 2·0.

The partial-circular profiles were selected since hull resistances are the result of the rate of acceleration or deceleration of masses of water. A gentle curvature, having the greatest possible radius, stretches the work timewise and causes the least acceleration.

The above profile proposal is a good first approximation to an ideal shape. It is also a form which can be steered readily to obtain rapid turning or tacking. It may require modification due to such factors as the shape of the hull's surface waves generated alongside at some particular speed. Also, the "stalling" angles of all portions of the wetted hull's after surface, in respect to its direction of motion, must be considered. For simplicity, the reference series employs only profiles which are circular segments. Other profiles employing modifying factors are studied separately in a series of experiments.

Five reference models have been built as illustrated in Fig. 1. All are

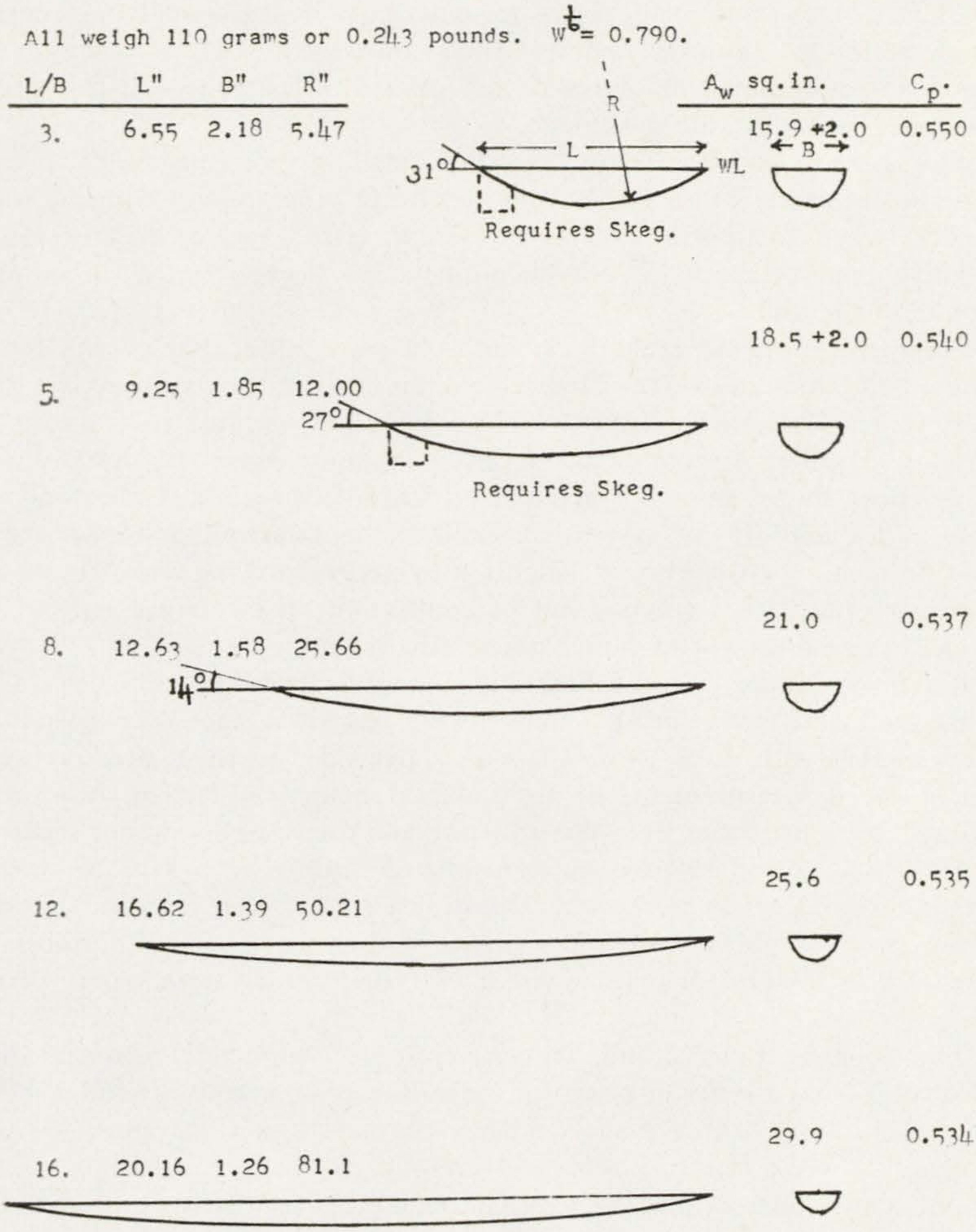


Fig. 1

ballasted to weigh 110 grams which gives the desired displacement.This ballast is located amidships and low so as to give some small degree of gravitational stability to enable the testing of single hulls. These models differ only in their length-to-beam ratios which are 3, 5, 8, 12 and 16. The models will be referred to by these numbers in the discussion which will follow.

The Stalling Angle

Why does a flag flutter in a breeze? It is for the same reason that so many dinghies and sailing hulls snake back and forth like a fish's tail when one tries to tow them with a power boat. These are all unstable forms.

In order to damp out the described fluttering motion, skegs, keels and centreboards are usually used. As a last resort, rudder action is additionally employed. Such counter-measures are downright bad design. It is generally much better to eliminate faults at their source rather than to counteract them. The mentioned measures do not get rid of the causes of this excess resistance and unstable turbulence.

The faults in the above craft are called "stalling" which is well known to airplane designers. These result from the abrupt generation of whirling water vortices when any portion of the afterbody wetted surface area exceeds a negative angle of about 15° plus or minus a few degrees to the direction of motion of the hull.

Commercial towing tanks with multiple restraining attachments to the model hull, from an overhead carriage, often obscure the nature of the difficulty under discussion. Chapman, in his early towing tank, used a tow-line through a pulley system actuated by a falling weight. He undoubtedly experienced flutter since his layout is pictured with an added after-end tow line, pulley and weight system to stabilise the direction of model travel. The difference between these weights provided his towing force. It takes a towing means with a single point of application on a forward part of the model to reveal the vortex flutter under discussion.

Reference Models 3 and 5 both suffer severely from this difficulty. They snake back and forth during a tank towing test. It is necessary to stabilise these models with skegs, one square inch per side, on their after bodies to obtain speed measurements of any value. I hate to reflect on how many sailing craft must suffer from this affliction and their owners do not realise it.

Models 8, 12 and 16 show no signs of fluttering when towed. No stabilisation appendages are necessary. The difference between these models and those described above is that the angles of their stern wetted surfaces are smaller than the critical angle of about 15°, above which stern water vortices are generated.

The book by Prandtl and Tietjens entitled "Applied Hydro and Aero Mechanics" has a series of beautiful water-flow photographs around a sphere and other shapes which clearly indicate the nature of these stern vortices. Apparently, clean stream-line flow always occurs in the fore-body.

The above vortices may be why fish usually have their maximum cross-section forward of mid-length. This eases the angle of the after-body surfaces with the direction of motion. The increased curvature resulting in the fore-body does not cause vortices. A fish, of course, is completely immersed in its environment. It does not generate harmful gravitational waves on the surface as a boat does. Due to the presence of surface waves, boat designers would be unwise in imitating the shape of a fish. This will be seen later in some measurements. It will be discussed at that time.

Returning to the problem of stern vortices affecting the behaviour of a boat, cut-and-try experiments over many years have revealed that performance is somewhat improved by broadening and flattening the after-body on many boats. In the writer's opinion, one of the reasons this is helpful is because this is a fortuitous method of reducing the angle of the surface to the direction of motion. Beware of double-enders which have low length-to-beam ratios!

Multi-hull designers seldom use low length-to-beam ratios, therefore the flattened stern trick may need further investigation in their case. We will examine this subject later.

Comparison of Reference Series

Before presenting the measured data of resistance versus speed, the dimensionless coordinates used in its graphs should be reviewed briefly. In Chapter XXI, the writer described how the speed-length ratio $V_B/\sqrt{L}$ and the speed-weight ratio $V_B/W^{1/6}$ were equally good for scaling so that the model's pressure resistance-to-weight ratio R_p/W applies likewise to the hull at full size.

Displacement hulls, particularly at low length-to-beam ratios, meet a squatting "hull speed" barrier which begins at $V_B/\sqrt{L} = 1{\cdot}34$ and peaks at 1·78. At 1·34, the length of the wave of water, generated alongside, just equals the waterline length of the boat. At 1·78, three-fourths of the length of a water wave equals the length of the boat. If this speed barrier is dominating, it seems quite proper to designate speeds of various sizes of boats with the speed-length ratio as Froude proposed. Most bumps and hollows in resistance curves are due to the relation of boat length to the length of its formed water waves. This will be demonstrated later using measured data.

For planing hulls and for hulls having a high length-to-beam ratio, the "hull speed" barrier can be penetrated by extreme power or because of low amplitude waves, respectively. For these higher speeds and also for the low speed range, it is quite unfair, as will be shown later, to make comparisons of the merit of boats based on the same value of $V_B/\sqrt{L}$. This penalises length even in those cases where excess length, resulting in too much wetted surface, is not effective in producing speed. For this reason, the writer prefers the speed-weight ratio $V_B/W^{1/6}$, which is also used in the British "Circular Unit System" as "circular K", except that pounds will be used for small boats rather than tons for ships. This is particularly accurate when all models have the same weight. This is the case for the models to be discussed. Using the speed-weight ratio, it is the designer's free option how he distributes a given weight of material. The data will be presented in this form as well as with the conventional speed-length ratio.

Since water resistance curves are more or less square law with speed,

TABLE A

Measured Total Resistances for Multi-Hull Reference Models of Fig. 1. All Models
Weight = 110·0 grams or 0·243 lbs. $W^{1/6}$ = 0·790. Fresh Water. Temperature 55°F. $\mu/\rho = 1{\cdot}30 \times 10^{-5}$.

L/B	Symbol	$R_T/W\%$	1·10	1·69	2·51	3·66	5·07	6·74	8·83	11·4	16·5	23·2
3	○	V knots	0·577	0·680	0·811	0·930	1·01	1·07	1·12	1·18	1·28	1·40
5	□	,,	0·681	0·847	1·00	1·12	1·20	1·28	1·35	1·47	1·83	2·51
8	△	,,	0·750	0·976	1·15	1·33	1·48	1·65	1·78	2·05	2·60	3·21
12	×	,,	*0·814	1·01	1·23	1·48	1·72	1·90	2·11	2·47	2·96	3·53
16	●	,,	0·770	*1·02	*1·24	*1·52	*1·78	*2·07	*2·37	*2·66	*3·11	*3·65
3	○	$V/\sqrt{L}$	*0·781	0·922	1·10	1·26	1·37	1·45	1·52	1·60	1·73	1·90
5	□	,,	0·777	*0·965	*1·14	1·28	1·37	1·48	1·54	1·67	2·08	2·86
8	△	,,	0·735	0·957	1·13	*1·30	1·45	*1·62	1·74	2·01	*2·55	*3·15
12	×	,,	0·690	0·858	1·04	1·25	*1·46	1·61	1·79	*2·09	2·51	2·99
16	●	,,	0·595	0·788	0·958	1·17	1·38	1·60	*1·83	2·05	2·41	2·82
3	○	$V_B/W^{1/6}$	0·730	0·861	1·03	1·18	1·28	1·35	1·42	1·49	1·62	1·77
5	□	,,	0·862	1·07	1·27	1·42	1·52	1·62	1·71	1·86	2·31	3·18
8	△	,,	0·949	1·24	1·46	1·68	1·87	2·09	2·25	2·60	3·30	4·07
12	×	,,	*1·03	1·28	1·56	1·87	2·18	2·40	2·67	3·12	3·75	4·47
16	●	,,	0·976	*1·29	*1·57	*1·92	*2·25	*2·62	*3·00	*3·37	*3·94	*4·62
3	○	K_H	2·06	2·25	2·34	2·54	3·06	3·66	4·34	5·07	6·21	7·32
5	□	,,	1·48	1·47	1·56	1·81	2·20	2·56	3·02	3·30	3·09	2·52
8	△	,,	1·22	1·11	1·18	1·30	1·45	1·54	1·74	1·69	1·52	1·40
12	×	,,	*1·04	1·03	1·03	1·04	1·07	1·17	1·24	1·17	1·17	1·16
16	●	,,	1·15	*1·02	*1·02	*0·993	*1·00	*0·982	*0·982	*1·01	*1·06	*1·09

$$K_H = \frac{R_T/W\%}{(V_B/W^{1/6})^2}$$ Since weights are equal, $V_B/W^{1/6} = 1{\cdot}256\, V_B$.

Note: *Indicates fastest in group.

the steepness of such curves tends to conceal small variations which may be of interest. Thus by using the graph coordinates, as presented, and saying that the ordinate $R_T/W\%$ is a function of the abscissa squared, that is, $K_H\ (V_B/W^{1/6})^2$, one gets the simply derived and proper total coefficient $K_H = \dfrac{R_T/W\%}{(V_B/W^{1/6})^2}$. This is sensitive to other than speed variations. It is much easier to use this coefficient than the conventional coefficients which are related to wetted surface areas. These are hard to determine when rough wave profiles are generated or when any degree of planing or squatting is involved. When speed is related to weight, one is dealing with a fixed quantity which is easily measured.

The measured data on the five reference models, whose dimensions are shown in Fig. 1, are given in Table A, so that the reader may compare with them or employ them as he chooses. The static wetted areas A_W and the prismatic coefficients C_p also appear in Fig. 1. Graphs have been drawn to help analyse these data.

Fig. 2 is a conventional plot of R_T/W versus the speed-length ratio $V_B/\sqrt{L}$ for all five reference models. It gives the impression that, at middle and the higher speeds, it is hard to choose between Models 8 and 12 as being best. The advantage alternates back and forth at various speeds. At the lower speeds, Fig. 2 and Table A show that lower length-to-beam ratios are preferable. This is due to smaller wetted areas as will be seen by referring to Fig. 1. It would be still more marked if Models 3 and 5 did not suffer from

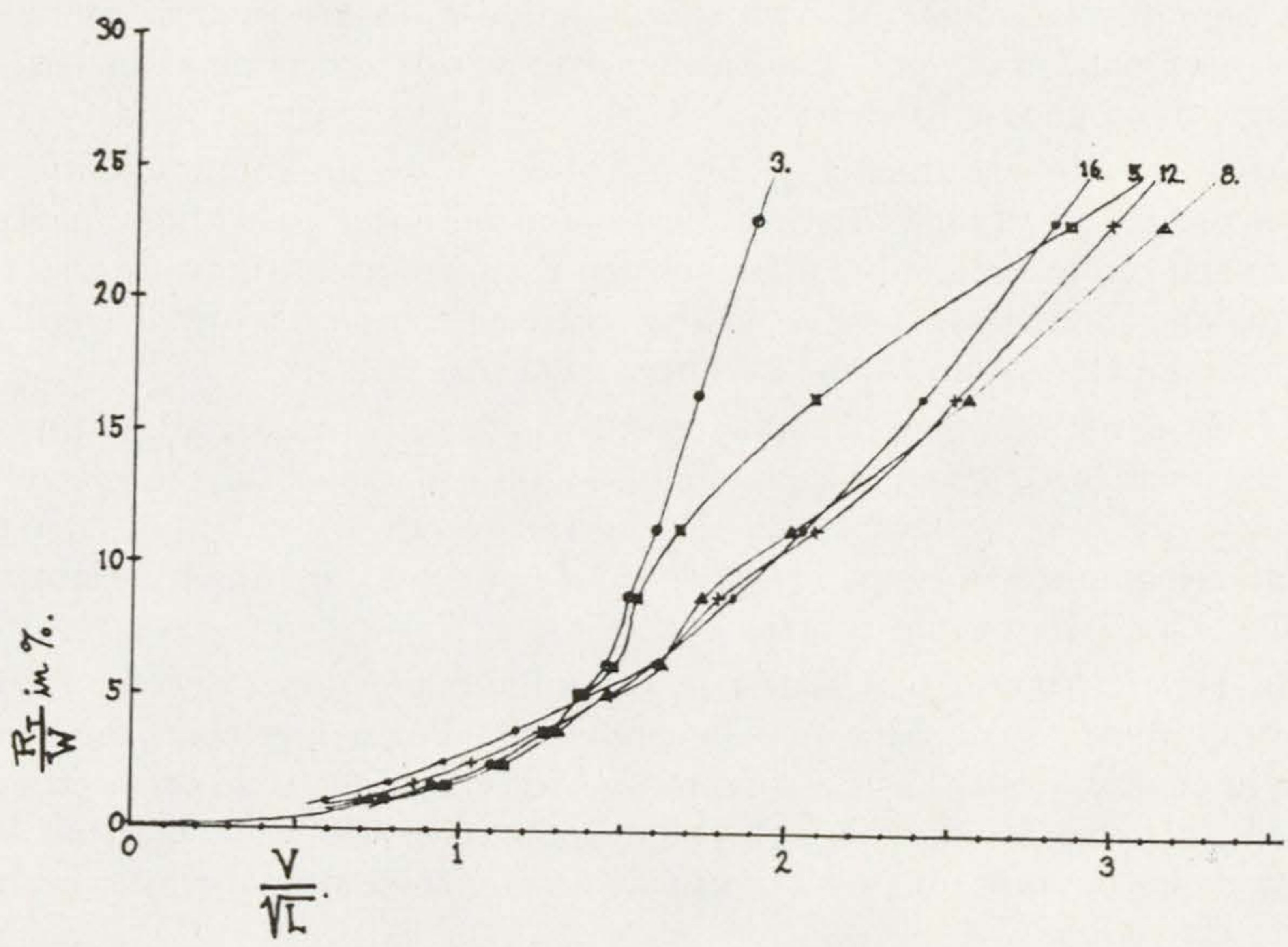


Fig. 2

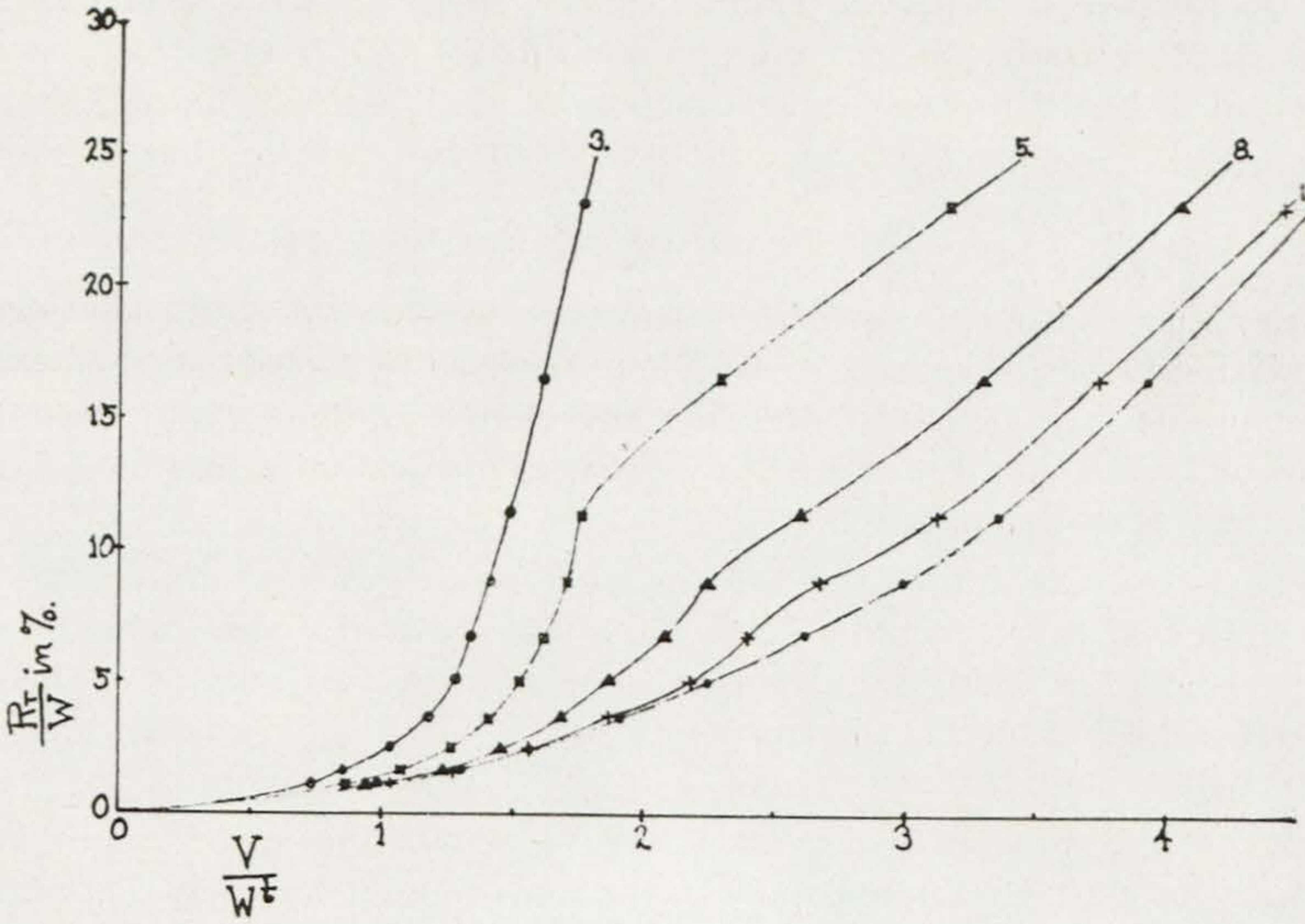


Fig. 3

stern vortices and require skegs. This region is the weakness of many multi-hulls. It is further emphasised by having the wetted surface inefficiently distributed among several smaller hulls rather than on one larger hull of the same displacement. At high speeds, multi-hulls are in their glory but they need wind. For good performance over a wide spectrum of speeds, the writer would choose Model 8.

Another comment about Fig. 2 is that if one is required to design to some particular length, a high length-to-beam ratio will force a very light displacement and can be used only for frail racers. For comfortable cruising displacements and roominess, there is no alternative to choosing a lower length-to-beam ratio. Here again Model 8 seems a good answer.

If one is not racing under some speed-length rule but ardently wants the fastest boat for a given displacement, a different choice of models might result. This may be seen by comparing the speeds V_B in Table A. When these are graphed in terms of the speed-weight ratio, in which weights are equal, Fig. 3 shows the results.

In Fig. 3, Model 16 is fastest in the middle and upper speeds. At low speeds, Models 8 or 12 would be preferable. For a fast boat, the writer would choose Model 12 as a compromise since light air is so often encountered. In strong winds, the high potential speed of Model 16 may not be a wise choice because rough water usually accompanies strong winds and may force discretion.

As was stated previously, one gets a more sensitive or a "blown up" view of variations, other than speed, when the total resistance coefficient K_H is examined. In Fig. 4, it is plotted against $V_B/W^{1/6}$. This graph confirms the merits discussed in regard to Fig. 3. The smaller K_H becomes, the greater the merit of the hull. Here one might ask what are the reasons for the coefficient peaks in the various curves? Since it is suspected that they are due to wave profiles, plotting K_H against $V_B/\sqrt{L}$ should give information. This was done in Fig. 5.

Fig. 5 produces a perfect alignment of the resistance peaks of K_H at a speed of $V_B/\sqrt{L} = 1{\cdot}78$. There is drawn, in the upper right of the graph, the relation of the hull length to the wave profile for this value. This relationship produces an extreme tendency to squat by the stern. Thus it is seen that the study of coefficients, as shown in Figs. 4 and 5, is a powerful tool for analysis. In fact, when one gets experience in manipulating towing tank data, a preference may be acquired for employing the coefficients exclusively in comparing the merits of differently shaped hulls.

Departures from Reference Shapes

It was stated earlier that while the reference series' geometry produced forms of low resistance, compared to many other forms, certain departures from the reference shape might produce further gains. Some of these possibilities now will be examined.

First, a study will be made of the effects of placing the maximum immersed cross-section at points other than mid-length. To avoid an extreme value of L/B, Model 12 will serve as the reference. A model was constructed which was

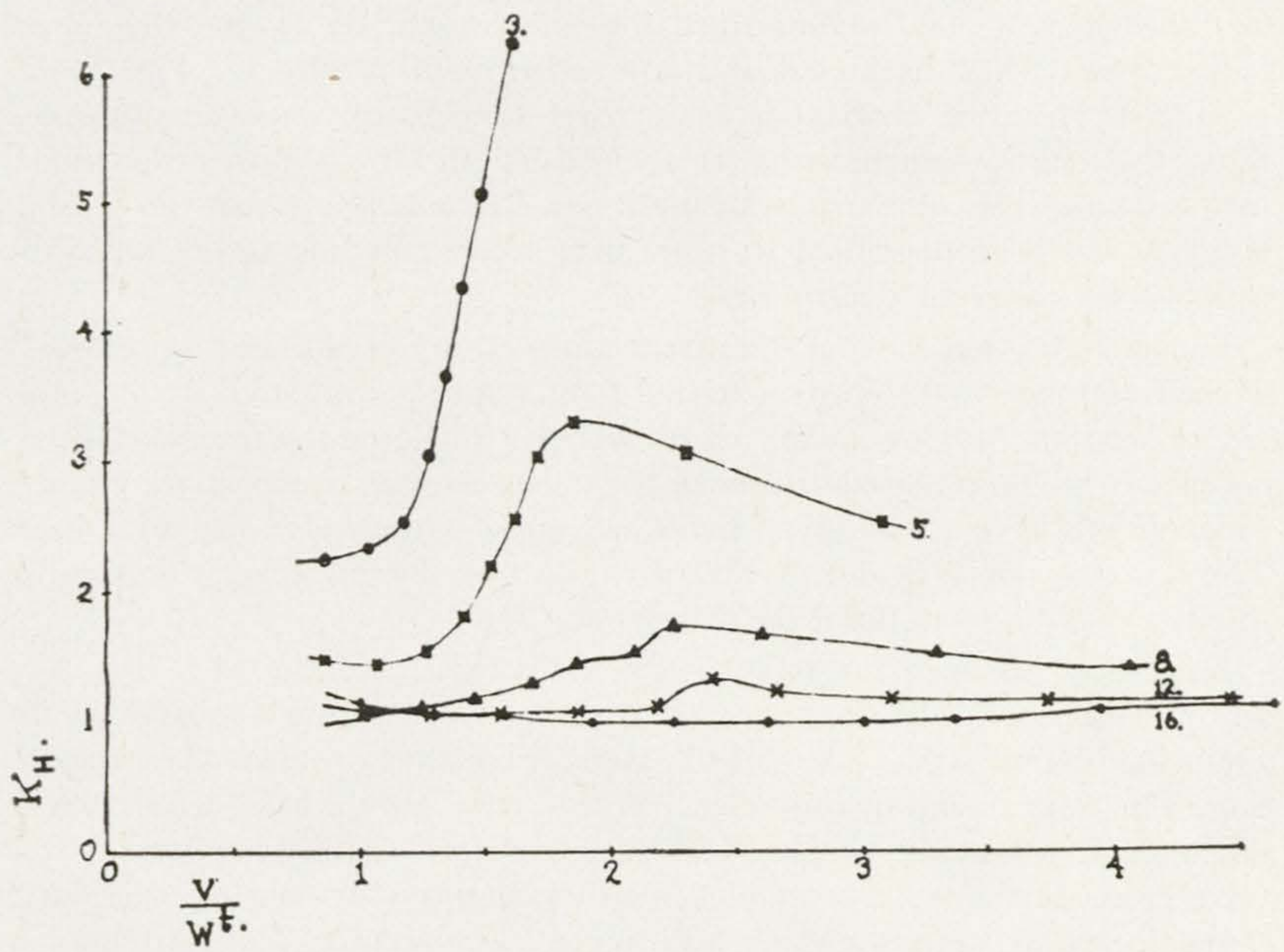


Fig. 4

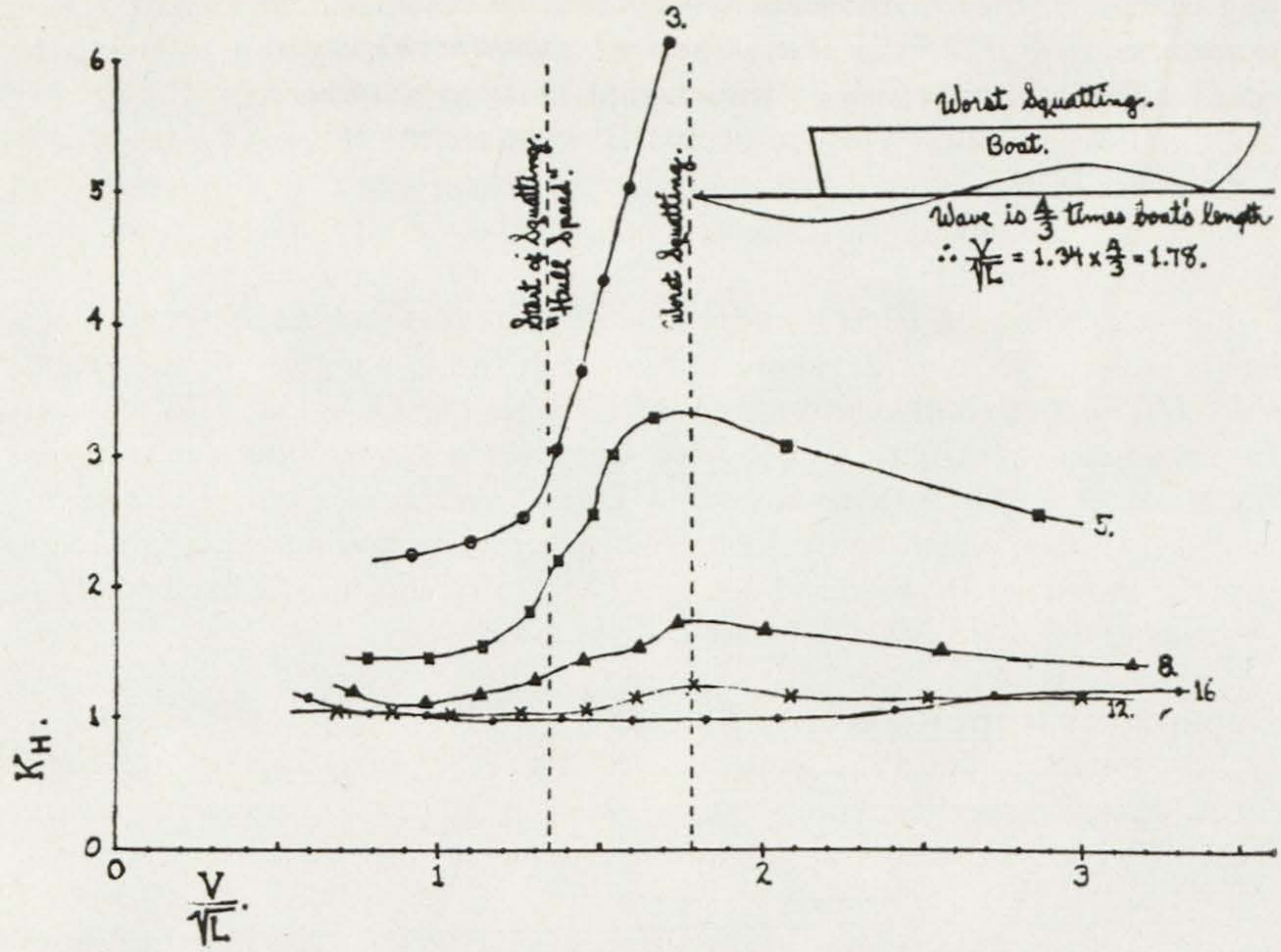


Fig. 5

the equivalent to Model 12 in all respects except that the maximum section was shifted to a point at one-third the hull length. By towing the model both forward then backward and comparing with Model 12, Fig. 6 was produced. Here the abscissa is again $V_B/\sqrt{L}$ to study wave relationships. Since the length is unchanging, this speed-length ratio is now proportional to speed so direct comparisons of merit can be made. Note that the scale of K_H now has been magnified 10 times to prevent crowding and to make the conclusions easier to determine.

Fig. 6 shows that moving the maximum section forward and more nearly aligned with bow wave crests is harmful at all speeds compared with a mid-length location. Moving the maximum section aft helps at intermediate speeds because it becomes more adjacent to wave depressions. However, the trend is unfavourable at very high speed and it becomes definitely worse at low speeds. The writer is not in favour of adversely affecting the low speed range, since this is already a weak point for this type of hull.

Since K_H has been magnified 10 times in Fig. 6, compared to Fig. 5, a new curiosity has come into view. It is the hollow that has appeared in the coefficient curves at $V_B/\sqrt{L} = 1{\cdot}07$. Here again wave profile is the explanation. The relationship of hull length to this wave profile has been drawn in the upper right of the graph. Note that the stern is fully supported by a wave crest. If the wave crest moves either slightly forward or backward, some degree of stern squatting will appear. Apparently, this satisfactorily explains the locations of these troughs in the curves of the coefficients.

If each cross-section of the after half of Model 12 is broadened and its draft flattened, so as to keep the section area unchanged at each station, the displacement and prismatic coefficient would be unchanged. Such a model was built and tested. Its performance is shown in Fig. 7 together with that of Model 12 as a comparison. Note that the broadened stern areas become somewhat better aligned with wave hollows in these ranges of speed. Evidently, this is a measure whose adoption might be considered. The performance is improved except at extremely high speed, when a wave crest moves well aft, and at low speeds where its greater wetted area becomes noticeable in the performance.

I have read where stern flattening was employed in the hope of reducing "hobby-horsing". I believe it may be a beneficial alteration, but not for that reason. All the longer models prove by test to be highly damped as to pitching oscillation. This is because of the great height of the longitudinal metacentre represented by the centre of radius R in Fig. 1. It is only necessary to keep the centre of gravity reasonably low to achieve this.

A way to produce a slight flattening along the entire length of this reference hull shape is to lift it partially out of water. Since it was desired that all models weigh the same, a new model was built which was patterned after Model 8, as a good cruising choice, but with all the linear dimensions increased by 10 per cent. It was provided with reduced ballast to equalise its weight with the others. This resulted in a beam-to-draft ratio equal to 2·7 instead of 2·0. The length-to-beam ratio is reduced very little. Its performance is indicated in Fig. 8 together with Model 8 as a comparison. In

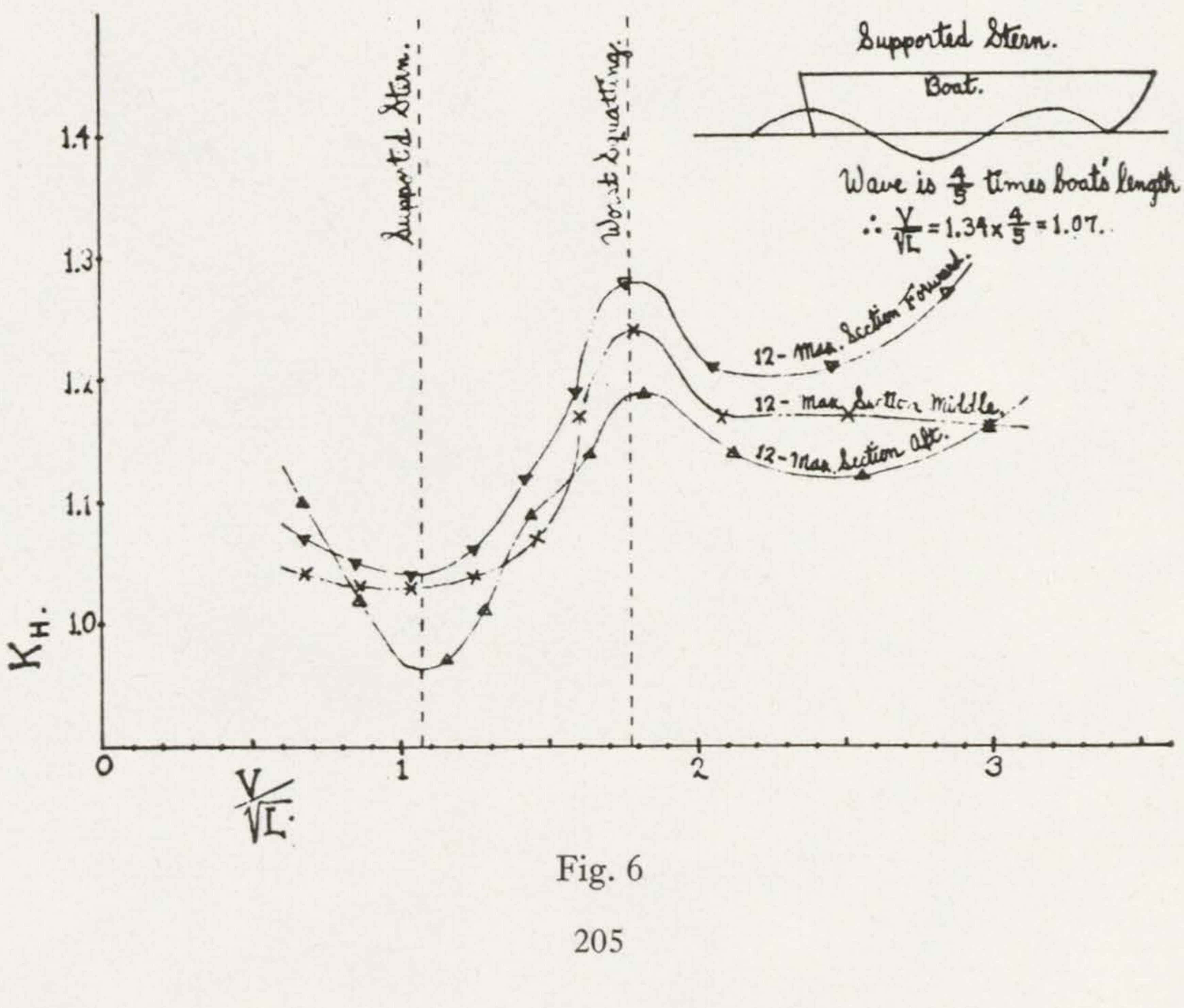


Fig. 6

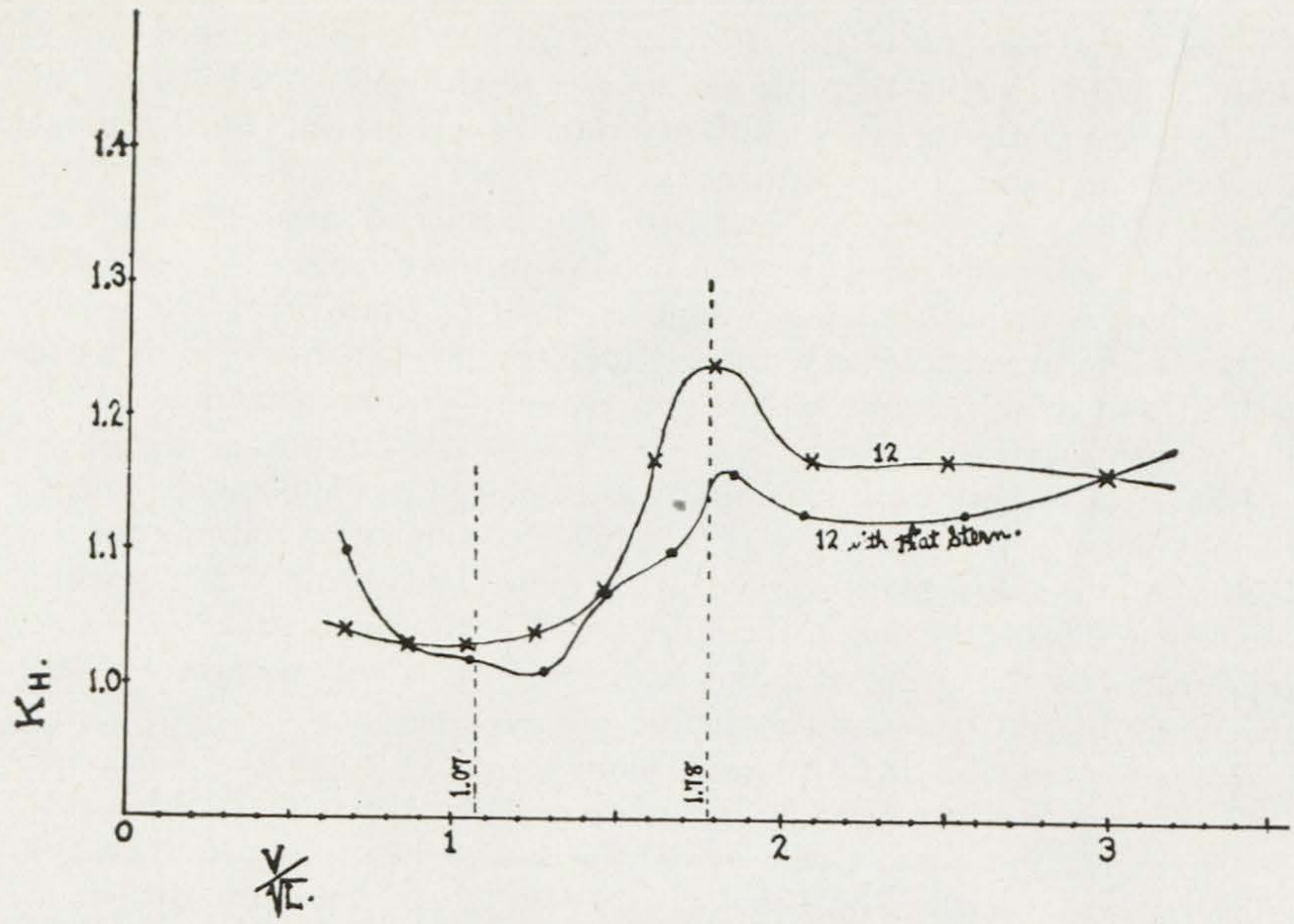

1.4
1.3
1.2
1.1
1.0
KH.
0
1
2
3
1.07
1.78
12
12 with flat Stern.
V/√L.

Fig. 7

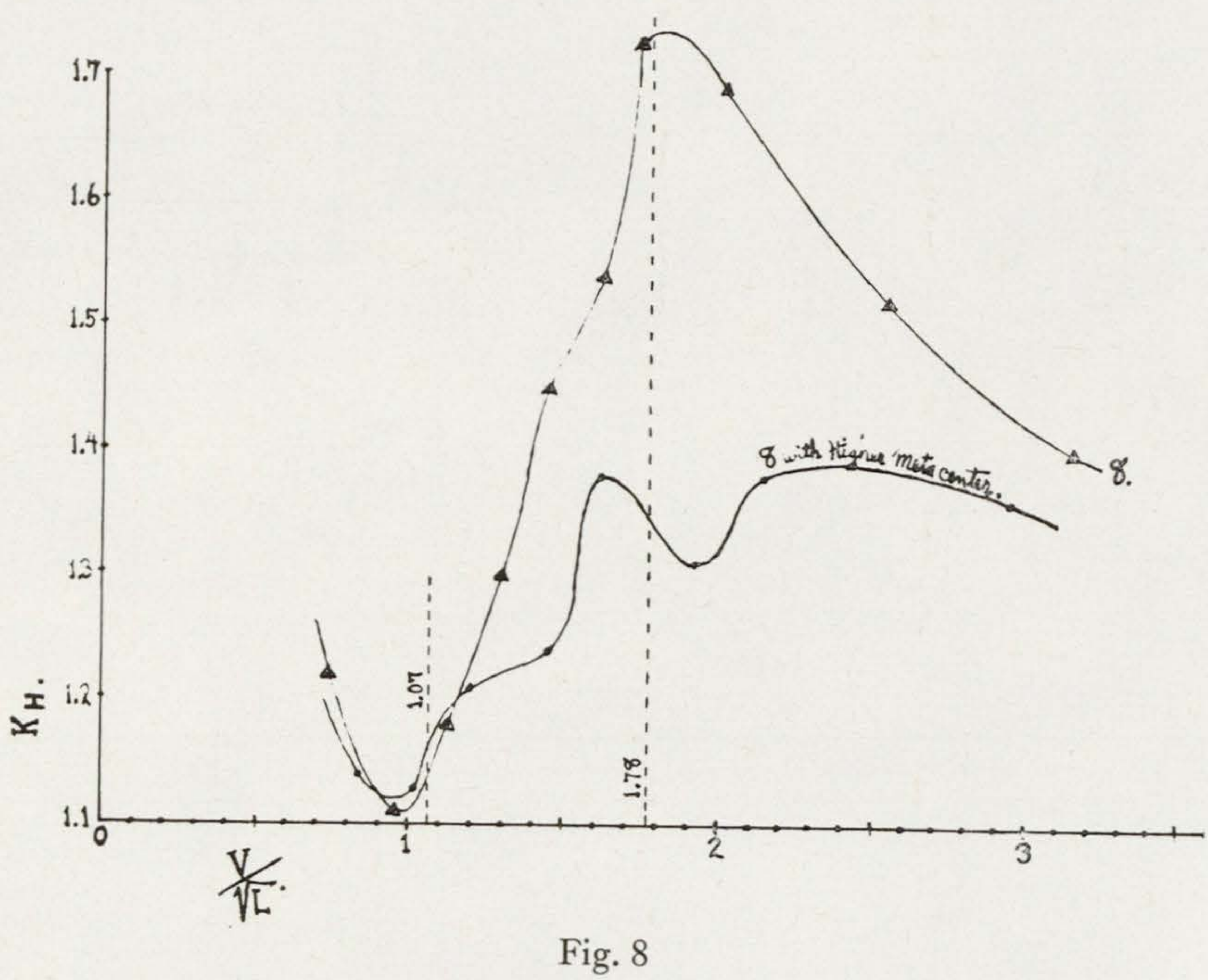

1.7
1.6
1.5
1.4
1.3
1.2
1.1
KH.
0
1
2
3
1.07
1.78
8 with Higher Meta center.
8.
V/√L.

Fig. 8

spite of a slight increase in wetted surface, the improvement in reduced pressure resistance is appreciable at each side of the worst speed-length ratio for squatting. This results from the lower area of cross-sections, due to less draft with little change in beam. Note that the maximum cross-section is in the vicinity of the crest of the bow wave, for these ranges of speed-length ratios, as appears in sketch on Fig. 5 for the particular speed of $V_B/\sqrt{L} = 1{\cdot}78$. For this reason, the smaller cross-section, due to less immersion and greater length, would be expected to help.

Final Remarks

While the characteristics of multi-hull running resistances have been discussed somewhat at length, in this article, the writer was really trying to demonstrate the value of the small laminar flow towing tank which was described in Chapter XIX. It was built as a recreation to occupy some evenings one winter, that of 1946. The results were so stimulating that this hobby has persisted ever since.

The subject of running resistances of individual hulls may seem moderately well worked over. For multi-hulls, simply add the resistances and weights of individual hulls for a widely spaced multi-hull configuration. For closer spacings, separate tests should be made.

It is in the area of simulated windward performance and its required stabilities that the tank experiments are proving to be in virgin territory. This region is the most exciting of all. Here may be found such things as fast but non-heeling configurations. Also, answers to the controversies over rounded versus vee sections for hulls come to light. I wish that many laminar tanks would share in this work and that descriptions of their results would be freely exchanged in the AYRS publication.

It takes a cooperative mass-attack to make rapid progress. Secrecy causes stagnation. For every idea donated to the common pool by one individual, he may get a dozen ideas, unthought of, in return.

If need be, let the secrecy of competitive racing and commercialism be restricted to the judicious balancing of compromises in the practical development of known fundamentals. Let pure research into these fundamentals be amateur in spirit.

CHAPTER XXIII

TESTING THE BALANCE OF SAILING CRAFT USING SMALL MODELS

by Edmond Bruce

February 1949

For many years, the prediction of the performance of full sized boats from simple test data on small models has had a doubtful reputation. The trouble has been that there are superimposed a number of types of hull-to-water resistances rather than one. Each follows a different natural law as the dimensions are expanded from model to boat in size. It is the correct proportioning of these resistances with size and speed that has made the work of naval and commercial towing tanks a complicated business.

Regarding sailing craft, the perfection of balance or "tuning" may well be of greater importance than any further refinements in a good hull shape. Balance occurs when the centre of the effective effort of the wind on the sail plan is in the same vertical plane with the centre of water resistance acting on the hull. This is illustrated in Fig. 1. When balance is accomplished, a boat follows a straight course without the necessity of countering an error in balance by off-centre steering with its consequent slowing down of the boat.

A method of model testing for sailing craft will be described which concerns only balance. Correctly done, it should contribute indirectly but importantly to obtaining small resistance to forward motion, particularly to windward. The method relies heavily on the proposition that resistance to side-slip of most sailing hulls is primarily eddy resistance. In comparison, other types of resistance to side-slip such as the so-called "gravity waves" forming on the surface (side-slip is very slow) or "viscosity resistance" over the skin of the hull, are unimportant and may be neglected. Thus side-slip resistance is governed substantially by one type of resistance rather than several. Its natural law is fortunately far simpler than those of the others. It presents no difficulties in predicting the balance of full size sailing craft from their small-scale models providing that the ratio of velocities is as the square root of the ratio of linear dimensions.

The above-mentioned theoretical assumption about the domination of eddy resistance, in the case of side-slip, was viewed with suspicion until checked by a series of tests, using the techniques which will be described, on one standardised hull form in model sizes ranging all the way from 9 in to 19 ft in length. All sizes gave practically the same answers as to the location of the balance point. While the smaller models had a greater percentage of scattering of measured values when tests were repeated, their easier and faster construction more than off-set this slight loss of accuracy. For further confirmation, three full size sailing auxiliaries were compared with their

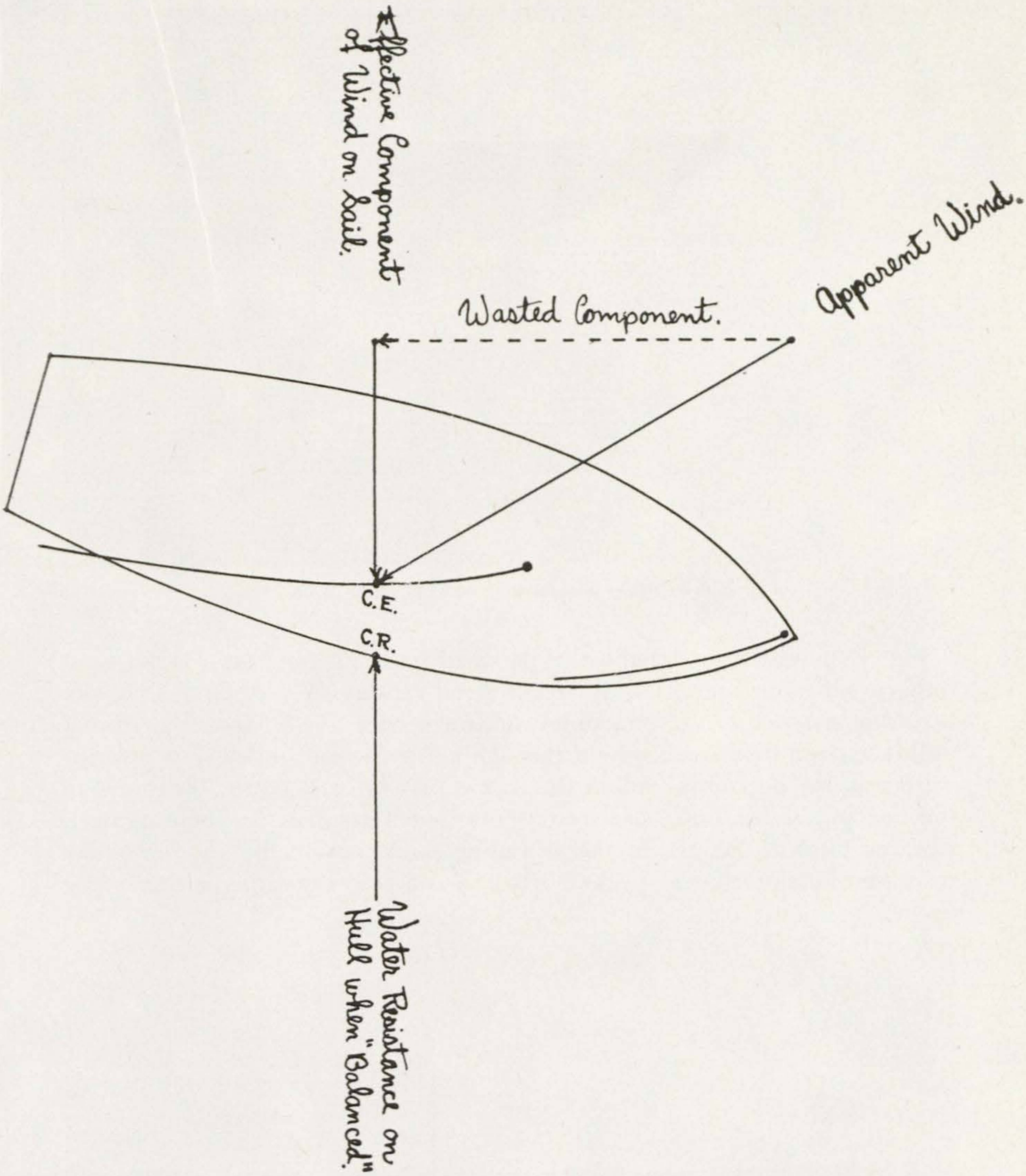


Fig. 1. Hull resistance exactly counters effective wind component when "balanced"

models as to balance. The results generated confidence in the testing techniques which now will be described.

Fig. 2 is a photograph of a small test model. It is accurately scaled down from the prospective boat in size, weight and location of centre of gravity. It is equipped with a stub mast supporting a horizontal rod centred amidships. This rod is at the calculated height of the centre of area of the working sail plan.

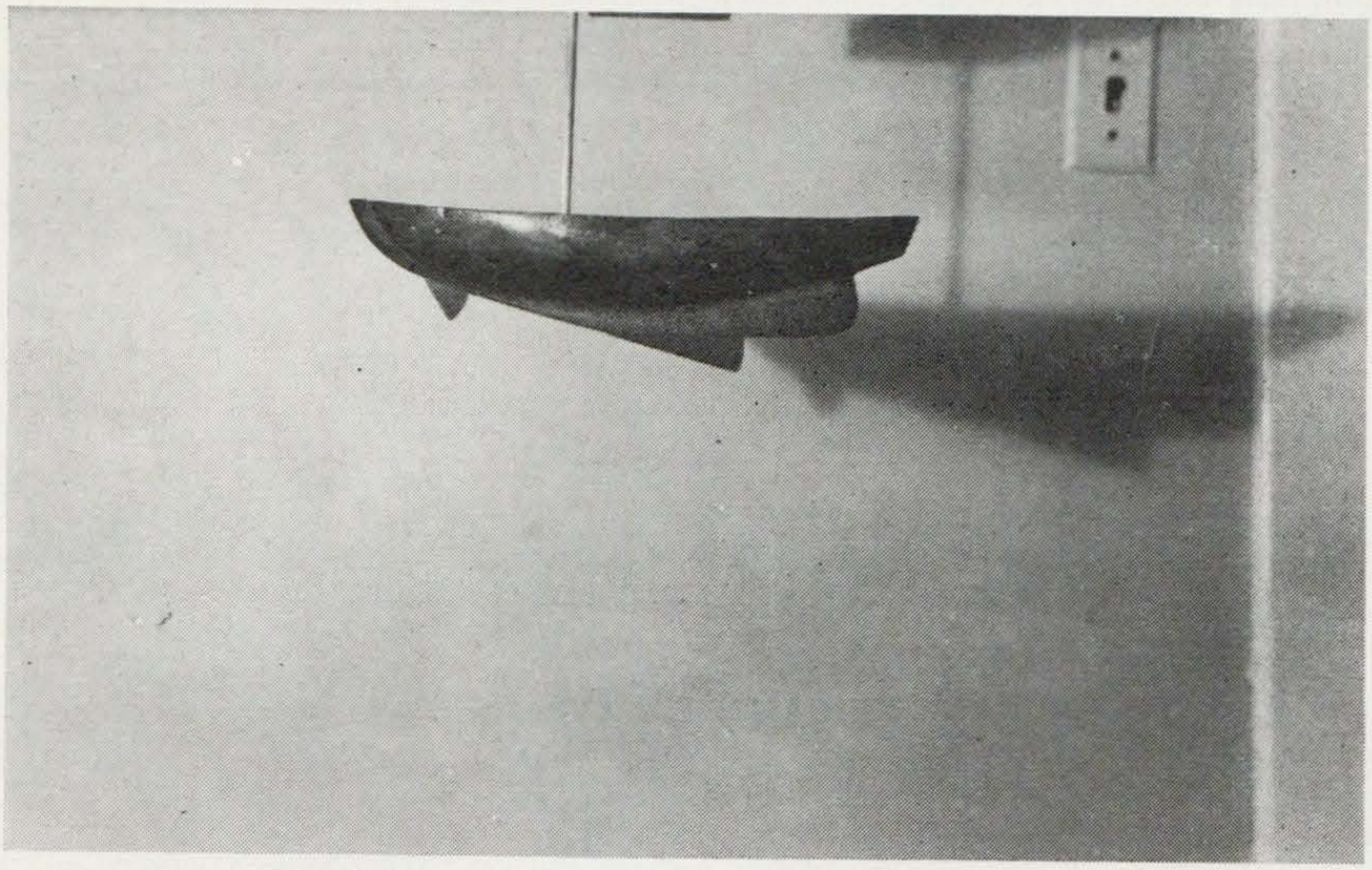


Fig. 2. A typical 12-in model used for tests of balance

Fig. 3 shows the model afloat in its small tank. Floating models are used rather than those supported by an overhead railway. A very long, fine, silk thread is attached to the horizontal rod, mentioned above, and a horizontal pull is exerted by a small weight through a low friction pulley. For a windward test, the horizontal pull of the thread may be, say, 60 to 70 degrees to the heading of the hull. As a result, the model assumes an angle of heel, yaw and pitch as dictated by the prevailing conditions. If the location of the thread and its attachment to the horizontal rod is in the same vertical plane

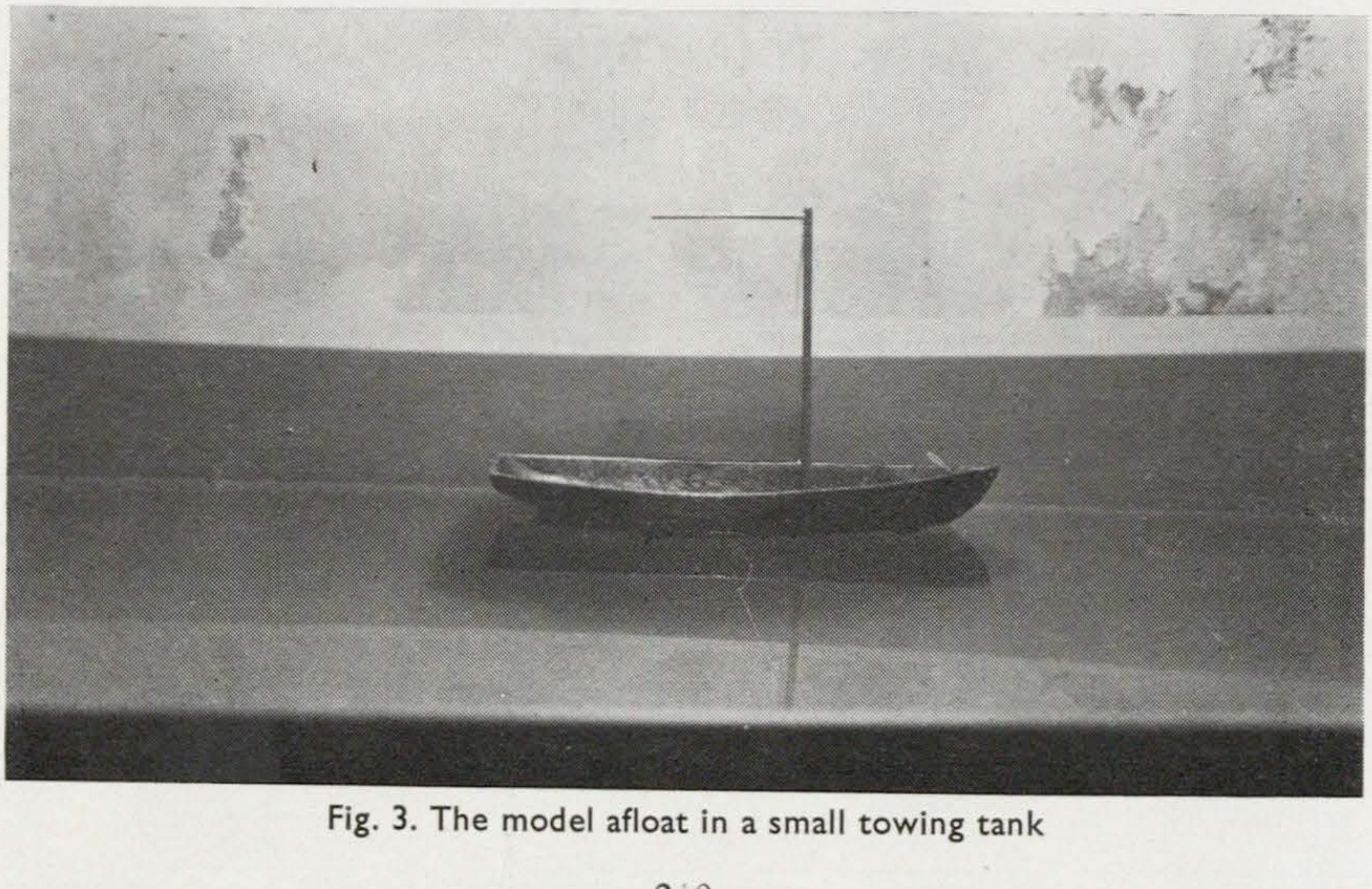


Fig. 3. The model afloat in a small towing tank

with the centre of resistance of the hull, the model will travel straight forward with very little side-slip. If the point of attachment of the thread is incorrect, the model will either head up or fall off depending on which way the attachment is in error. In this manner, the location of the centre of resistance of the hull can be determined for the conditions of the test.

Observations for the data should be made when the model approaches its ultimate speed for the conditions. If the tank is long enough, acceleration from a standing start is advantageous. If the tank is short, a preliminary push gives the same result provided it is carefully executed.

The size of the propelling weight, attached to the thread, should range from small values up to about one-twentieth of the weight of the model for the 70 degree angle mentioned. This results in a forward driving component of about one-third of the propelling weight. The heeling component will be nearly 94 per cent of this weight. It is not the propelling force but the resulting hull speed, measured by a photoelectric automatic recorder, which is used as the criterion for the location of the balance point. This is the subterfuge which avoids the usual inaccuracies associated with model size testing of full size boats. When the forward velocities of the respective hulls are proportional to the square root of their linear dimensions, they will have surface waves alongside which are geometrically similar in shape and proportional to the hulls in dimensions. The side-slip of the hulls creates eddies in these walls of water, the resistances of which determine the location of the balance points. These locations will be approximately the same for the boat and the model.

If one wishes, an attempt can be made to imitate the natural roughness of the sea surface by artificially generating waves in the test tank. Unless these waves are unduly large, they will have little average effect on the measurement of balance and can be dispensed with.

It is quite obvious that tests of balance for reaching and running can be made also by appropriately altering the angle of the propelling thread in the horizontal plane. Measurements as to the comparative speed of various models is a more complicated subject. This type of testing will not be included in the present discussion.

Among the investigations of balance, which were undertaken, was an interesting departure from conventional methods of designing hulls. This will be described as an example of what can be accomplished in a full size boat by means of inexpensive, preliminary testing of models.

When a straight sided body is tested with, for example, a 70 degree horizontal pull as described, it usually shows a centre of water resistance on the hull which moves forward with an increase in speed. Many hull designers try to so shape their creations as to prevent this movement of the location of the centre of resistance with speed. This is an attempt to produce a boat which remains balanced at various wind strengths and boat speeds without the necessity of a change in sail plan. Line 1, in Fig. 4, is an assumed plot of speed versus position of the centre of resistance (CR) which illustrates this condition.

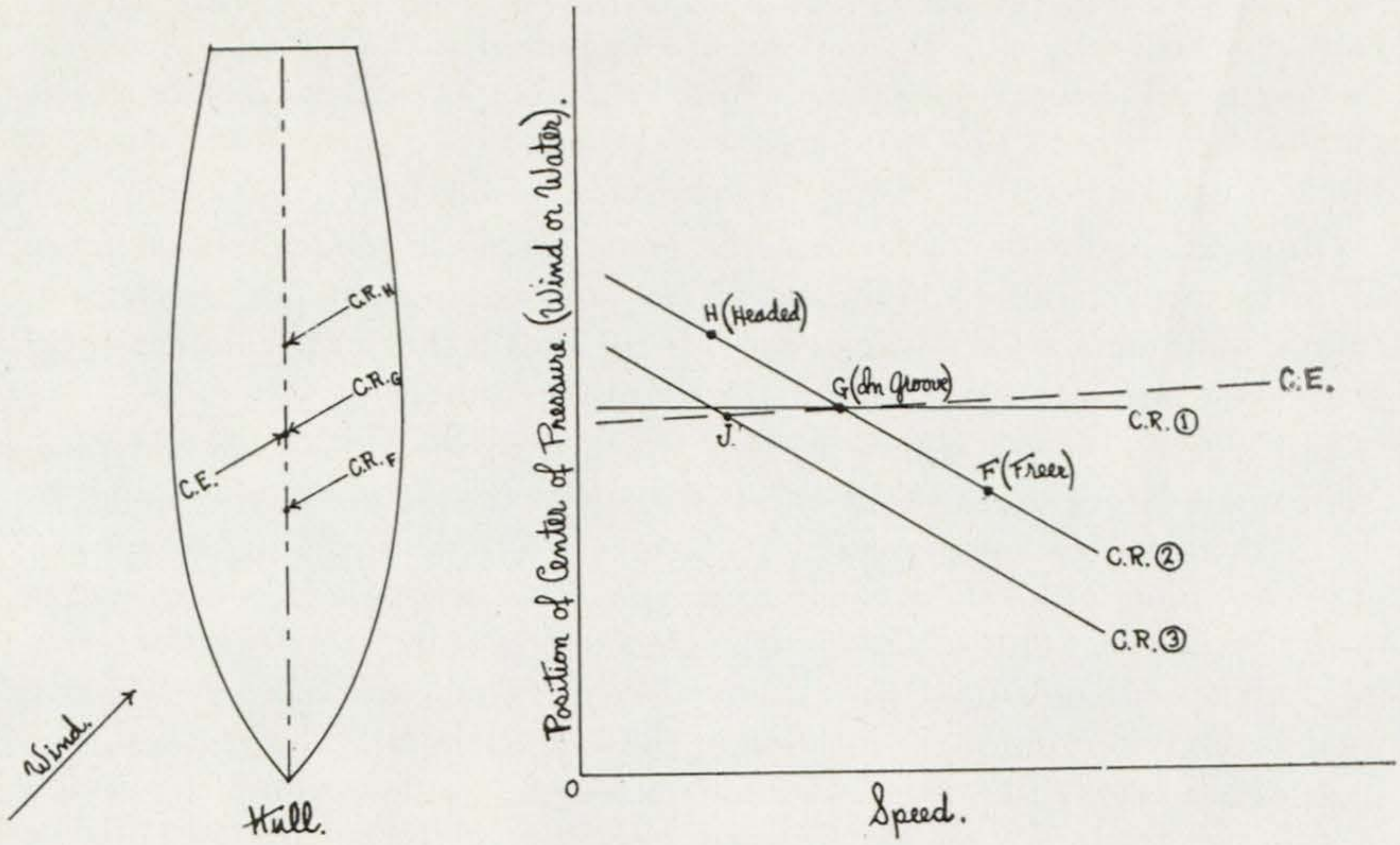


Fig. 4. Speculative Example

Having the plot of CR, one can design a sail plan having a centre of effort (CE) which matches it. The CE position of properly trimmed sails, gently curving to leeward and well strapped down, varies only slowly with wind strength. It might be as represented by the dash line marked CE in Fig. 4. This CE line compared with the line 1 of CR indicates a reasonable degree of balance over a wide range of wind strengths (and therefore speeds) since the positions for all the speeds indicated by these lines nearly coincide.

Speculation arose as to what would happen if conventions were disregarded and a well shaped hull were made in which the centre of resistance moves very rapidly. This CR is represented by the line 2 in Fig. 4. At the speed of point G, perfect balance with the CE is achieved. Now, if the boat's tiller were locked in the centre position and the sails were properly trimmed and cleated, the following astonishing results are predicted from the data for shifts in wind direction.

Suppose the wind heads the craft and as a result it slows down to point H. The CE is now ahead of the CR so the boat would fall off, the speed would increase and it would automatically work itself around to the previous stable heading at G. Similarly, if the wind became freer, the boat would speed up and the CR would move to point F. Here the CE is behind the CR. The boat would head up and again work itself back to point G. The speed at G can be called the "groove" of balance. The boat will automatically chase the wind around when it changes direction thus constantly restoring the same angle of heading to the wind.

Next consider a puffy wind. By the same type of reasoning as the above it may be shown that the boat will head up in the puffs and fall off in the lulls which, of course, is good sailing practice.

It is important to note that the above arguments hold for only one *average* wind strength or one *average* boat speed. Should the wind become permanently light, for example, one would experience a lee helm, as can be proved from the diagram. However, this can be taken care of if we, in some way, shift forward the hull resistance balance point to make the "groove" agree with the average wind strength. This is represented by line 3 and point J in Fig. 4. One also may prove from the diagram that adjustment of the hull balance point will determine the boat's selection of heading in respect to the wind. However, these arguments are restricted to the range of headings where a freer wind results in a faster boat speed. In other words, the discussion relates to beating and close reaching courses.

With the above performance characteristics as objectives, models were developed and tested step by step. These indicated that a broad, flat stern with a gradual straight run would give the desired movement of CR with speed without a sacrifice in hull speed. When heeled, this form approaches the first mentioned straight sided body except for the bow. In addition, an adjustable lateral plane area was desired to place the groove of balance to correspond with the average boat speed and heading.

Many centreboards simultaneously adjust lateral plane size and the balance point location. For experimental reasons, two independent centreboards were preferred. One was to be a large centreboard that altered the lateral plane area, to control side-slip and directional stability but which was so placed as to have little effect on the balance. The second centreboard was for balancing purposes only. Since balancing moments are the product of the force times the length of arm, a small board with a large arm is as effective as a large board with a short arm. For this reason, a small board as far forward as possible was considered desirable.

About the time of these experiments in 1945, there was published a design by Mr. Henry A. Scheel of a keel-centreboard sloop featuring a broad flat stern as previously discussed. A model was made from these lines. It tested to be a fast hull having, to a marked degree, the balance characteristics sought, provided it was modified to include the two centreboards as described. The photograph which constitutes Fig. 2 is that model. The curves which form Fig. 5 are its tank testing data for the various centreboard combinations and CE positions. A great deal of information can be obtained, by those with technical experience, by carefully studying and interpreting these curves. Figs. 6 and 7 show the full size boat being splendidly constructed, with Mr. Scheel's cooperation, at the Delside Yacht Basin at Riverside, New Jersey. These photographs can be compared with that of the model in Fig. 2.

How did the full size boat perform? Well, if you happen to see, off the Jersey shore, a 31-ft auxiliary sloop beating to windward or reaching along without anyone at the helm, it may be *Aqualure*. She can do this for hours in all wind strengths up to the point of reefing, to which many crews can attest. Fig. 8 shows that boat sailing unattended on a close reach. The skipper and crew have nothing to do but to daydream.

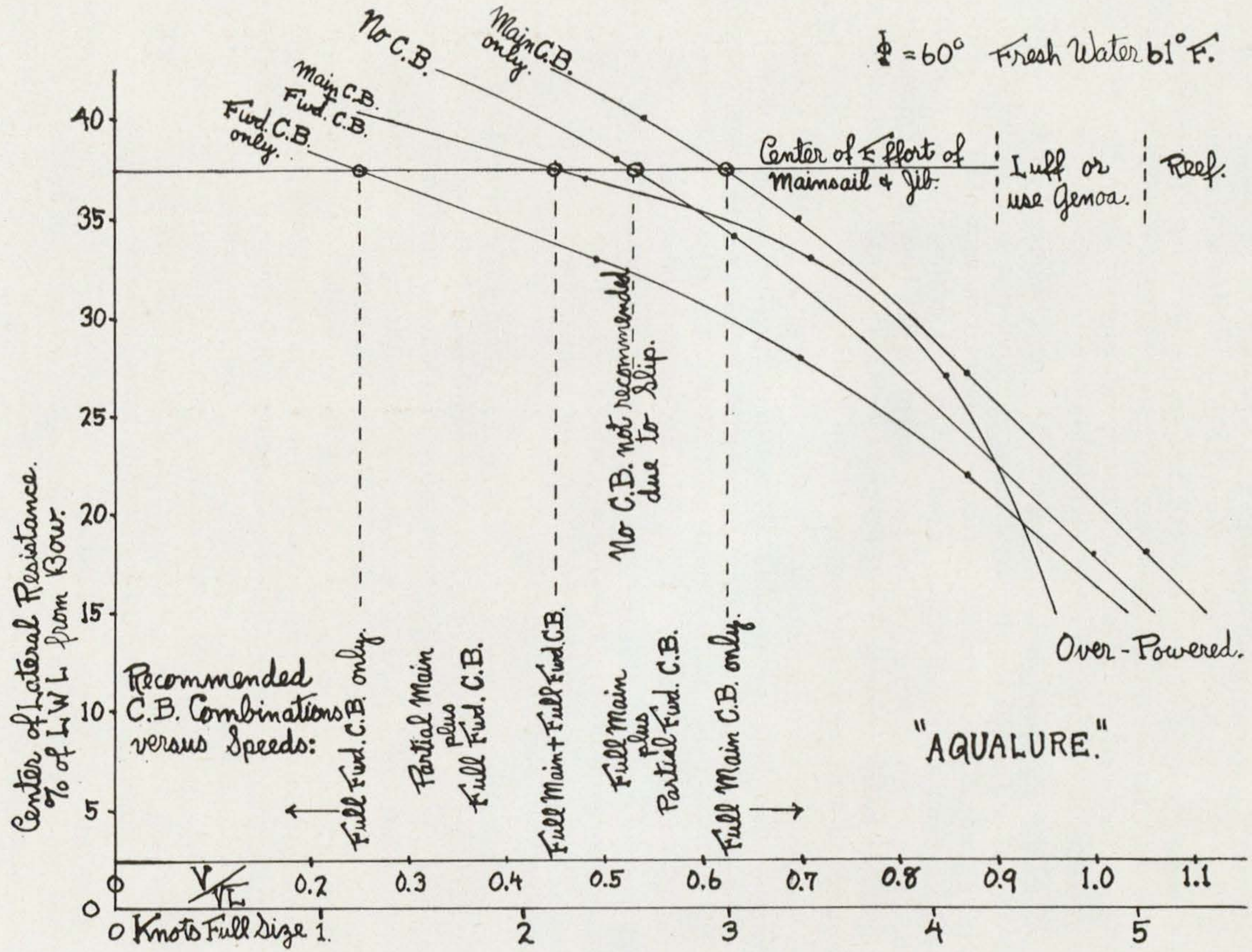


Fig. 5. Tests of Balance to Windward

Fig. 6. Construction of the full size hull

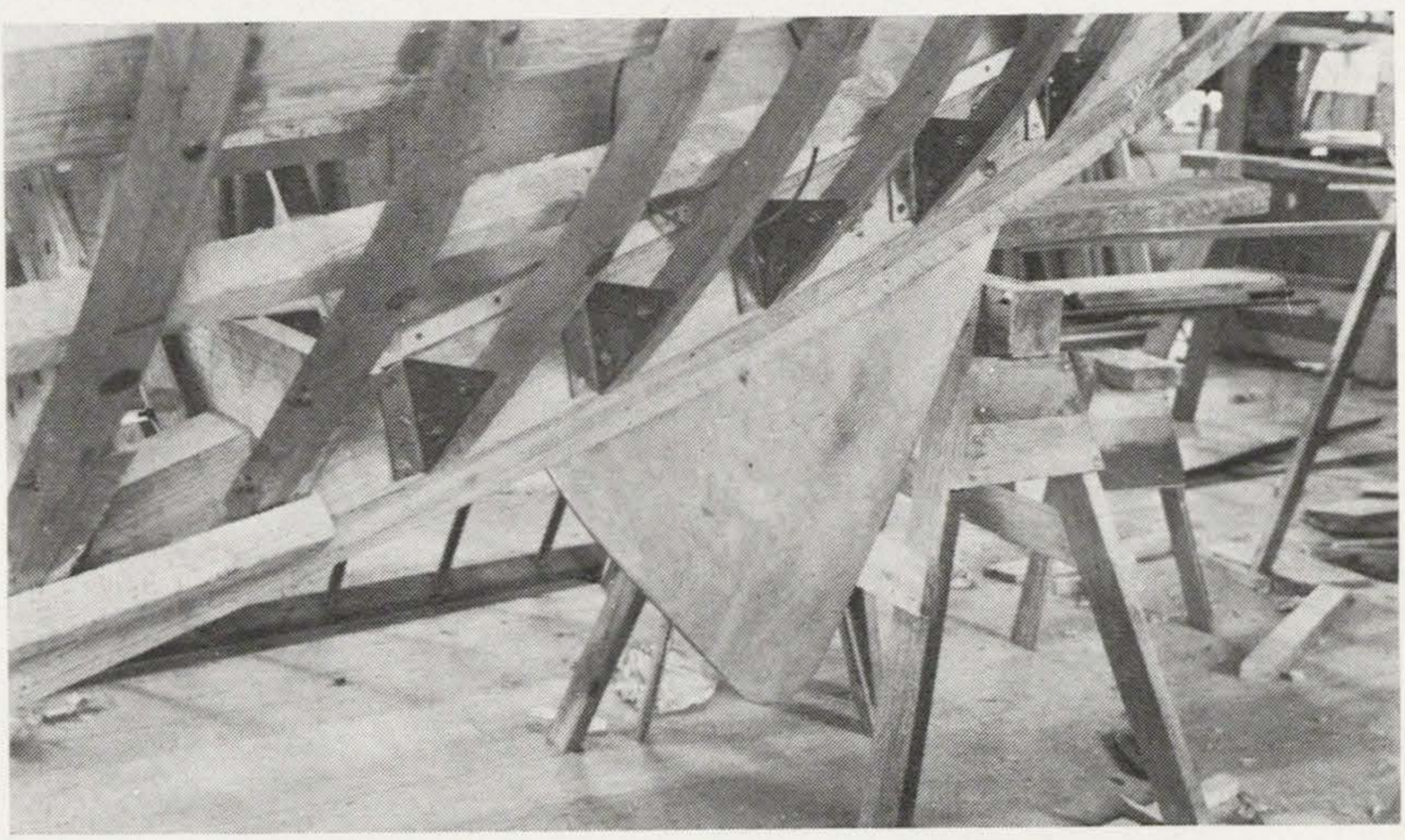


Fig. 7. A view of the balancing centreboard located forward

Fig. 8. Completed boat sailing unattended on a close reach

PART FIVE

SAIL MODELS

CHAPTER XXIV

SAIL MODELS

by Edmond Bruce

August 1973

A. *Sail Testing.* I have long believed that the best way to test sails is at full size and on the craft in which they will be used. In order that the performance characteristics of the hull do not complicate the situation, the concept of a "tethered test", to eliminate all hull effects other than windage, was devised. This method was fully described in Chapter I.

Progressively altering and testing sails at full size can be expensive, time consuming and involve a lot of work. In order to reduce expense and greatly speed up the testing process, experimenting with and measuring model size sails are in order, providing model data can be confirmed later at full size. These activities will be the subject of this chapter.

B. *Wind Tunnels.* Wind tunnel tests of model cloth sails are scarce. There has been encountered a grave difficulty. It is convention for wind tunnel workers to measure a model at the same "Reynolds' Number" as its full size counterpart. (Reynolds' Numbers were discussed in Chapter XIX). Only then are the air flow patterns relatively the same about the full size sail and its model. One must achieve this condition if accurate results are to be predicted from a scaled model without corrections.

Examine the equation for the Reynolds' Number in Chapter XIX. If other terms are constant, the only thing that concerns us here is that the product of the air speed times the test object's linear dimension, in the direction of flow, is kept constant to maintain the same Reynolds' Number. Thus a model cloth sail one-tenth the linear dimensions of the full size sail would have an air velocity 10 *times* that encountered by the full size sail. This would tear the cloth model to shreds. This speed of air flow also would be expensive to achieve.

The above is the principal reason why data on model cloth sails presently are scarce. A few experimenters have attempted to make models of the full size cloth sails out of sheet metal to stand the high velocity of air. This has not worked well since the metal sail does not have the luffing, flexibility and fluttering characteristics of a cloth sail. The resulting measurements are therefore not equivalent, especially hard on the wind where a sheet metal sail does not luff. It is far superior to a cloth sail in this region.

C. *Proposed Wind Tunnel.* The writer believes that he has found a way out of the model sail dilemma. One might treat the sail calculations exactly as was done for the model hull in Chapter XIX.* There the Froude Number

*See quotation from AYRS 45 at the end of the chapter.

v^2/gL simplified to $V/\sqrt{L}$, was employed as a non-dimensional scaling factor. Since this is only accurate for pressure resistances, the frictional resistances would be scaled separately through calculation by means of the Reynolds' Numbers versus the Schoenherr coefficient data. The resulting scaled pressure resistance would then be added to this frictional resistance to get the total resistance.

The advantage of the described approach is the low air speeds that are now permitted for the wind tunnel tests. For example, to keep $V/\sqrt{L}$ constant during scaling, a model sail of 1/9 full size would require an air speed of $\sqrt{1/9}$ or 1/3 that of the full size air speed. Thus a 15-knot wind on the full size sail requires only a 5-knot air flow in the proposed wind tunnel for a nine-to-one scale.

The expanded sketch in Fig. 1 shows the component parts of the air pressure unit for the proposed wind tunnel. We will describe later why pressure rather than "suction" was selected for the air stream movement.

Referring to the sketch, an original 3-blade fan proved to have an irregular air-flow. It was replaced by a 4-bladed AC fan with considerable improvement.

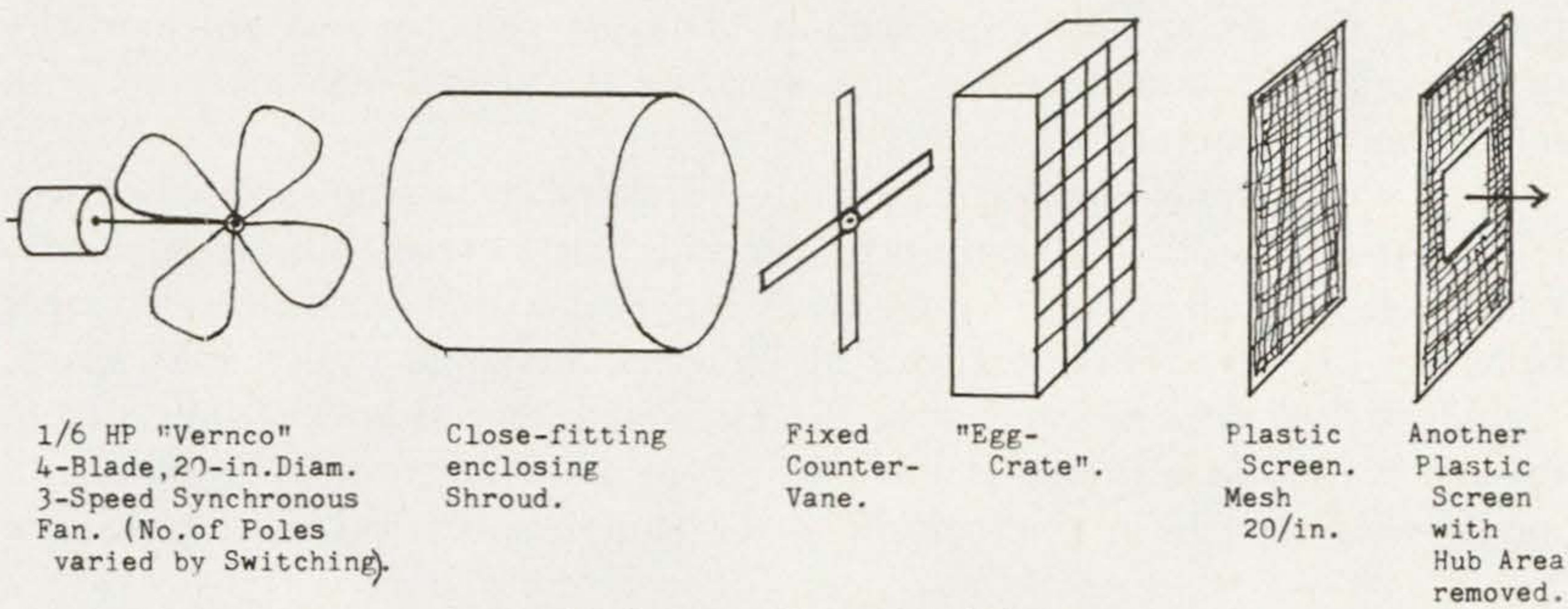


Fig. 1

This latter fan has three synchronous speeds so that the speed of air flow can be relied upon to hold constant. The speed is varied by rearranging the motor's numerous pole pieces by switched reconnections into three different group arrangements.

The fan blades are enclosed in a tight fitting circular shroud to avoid air losses at the tips of the fan blades. At the exit of this shroud was attached a 4-blade, fixed counter-vane which removes the violent swirl of the air stream exiting from the fan. This counter-vane design required cut-and-try experimentation.

A simple device for exploring by hand the turbulence and relative speed of the air stream is a 6-in length of thin Nylon thread tacked to the end of a 3-ft, thin, wooden stick. Air turbulence is revealed by the fluttering of the thread. The relative air speed is shown by the angle of the thread to the horizontal. This device proved invaluable in exploring the steadiness and velocity distribution of cross-sections of the air stream. Several types of accurate anemometers are at hand for absolute measurements.

Referring again to Fig. 1, the "egg-crate" baffle of 1-in square apertures is useful in straightening out the coarse grained turbulence of the air stream. This is followed by a standard 20-per-in mesh, plastic screen to smooth the fine grained air turbulence. Beyond this screen, the air flow tested to be smooth but somewhat deficient in air velocity co-axial with the hub of the fan. This was cured by a second similar plastic screen with a section removed around the axis of the air flow. A steady air flow of uniform velocity across the stream cross-section was thus achieved at somewhat less than half the original, unfiltered fan air velocity.

Next came a pleasant surprise. Exploration of the cross-section of the air stream close to the fan revealed smooth flow with nearly uniform velocity at all points. A sharp boundary was observed between the moving air and the stationary air near the outer edge of the air enclosure. The surprise came when the measurements were moved to a point about 3 ft along the air stream. The same sharp edge was observed for the air flow. There was little divergence in the air stream cross-section. The air velocity was substantially unchanged. The boundary was now shearing air against stationary air with no confining structure.

Most wind tunnels have considerable difficulty correcting for air bounces off of the hard walls of the tunnel. Our wall was soft air. The edge disturbance was so small that one could safely ignore it within reasonable distances from the fan exit. Therefore, our air flow has invisible walls! This sharp, boundary flow does not appear at the fan's air intake side. For this reason, the fan is used as a pressure unit and not as a suction unit as employed in many wind tunnels. A photograph of the complete driving unit appears as Fig. 2.

D. *Test Section.* A circular topped table on casters was used as a testing area for models. It is located a convenient distance beyond the filtered air exit but aligned with its axis. The sketch labelled Fig. 3 shows the arrangement. Fig. 4 is a photograph of the actual equipment.

Note that a rectangular aperture has been cut in the table top. A shallow baking pan fits snugly into this aperture. The pan is half filled with water. Floating on the water is a circular disk on which model sails are mounted as shown in the photograph labelled Fig. 4. Fig. 3 is a sketch of the details of this table and its force measuring means.

If one measures the magnitude of the total resultant sail force and its angle to the air flow direction, we have the answers desired for the conditions of the experiment. The measuring equipment can be kept simple if we measure this single total force and its angle to the wind. From these, the components of drag, in the direction of air flow, and of lift, normal to the flow, can be calculated. Separate instrumentation for each of these two components is not necessary if equilibrium is employed.

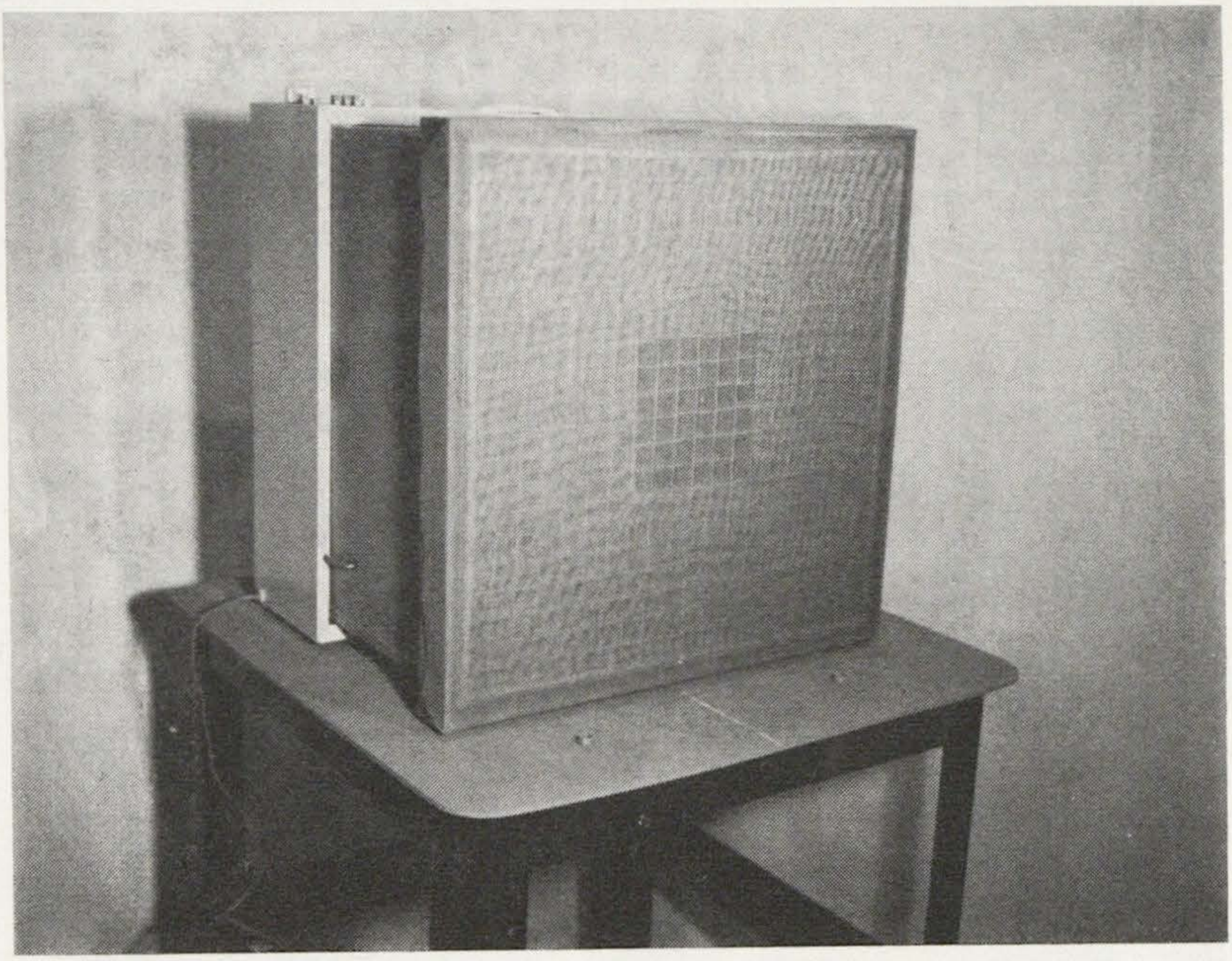


Fig. 2

A = Circular Plywood Table Top. Edge marked with Angles from Centerline to Air Flow.

B = Table Legs.
C = Shallow, Rectangular Baking Pan. Nearly filled with Water.
D = Pulley leading to Balancing Scale below Table Top.
E = Hole for Thread leading to Balance.
F = Circular Float for mounting Sail and Mast. Edge marked with Angles to the Centerline.
G = Rotating Arm for Thread Attachment held by Thumb-Screw.

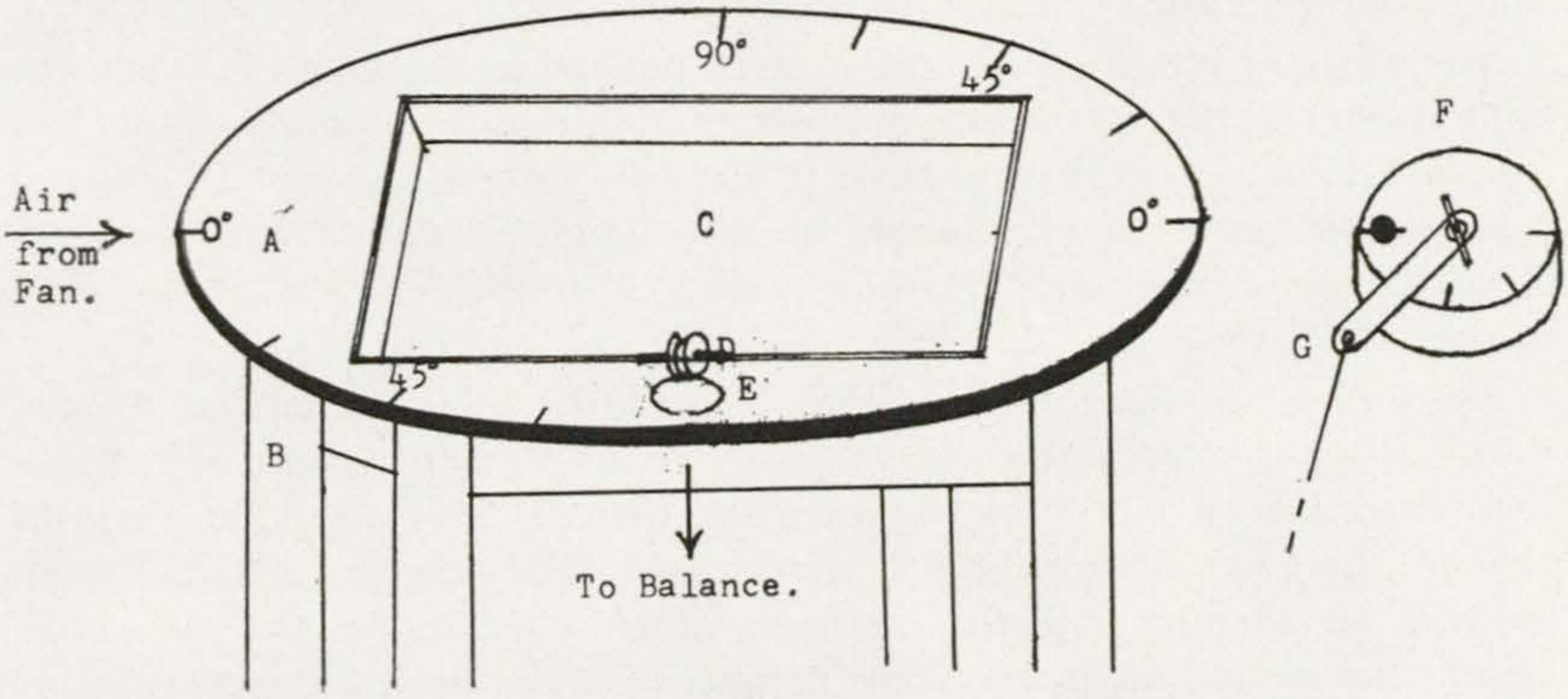


Fig. 3

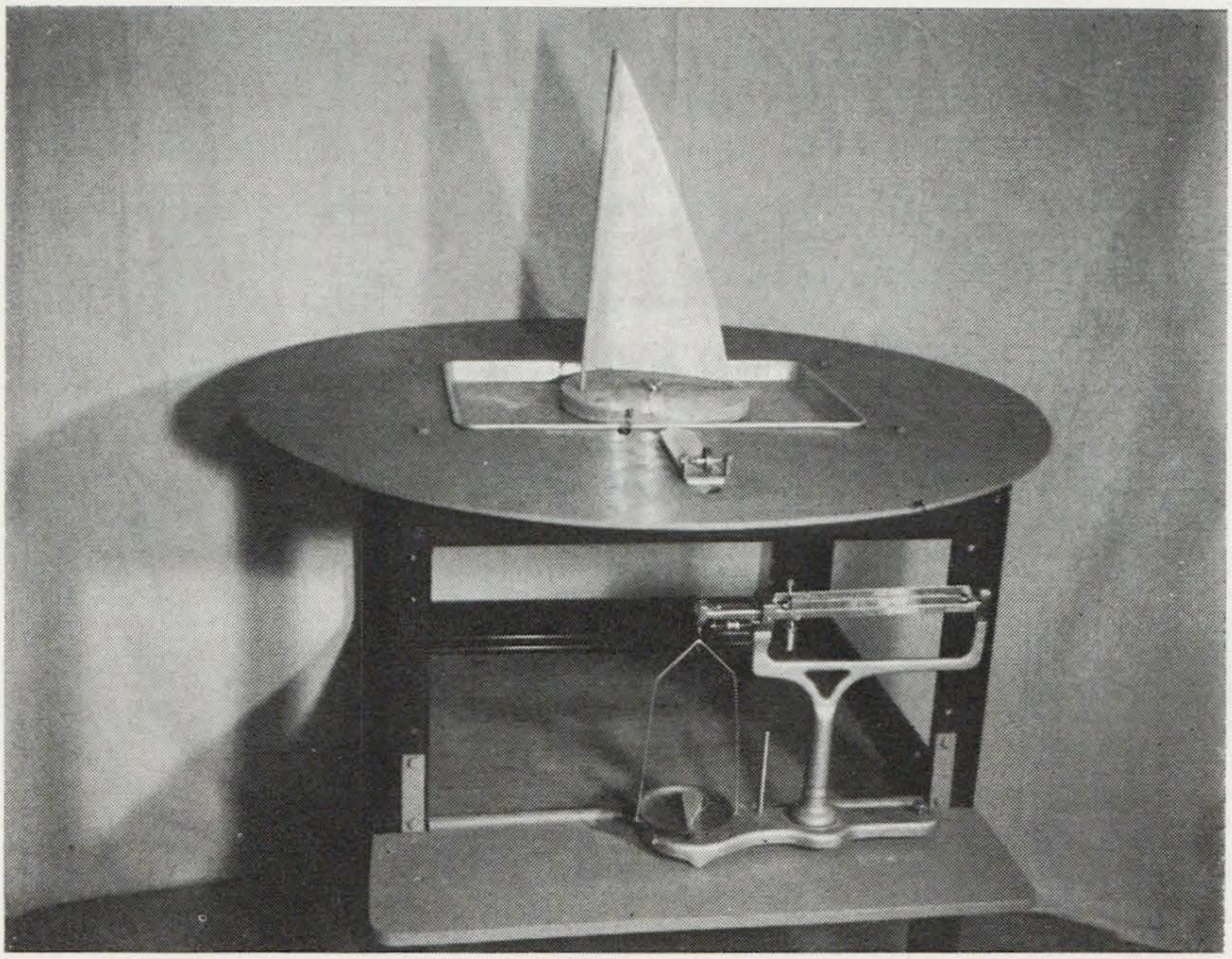


Fig. 4

The pull in the restraining thread is measured by a balance scale. The reduction in the apparent weight of the object tied to the cord and laying in the scale pan is this force. This is equal to the total sail force when equilibrium has been established. The evidence of equilibrium is no horizontal movement by the restrained float. To avoid movement, the cord attachment to the float must be aligned, in a horizontal plane, with the centre of effort of the model sail. Thus, the location of the centre of effort of the sail can be obtained by sighting along the thread. The angle of this thread to the direction of the wind gives us the force angle to the wind for use in a polar plot.

The angle of attack of the sail is often defined as the angle between the sail's boom and the wind. Strictly speaking, this is only the angle of attack of the sail's foot. Where there is twist in the sail, various horizontal chords of curvature at various heights should be considered. To avoid these complications, the above mentioned boom is usually used together with a description of the sail's twist.

Using the equipment shown in Figs. 3 and 4, the angle of attack is adjusted by rotating the table on its casters. To have no float movement, the thread arm labelled G in Fig. 3 is experimentally rotated. This arm is only a convenient method of providing a continuously-variable, thread-attachment position for aligning with the centre of effort of the model sail. At equilibrium, the index line on the float (parallel with the boom) is often parallel with a long side of the pan. If not, its departure angle should be measured and applied to the force angle data. Cut and try manipulations of the adjustments are performed to achieve stability of the float.

E. *Model Sail Measurements.* Studies of sail models, with the equipment described, have barely begun. However, these facilities have been available for several years. There is just too much for one person to do as a hobby. Priority has been given to instrumentation projects for performance measurements. A few confirming model sail tests have been conducted. These will be mentioned briefly in the following. A list of dozens of proposed experiments has been compiled. If we were to hold up this book until these have been completed, years will have passed.

Confidence in our model sail measurements has been achieved from the following tests: We have full size measurements on the sail of an International 12-ft dinghy. These were given in Chapter I, Fig. 10. A model of this sail was made from thin polyethylene plastic sheet. It was placed on a round wooden mast properly scaled except the original mast was pear-shaped in cross-section and was rotating. Sail battens were made from tooth-picks.

As previously discussed, the test method employed involved an overall polar plot of the total force and its direction for each of various boom angles to the wind at a fixed wind speed. Friction was calculated from curves of frictional coefficients versus Reynolds' Numbers. In some cases, the frictional resistances were small enough so that they might be neglected in rough work. The difference was termed, as is usual, the residual resistance. The residual pressure resistance of the model was scaled to full size by the modified Froude Number. The result was compared with the residual resistance of the full size sail.

The general form of these two curves was quite comparable. The force magnitudes varied slightly from each other for corresponding force angles, over a range of 2 to 7 per cent, all favouring the model. An exact match is obviously difficult to achieve since the masts and stays are not alike. Duplicating the sail belly and twist is almost impossible. The real wind is more fluctuating than the wind tunnel wind. In spite of these absolute differences, it is felt that good relative comparisons can be made between various models. All in all, one can be well satisfied with the results achieved. The better model should also be better at full size.

The writer has long been curious about the relative merits of identical soft versus thin rigid sails. To test this, the equal size and shape aluminium sheet sail shown in Fig. 4 was constructed. It proved to be quite superior to the soft plastic sail at low angles of attack and about equal elsewhere.

Since a rigid sail is capable of self-support, the same sail without the round mast was tested. This clearly showed improvement, especially to windward. The lift-drag peak on a polar curve was much broader. Thus winds that vary rapidly in direction can be better tolerated.

To simulate a wing mast, modelling "plasticine" was applied in streamline fashion to the forward third of the sail. Various thicknesses were tried. Nothing proved to be better than the thin rigid sail without a mast. If one uses a thin fibreglass rigid sail strengthened by its own compound curvatures like an egg-shell, how can it be stowed when a craft is at a mooring? A two-way proa design type of hull would permit a sail having a one-way curvature. Incidentally, a one-way curvature on an underwater canted foil is also permitted by a proa.

Part of Letter from Edmond Bruce to John Morwood

Reprinted from page 25, AYRS 45, Oct. 1963

Dear John,

The matter of scaling to full size is of great concern to every wind tunnel worker. Sails have no gravity waves to contend with such as hulls do. However, theoretically scaled flow patterns are similar only when the Reynolds' Numbers are the same. This means that at normal air density the smaller the model, the faster must be the air flow, since $\frac{vL}{\mu/\rho}$ = constant. To avoid this high air speed, modern wind tunnels use variable density test chambers to satisfy the equation. I can not help but wonder if all this complication can not be avoided by separating the pressure and frictional resistances and scaling them separately to full size as is commonly done for hulls.

EDMOND BRUCE

PART SIX

HYDROFOILS FOR ANTI-HEELING, LIFT, AND STEERING

CHAPTER XXV

OPINIONS ABOUT HYDROFOILS

Reprinted from AYRS 51, April 1965
and AYRS 74, Oct. 1970

by Edmond Bruce

A properly oriented hydrofoil produces a large reaction component of force at right angles to its direction of motion, relative to the water. This is in addition to a drag component which opposes the motion.

A hydrofoil's use as a rudder for steering a boat is commonplace. It is used often as a lateral plane area on sailing craft to permit progress to windward. The additional possibilities of using hydrofoils, as lifters of hulls above water and for the stabilization of heeling, have appeared in a number of AYRS writings.

The present writer would like to express his opinion about the limitations in the use of hydrofoils as lifters of sailing hulls. Nevertheless, praise is in order for their success in avoiding heeling at all speeds, without adjustment. This was achieved in the writer's experiments, first with models and finally on a full size sailboat.

Lifters

Lift resulting from buoyancy is free. Lift obtained from hydrofoils must be paid for by induced drag. A precise criterion as to which method is better for a boat, when employed separately, is to compare the lift-drag ratio of the hydrofoils, of adequate area, with the buoyancy-drag ratio of the displacement hull, at a given speed. The latter ratio is synonymous with the weight/resistance ratio of the hull. Buoyancy just equals weight when dynamic lift is not present. This ratio is the reciprocal of the resistance/weight ratio commonly used in performance curves plotted against, say $V_B/\sqrt{L}$ or $V_B/W^{1/6}$.

Referring to Fig. 1, there are graphed, as examples, the weight/resistance ratio versus $V_B/\sqrt{L}$ for Models No. 5 and No. 12 of the writer's article in Chapter XXII. The speed in knots is indicated for an assumed water-line length of 25 ft. Also appearing are dotted lines which are independent of speed, one of which represents Lift/Drag = 10. This is about as well as deeply immersed, lifting hydrofoils have done in the presence of strut drag, rudder drag and other limitations. The dotted line indicating Lift/Drag = 6 represents an exceptionally good planing hull rather than foils.

It is seen that, up to "hull speed" of $V_B/\sqrt{L} = 1{\cdot}34$, the lifters are completely out-classed by buoyancy. Merely lifting a hull out of water does not mean success. It takes about double hull speed to make the lifters show some profit over these particular hulls. Sailing craft, in variable winds, must

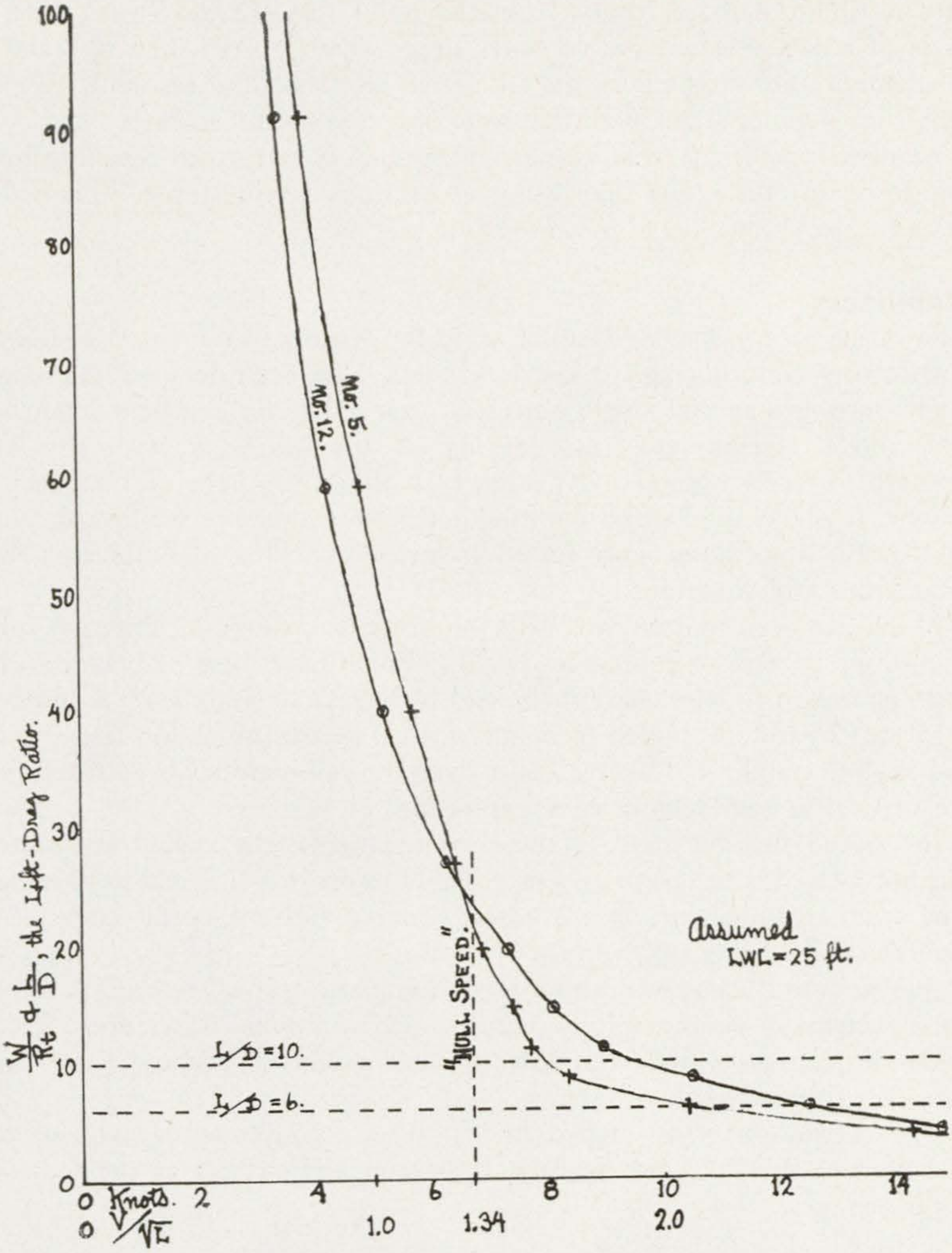


Fig. 1.

efficiently cover a wide range of speeds to be satisfactory. Racing motorboats are designed for top speed. The verdict or a compromise is up to the reader.

At this point, I would like to promote thought on some different approaches to lift. Since the wind is the source of all sailing power, it appears that hull lift could be accomplished more efficiently by properly angling the sails somewhat horizontally. An angle of attack would be provided which gives a lifting component to the sail force as well as driving and side-force components. This type of lift is familiar to ice-skate sailors. Thus sail lift would be employed rather than the indirect dynamic lift of the water. This water lift, with its induced drag, results from the hull's forward movement with an angle of attack. Surface gravity-wave drag, which can be high in water, is substantially non-existent in the air. Therefore less drag results if the hull avoids an angle of attack with the water but uses sail lift instead.

Another type of lift, that appears intriguing, is to convert a sailing hull's side-force into lift rather than using its precious driving force. This will be described in greater detail in a following section.

Stabilizers

Now let us turn to heeling stabilizers. Many visitors to the writer's laminar-flow towing tank, during the last four years, have seen demonstrations of a model having a special single outrigger attached to an excellent main hull. This model is completely non-heeling on any course or with any wind strength. This is obtained dynamically without the help of buoyancy or weight. It is also the highest pointing and fastest model to windward, under comparable conditions, ever tested in my tank. This includes numerous catamarans and trimarans.

Much has been written in AYRS publications concerning different forms of righting devices to counteract heeling. Some have used buoyancy to leeward or weight to windward at the end of an arm of some sort. A few have suggested hydrofoils angled from the vertical as a combination lateral plane and heeling stabilizer. In some cases, even the sail plan has been tilted from the vertical to help achieve counter-heeling.

In re-studying the merit of these arrangements, the angled sail method was not viewed with favour except possibly to provide lift instead of reefing. The driving component, on a windward course, falls off as the *square* of the cosine of the angle of tilt from the vertical.

Buoyancy at the end of a leeward extending arm seemed inferior to out-of-water weight to windward. The latter avoids additional water drag. This is probably the reason why the Micronesians preferred keeping their single outrigger to windward.

The suggestion of an angled hydrofoil as a combination stabilizer and lateral plane was most interesting. It became the subject of the following experiments:

Single Outrigger

A sailing combination, employing a single outrigger, is shown going to windward in Fig. 2. A cross-section is drawn which is in a vertical plane containing the sail's centre of effort, CE. This outrigger configuration has been chosen among several possibilities because of its simplicity. Also, the need for an end-for-end reversal of hull motion when tacking, such as is associated with some single outriggers, has vanished.

Let us examine the magnitude, direction and location of the forces involved. A sail force vector, in a horizontal plane, is always countered by an equal and opposite horizontal component of the total water force, after acceleration ceases. Among the vertical components, the weight force vector is always downward, It is opposed exactly by the vector sum of the forces

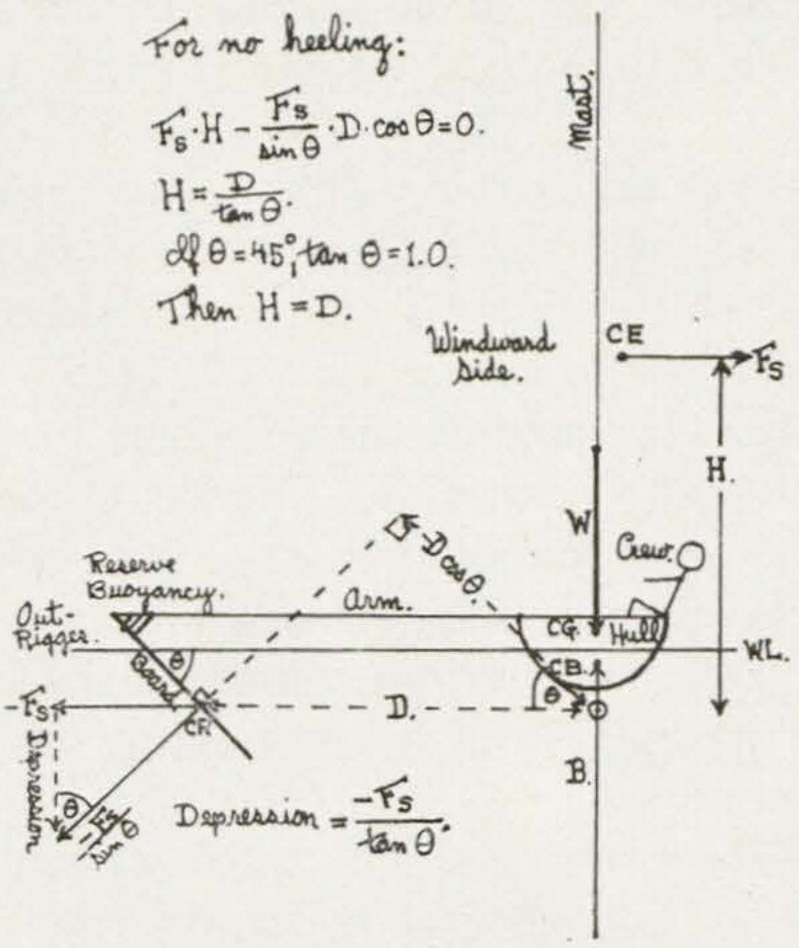


Fig. 2a. Port tack.

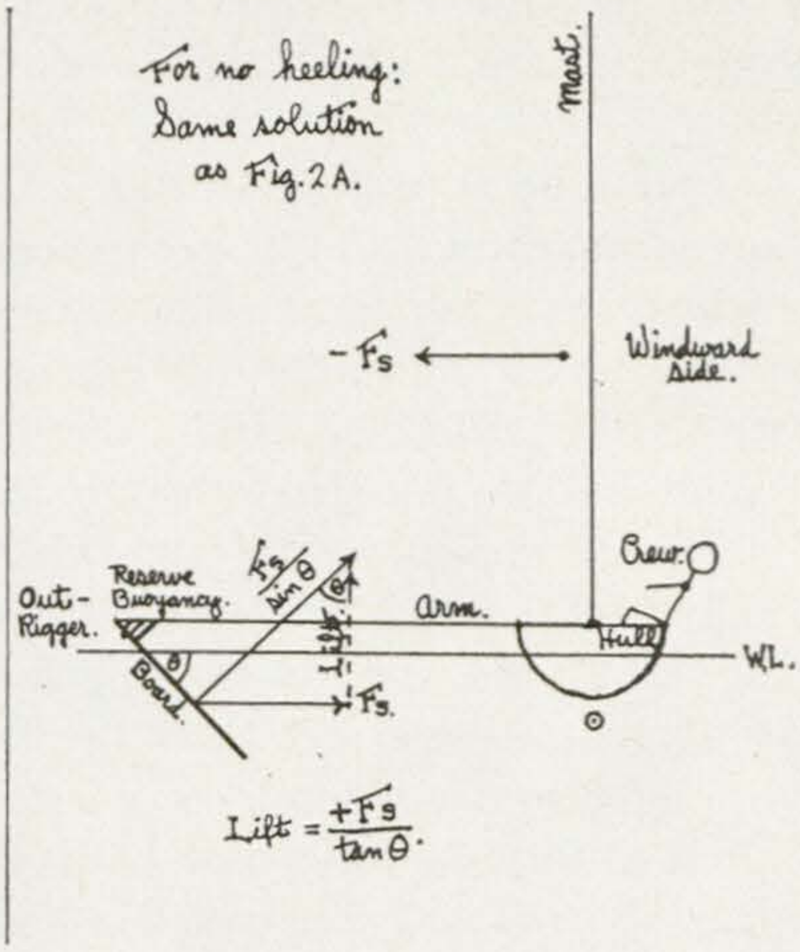


Fig. 2b. Starboard tack.

of buoyancy and of dynamic lift (+) or depression (–). If these forces, projected on the common sectional plane, are so positioned that the lateral heeling moments, including the sail, are just countered by the lateral righting moments of the remaining forces, no heeling would occur.

Referring again to Fig. 2, one is permitted to sum up the moments about any point whatever, within the projection plane, since the result will be the same. For simplicity, point 0 is used. It is the depth of the centre-of-resistance, CR, of the thin, flat board, assumed to dominate, but under the centre-of-gravity, CG, of the complete hull. The moments of both weight and buoyancy disappear, for this case, since their moment arms have no length.

Note that the crew counter-balances the outrigger weight. This keeps its flotation out of water to avoid water drag during steady progress. This flotation is used for static stability when at rest. It also makes a smaller contribution toward stability during acceleration. However, since the sideways component of steady state motion is so rapidly accomplished, no more than a slight lateral bobble would occur even if the flotation were not in the water during this period.

The board may move in and out of the water by wave action, thus changing its immersed area over quite a range, without changing the righting force or its moment. As the board comes out of water, its side-slip increases. This is equivalent to a larger angle of attack in respect to the resulting direction of travel. This larger angle of attack compensates for the reduced area. The righting moment is substantially unchanged up to the point of "stalling". This does not occur until the angle of attack becomes greater than about 15°. The original angle of attack should be only about 4° to produce the largest lift-drag ratio of which the board is capable.

In the full size experiments, over half of the board area could come out of the water and still provide good compensation for the heeling moment of the sail. Beyond this point, the crew weight should be shifted toward the outrigger. There is ample time to do this as is the case when any small boat heels.

The solution appearing on Fig. 2A shows the requirements for no heeling at any strength of wind or boat speed. If the board's plane angle from the vertical is 45°, the horizontal distance of the board's centre-of-resistance from the hull's centreline just equals the height of the sail's CE above the board's CR. At this separation, the waves generated by the outrigger and by the main hull do not strike the opposite hull. If either did, this would result in increased resistance overall. With an arm longer than this, one would actually heel to windward, rather than to leeward, in a puff of wind.

Fig. 2B shows that, on the opposite tack, non-heeling continues to exist. This single outrigger need not reverse its hull travel, when tacking, as has discouraged so many admirers of such craft.

There is an odd difference between the two tacks. The whole system is slightly dynamically depressed when the outrigger is to windward. The system is slightly lifted when the outrigger is to leeward. In practice, little difference is noted between tacks. The board is a bit more efficient when its pressure side is uppermost. This largely compensates for an increased apparent weight on this tack. Water does not tend to go around the lower tip of the board from the upper high pressure side to the other side at lower pressure. It is much like dirt in a shovel. This was observed on the model with powdered rosin suspended in the water.

Note that the above mentioned lift or depression is generated from the sail's non-productive side-force. The previous criticism of lift from planing hulls and foils was based on its dissipation of the sail driving-force component. This side-force concept deserves more study by all of us.

A small difference in balance between tacks appears in Fig. 3. This can be

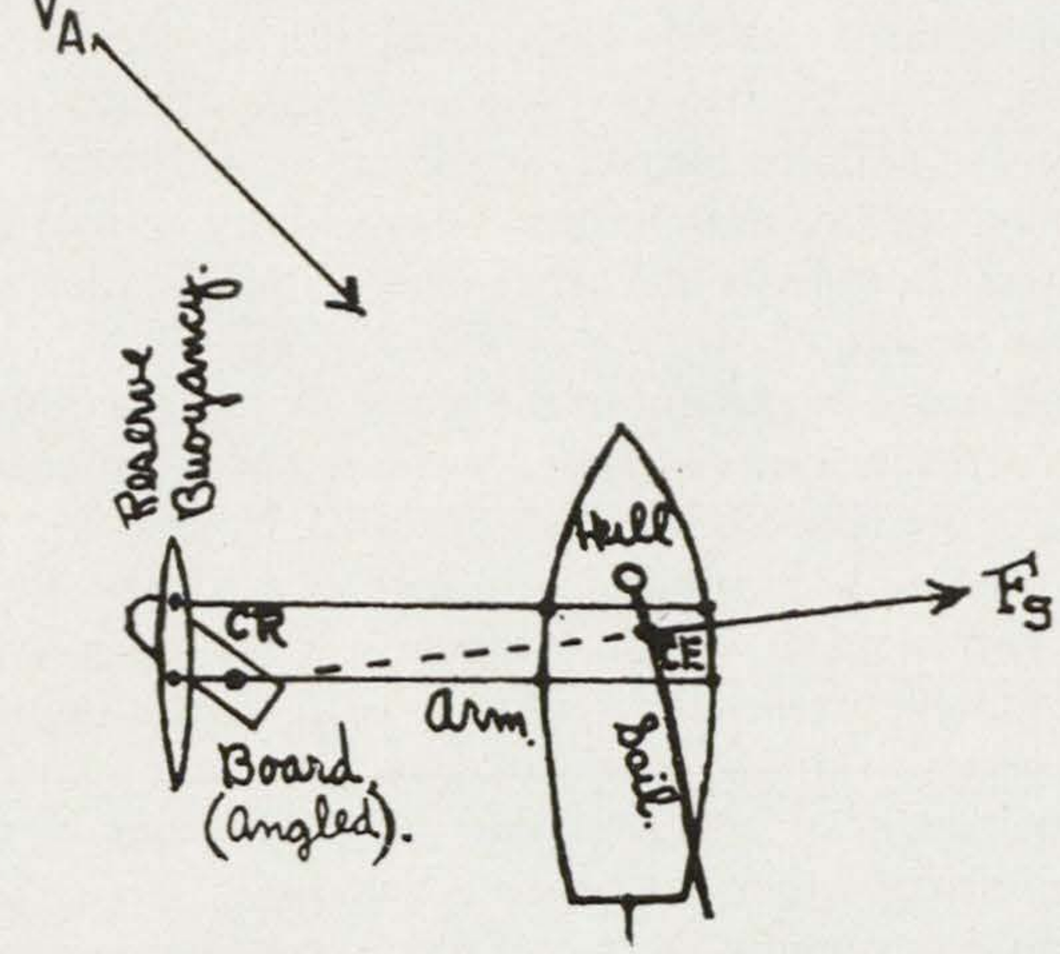


Fig. 3a. Port tack. Board adjustment for balance.

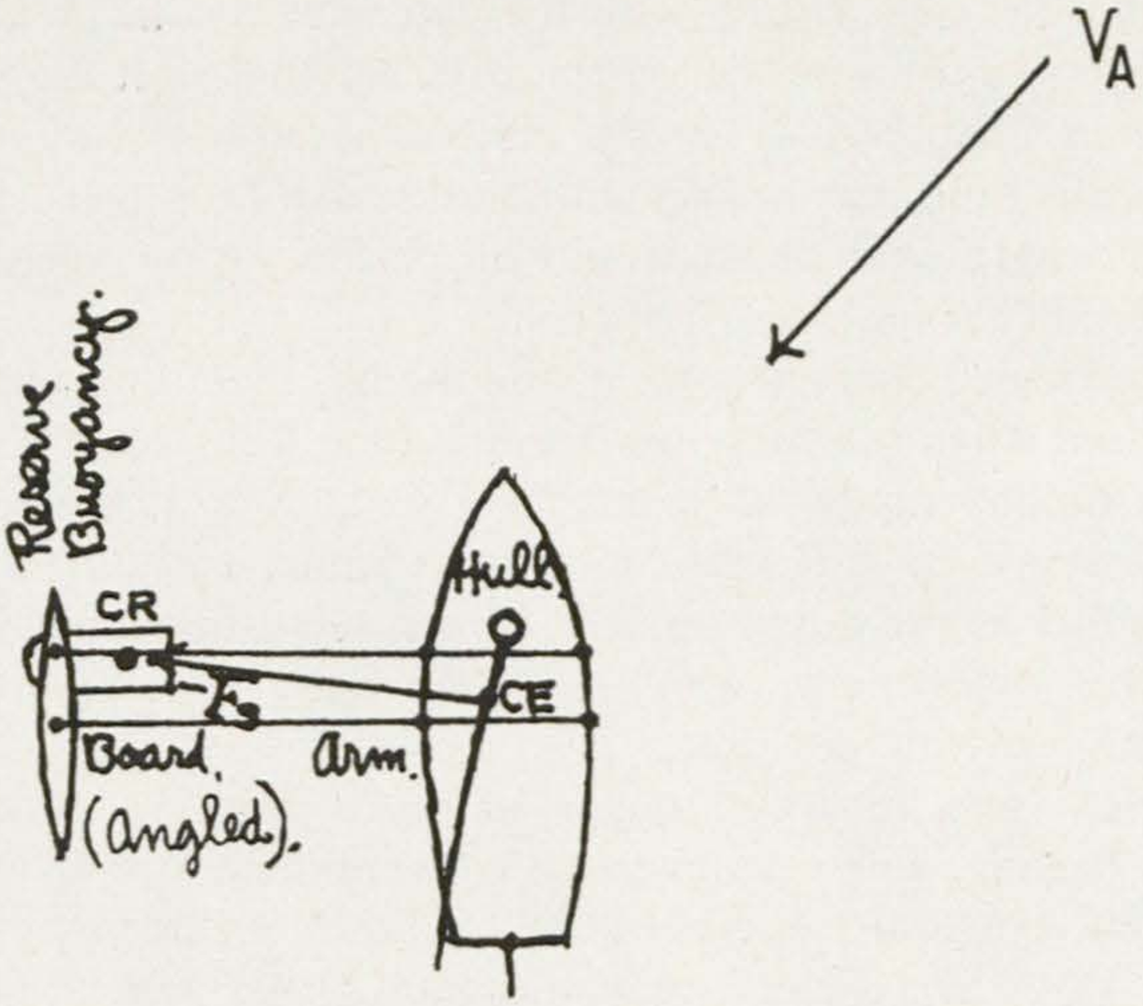


Fig. 3b. Starboard tack. Board adjustment for balance.

rebalanced by slightly altering the position adjustment of the pivoted board, as shown, by an opposing pair of control lines. The board's centre-of-resistance should be swung a little more forward when the outrigger is on the opposite side of the boat from the wind. Snappy tiller action is advantageous during tacking as is true for any light boat.

Surface piercing foils often have two types of difficulties. One is "cavitation" and the other is air "ventilation". A large area board is used to reduce the pressure per unit area to avoid cavitation. Air ventilation down the low pressure surface, if present, often can be blocked by a "fence". This may be obtained through slightly immersing the outrigger's buoyancy form by a shift in the crew weight toward the outrigger. Neither of these two potential difficulties has appeared either in the model or at full size. Without the reserve buoyancy in the water, the board will totally ignore the presence of waves.

The entire outrigger should be as light as size and ruggedness dictate. While not employed in these tests, an inflated vinylised nylon shape might be excellent as the outrigger's light-weight reserve flotation. As to size, I believe that the boyancy form should be small enough to allow large waves to gently break over it rather than absorbing the shocks of riding the wave profiles. The float, used in the present experiment, was larger than appropriate for racing. A cruiser, insisting on complete safety off-shore, may desire a large outrigger. Its totally-immersed effective buoyancy might be made equal to its out-of-water weight to provide the same degree of stability on a lateral roll toward either side when dynamic stabilization is not available.

For practical reasons of lateral spread, John Stoddart has kindly suggested that users may want to make the outrigger's arm a hinged, folding pantograph This would be useful in entering slips or when auxiliary power is employed in narrow channels.

I will not burden this writing with the extensive details of tank test data. Model work led to a full size trial on the International 12 ft dinghy described by the writer in Chapter I. This was chosen because of the extensive data that exists on this hull. Any sailing craft could have been used. One having a high value of length over beam would be preferable for speed since main hull lateral stability is no longer important.

Every performance characteristic of the model, including increased speed to windward and when reaching, was confirmed at full size. Fig. 4 is a photograph of the dinghy model with outrigger. Fig. 5 is a photo, including a smile of success, of its full size counterpart under sail and using a 13 lb aluminium ladder as the outrigger arm. The reserve-buoyancy form and the board, for this experiment, were made of water-proof plywood. Hull's regular centreboard was not used.

The principal gain in speed seems to result from increased sail drive through non-heeling. For example, if a conventional, strong-wind, leeward heel of, say, 20° is avoided, the sail drive would be greater by approximately 13 per cent. A 30° heel avoidance would gain 33 per cent. These gains are far larger than possible reductions in hull resistance through being sailed upright. Avoiding wave-interference between main hull and outrigger is worth something in speed. Also, a minimum of increased weight and wetted surface is tolerated when only a single small outrigger is used. All of these factors give the structure advantages over catamarans and trimarans.

My hesitance in showing the tank curves, of the original boat versus this hull and sail with the added non-heeling outrigger, is that, for best windward sailing, the original boat had a centreboard which tested to be too small. This was rectified in the outrigger with a startling improvement. For this reason, a comparison would appear to be excessively optimistic.

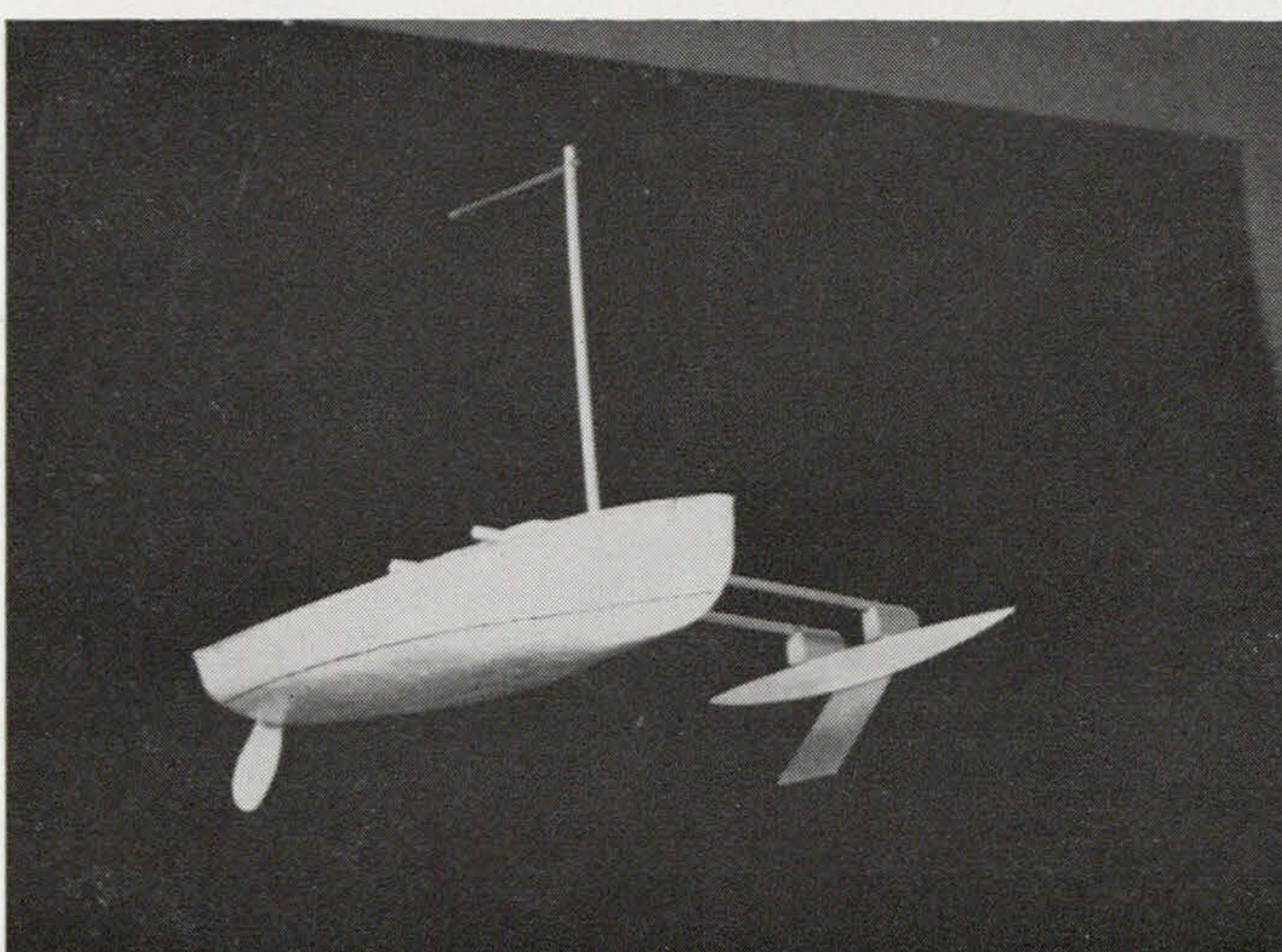


Fig. 4.

Fig. 5. Edmond Bruce sailing with a single canted foil.

I must mention the only criticism I have heard about this outrigger project. A teenager remarked, "What are you trying to do, ruin sailing? I like to heel".

Further Experiments

Since sails with curvature are better than flat sails, the same should be true of boards. This has been the experience in two of my other tank projects, one of which is now being observed in full size tests. As a result of model work, a study at full size of curved, thin-plate, angled boards on outriggers is planned for the future.

Two boards, each shaped for a particular tack, will be used one at a time. These will be located at each end of a self-sliding, lateral arm. Each will have its own separate reserve buoyancy. This is because self-buoyant, *thick* foils, in water (also in air), are known to "stall" too easily at sail-boat speeds, thus ruining their lift-drag ratios.

The above thick foil "stalling" or "separation" is revealed in low-speed wind tunnels. In high-speed wind tunnels or in aeronautics, this does not occur so easily. A model airplane with the thick wings of its full size counterpart probably will not fly. Thin wings must be substituted. Nature provides insects and the smaller birds with thin wings. Fish have thin fins except the largest.

With the above automatic sliding outriggers, a high degree of directional stability will exist since the board in use will be extended with its resistance far to windward on either tack. The sail force will lead away from the centre of water resistance, not towards it.

Even if AYRS members like to heel, as did the mentioned teenager, the improved speed to windward and especially when close-reaching, for the same sail area, should prove interesting. With the heeling stability that has been achieved, one wonders what is the upper area limit for an enlarged sail plan.

ADDITIONAL NOTES

Part of a Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 61, July 1967

Dear John,

Your discussion of stability did not include the possibility of the non-heeling foil of the first part of this chapter. To me, this has been one of the most exciting developments in a life-time of sailing. I do not know why it has not caught on. However, it should not be ruined by a poor sail area to weight ratio. The principal merit of the scheme is the large sail area it permits with stability for a given weight.

This past summer, I equipped an 80-lb canoe, 18 ft long, with a single non-heeling foil, on an outrigger, and 150 sq ft of sail. The resulting total weight of 287 lbs, including a one-man crew, gave $\frac{\sqrt{As}}{\sqrt[3]{W}} = 1{\cdot}85$. This is a very high non-dimensional sail-weight ratio. This craft not only pointed high but had the greatest acceleration, without heel, in strong puffs of wind, that I have ever experienced. It scared me! This is a boat for a younger man than I am.

I would strongly recommend an ample rudder so as not to have a stalled rudder from over-powering by the sail. This is especially true in running where one cannot slow down because one cannot luff. Also, the forward half of the canoe should have a canvas cover to prevent swamping in waves.

Sincerely,

EDMOND BRUCE

Letter of May 7, 1967, from Edmond Bruce to John Morwood

Reprinted from AYRS 62, Oct. 1967

Dear John,

My correspondence on the non-heeling foils, described in the first part of this chapter, has increased greatly. Some of my answers to questions have been as follows:

My example of a non-heeling single outrigger was chosen for its simplicity. Of course it can be used double as a trimaran, if spread is no problem. The use of two foils does not economise on the arm length of each. The reaction to the sails' side force is then divided by two, if both foils are used simultaneously. Varying the foil area does not affect the optimum arm length. The rule-of-thumb that a line normal to the foil centre must pass through the sail CE is incorrect. The sail can be moved laterally anywhere without affecting its heeling moment. The criterion is to have the dynamic moments equal zero independent of the static moments of buoyancy or weight.

A trimaran has some marked advantages. By employing only the leeward canted foil on each tack, a speed-increasing overall lift is provided by the usually wasted side force without dissipating any of the precious driving force. When winds get dangerously strong, using both foils neutralises all lift or depression. If great directional stability is desired for self-steering schemes, only the windward foil should be used. Depression of the hull then results.

Catamarans having a rule-limited beam usually cannot achieve complete non-heeling. However, even partial neutralisation of heeling can easily double their heeling stability in strong winds.

EDMOND BRUCE

Letter of September 19, 1969, from Edmond Bruce to Dr. Clayton Feldman

Reprinted from AYRS 76, April 1971

Dear Dr. Clayton Feldman,

This is in reply to your letter of September 9. For the first year and a half after AYRS No. 51 was published, I received no correspondence whatever regarding my article on the critical non-heeling dimensions for the arm of canted foils. Since then, many letters have come in, mostly during 1969. You were a pioneer with your article in AYRS No. 62.

In writing for AYRS, I have tried to keep the mathematics at a minimum, otherwise one will lose many readers. This is unfortunate as simple algebra could keep experimenters, attempting heeling stabilization, out of trouble. I do not believe that those who have sailed a boat truly having the critical dimensions would be willing to accept any compromise, as the non-heeling performance drops so very fast, as I will now demonstrate theoretically.

Assume any two parallel hulls in the water (a tri may have one float lifted) called No. 1 and No. 2 with a sail centre of effort of height H. There is a connecting arm of length D to a single 45-degree foil on hull No. 1, as measured from the centreline of hull No. 2. The mast can be located laterally anywhere. Its only performance effect is its contribution to the weight distribution.

First, with the board to windward, $M_2 = 0$ when,

$$F_S \times H + B_1 \times D - F_S \times D - W_1 \times D = 0$$

where W_1 and W_2 are the respective effective weights and B_1 and B_2 are the respective active buoyancies of the two hulls.

Then, with the board to windward, $B_1 = W_1 + F_S (1 — H/D)$.

Assume that the safe limit for heeling is when this windward hull No. 1 barely leaves the water, then, $B_1 = 0$. The limiting lateral sail force F_S max., for this case is,

$$F_S \text{ max.} = \frac{-W_1}{1 - H/D} \text{ when board is to windward.}$$

Second, with the board to leeward, the safe limit is when the hull No. 1 is just barely pushed under the surface, thus B_1 is at its maximum. For this case, similar to the previous procedure, the general equation becomes,

$$B_1 = W_1 - F_S (1 - H/D).$$

Thus, its critical value is,

$$F_S \text{ max.} = - \frac{B_1 \text{ max} - W_1}{1 - H/D} \text{ when board is to leeward.}$$

Plots of the maximum safe lateral sail forces for these two cases are drawn in the attached curve which you requested.

Two further comments are important.

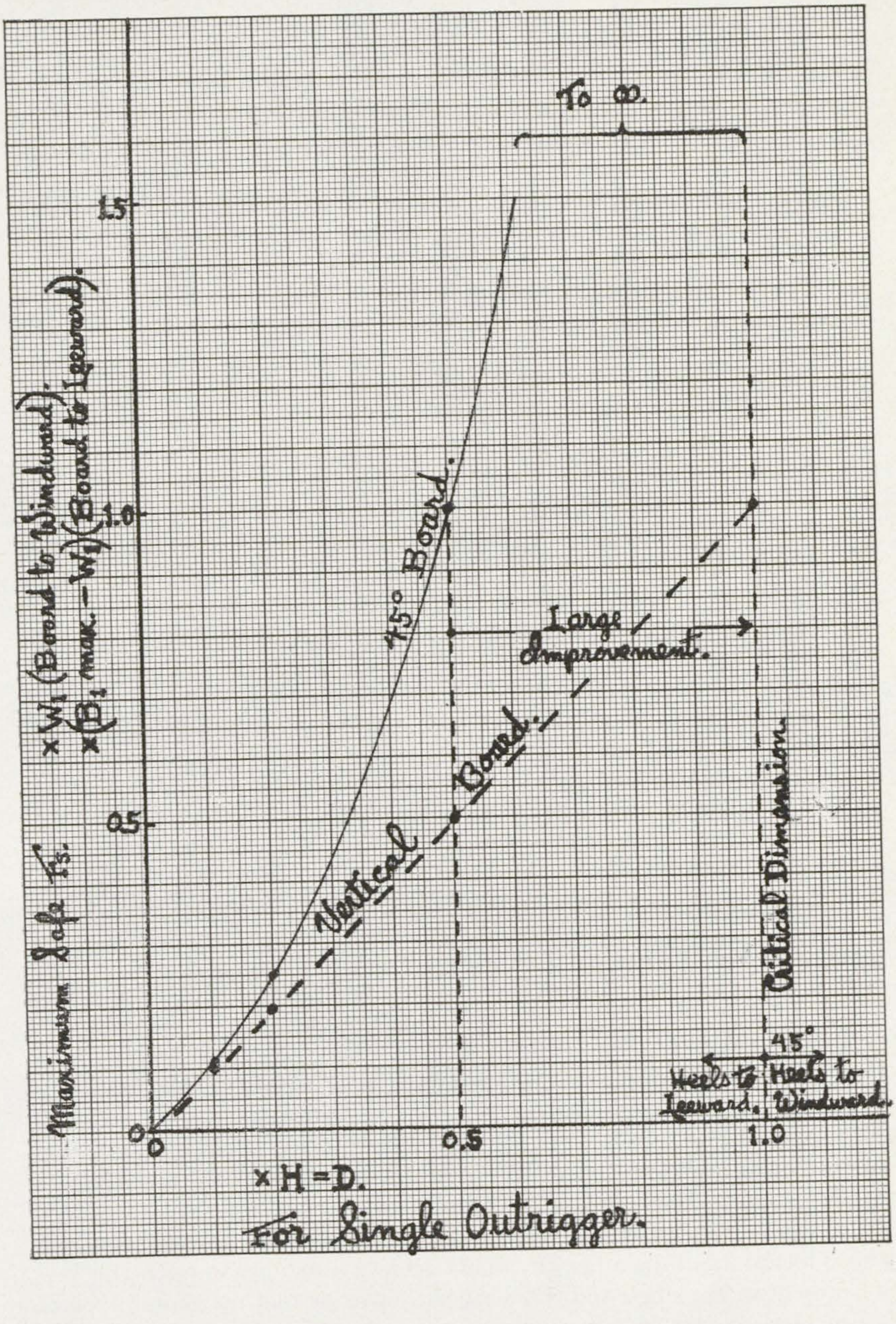
1 If the above type of analysis is extended to cover various weight distributions between the two hulls, this equation results:

$$\text{Critical D} = \frac{H}{1 - r}$$

where r is the ratio of weight of the foil's hull to the total weight of the craft with its crew. Thus D is smallest when r is the smallest. Therefore, the heavier the hull containing the foil becomes, the longer the critical arm length must be.

2 The lateral resistance in the water must be dominated by that of the board, not the hulls. The higher the lateral resistance of the hulls, the longer the arm D must be to compensate.

Considering all of these facts, the smallest span is achieved by a single outrigger craft having the lightest possible outrigger-board combination compatible with proper static stability considerations. This structure also has the least overall weight, the least wetted surface and the least overall drag. Its critical span is actually less than a corresponding conventional trimaran. It has about half the *critical* span of a canted board catamaran because of the favourable concentration of nearly all of its weight into a comfortable main hull. I currently maintain a demonstration boat of this


To ∞.
1.5
1.0
0.5
0
0
0.5
1.0
Maximum Safe Fs. × W1 (Board to Windward). ×(B1 max. − W1)(Board to Leeward).
45° Board.
Vertical Board.
Large Improvement.
Critical Dimension
45°
Heels to Leeward.
Heels to Windward.
× H = D.
For Single Outrigger.

type, designed for solo sailing, which has thrilled several inquiring sailors. It is beautifully balanced on either tack and it comes about equally well on both tacks. In strong winds, it has no competition by any boat, anywhere near its size.

Some apparent failures that have come to my attention have been by people who insisted on compromises. There have been cases which were due to extremely crude attempts at tuning based on bad "guesswork". One must tune the board in and out for non-heeling, then fore and aft so that the craft goes about equally well on either tack.

I always recommend first towing a 15-in model by hand in a swimming pool. Use a stub mast as described in the first part of this chapter. Adjust the board and overall tuning on both tacks. The tow cord should be horizontal and as nearly abeam as the performance will permit. Slide the cord's CE attachment point along the horizontal fore and aft rod until a straight course is achieved. When satisfied, transfer the model relative dimensions to the full size boat.

The model's CE balance point is bound to be slightly different on the two tacks, if the rudder is fixed. This can be compensated by moving the simulated crew weight fore and aft if the boat is small. If this is not practical, as in a larger boat, the rudder can accomplish this or a variable fore and aft position of the board can be used as discussed in the first part of this chapter.

The best adjustable board that I have seen was a circular board with an off-centre pivot. By simple rotation, nearly half of the board could be placed under water either somewhat forward or aft for windward work on each tack or out of water for running.

My small demonstration craft has a fixed board. It is shaped like a quarter circle segment with the curve forward. It has one-tenth the area of the sail. For running, one sits out opposite the board to lift it out of the water. This is not practical on larger boats therefore their boards should be adjustable.

Good luck and thanks for your articles in AYRS,

Sincerely,

EDMOND BRUCE

Letter from Edmond Bruce to John Morwood

Reprinted from AYRS 77, July 1971

Dear John,

If, in the foil application you mention (*Ed.*—A double foiler, heeling at 10°), there is any degree of surface wave, at a working angle of 35°, it would pay him to change to 45° when sailing, thus 55° when upright. In my own early experiments, I developed quite a wave popping out of the water surface for 35° at speed. Harry Morss had similar experiences.

For anyone interested, dividing the usual leeward foil into two parts, one placed forward and the other aft, would achieve a stability in pitch and yaw not present in the single foil. I want again to stress that the canted type of foil to leeward gets its lift mostly from the lateral component of the sail force. It does not appreciably rob the precious driving force component to obtain lift, as do so many foil proposals.

As to using both starboard and port foils (*Ed.*—The heeling double *Bruce foil*), several people, including myself, greatly improved their speed by dismantling one of the two outriggers. With double outriggers, one is hauling around a lot of unused junk and must tolerate unnecessary beam. Also, due to the balancing of outrigger weight, out of water weight becomes ineffective.

One might consider including a proa and your semi-elliptical square-sail with two canted foils to leeward and one under the hull in the alternatives. Problems are removed since a reverse in sail curvature is never called for because of the double direction of sailing. This might make possible a self-supporting sail without a mast. I have some wind tunnel evidence that such a sail would be superior to present wing-masts and battened sails in windward work.

About the failed experiment you refer to with a single outrigger. The foil was not only canted but of very high aspect ratio and *highly buoyant* through appreciable thickness in its hollow structure. It made an awful fuss in the form of waves and wake. It had the common mistake of so many experimenters. There should be *only one variable at a time* in a well conducted experiment. I suggested experimenting with models having *thin foils* and then to transfer successful dimensions accurately to full size.

I have done a lot of board "toe-in" experiments on various hulls in the towing tank. The best results always seem to occur when there is the same 5° angle of attack on *both* board and hull in the form of least drag angle. This means a board parallel to the main hull's centre-line. As for non-heeling, a slightly longer arm can compensate for the main hull's lateral resistance.

EDMOND BRUCE

AN EARLY APPLICATION

Letter from O. Holtman to John Morwood

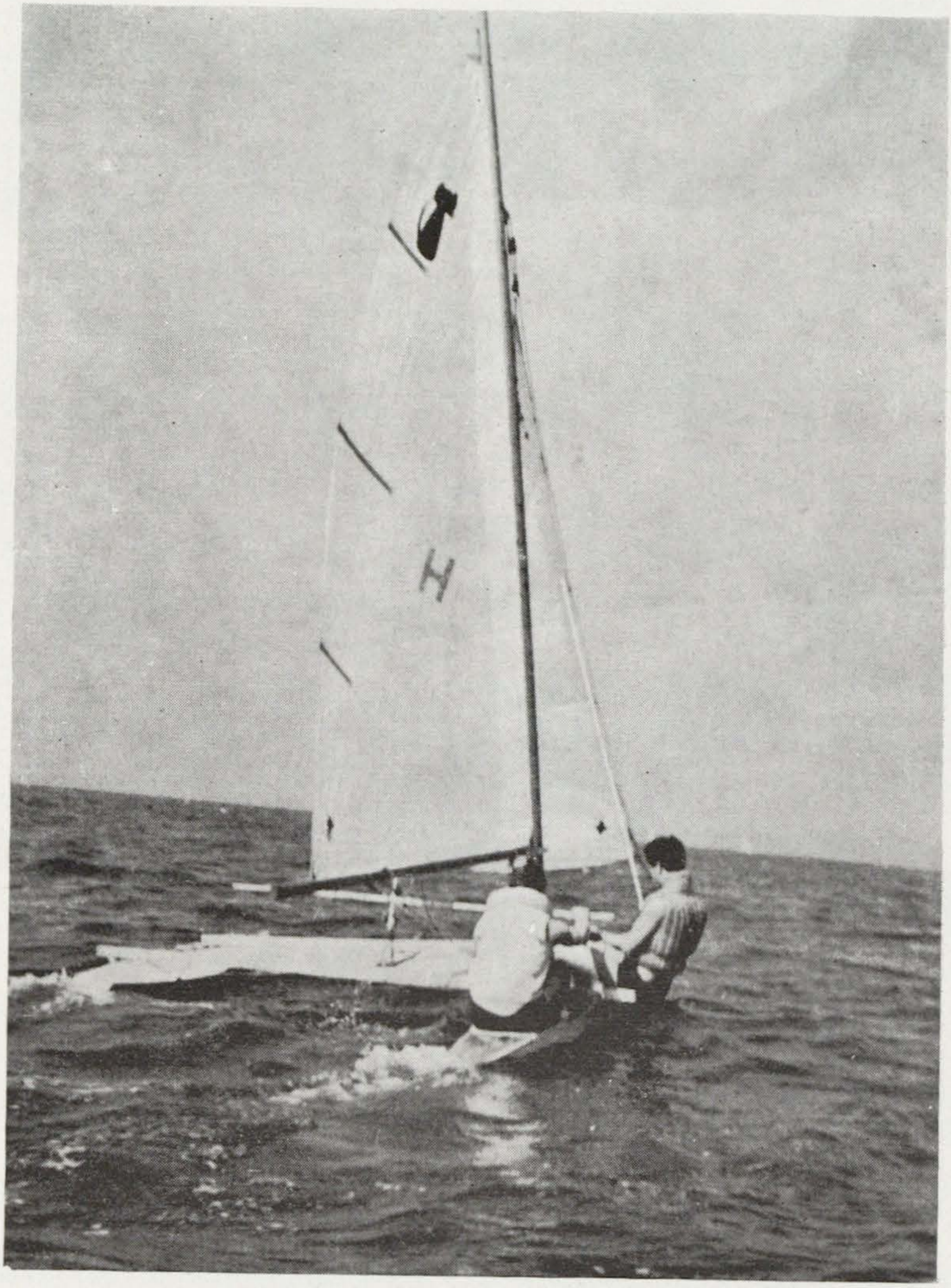
Reprinted from AYRS 62, Oct. 1967
and AYRS 74, Oct. 1970
Stoeberghlaan 16, Voorschoten, Holland
July 5, 1967

Dear John,

In 1963, I intended to sail and built a boat. The first catamaran was square box section, 12 ft long, weighed 300 lbs and had 100 sq ft of sail. Then, I found the AYRS publications and I accepted the following ideas:

1 L/B ratio = 12 (Bruce).
2 Unequal hulls (Morwood).
3 Rotating mast.
4 Half-circle bottom.
5 Aluminium, expanded foam.
6 The Bruce foil.
7 Boom vang.
8 Very sharp bow.

I took an aluminium race-canoe, rounded the bottom with foam and covered it with glass fibre and polyester resin. I had two tubes 6 ft long and laid them across the hull. To these tubes, I fitted two smaller tubes, also 6 ft long and, fitting snugly in each other, they made cross beams 11 ft long. The thicker tubes protruded on both sides of the hull and the stays were fastened to the after one while the mast stood on the forward one. The smaller tubes protruded only to port, thus making the craft a single outrigger and to their ends, the 8ft outrigger hull was attached. The small hull was made by the "opening up" system and had a 90° V form in the middle. The bow



O. Holtman's Bruce foil boat

was very sharp and the transom squared off. As published in AYRS No. 51 on page 66, the New Zealand Maori knew exactly the right dimensions.

My heart bounced. My mouth was dry, as I took the rudder and sheets. After 100 yards alone, I cried "Hy doet het" which is Dutch for "It works".

Tacking was difficult and I replaced the tubes to put the mast 1 ft out of the middle of the hull towards the outrigger. On holiday in France, the 420s and the *Flying Juniors* tried to catch me but I was faster. I was helped with tuning and the results were flattering for the Maoris. When the wind was more than force 4, I had to sit on the tubes to balance the boat.

In the North Sea, I sailed against a *Schakel*, 15 ft 7 in long, 30 per cent more sail than my boat but weighing 300 lbs to my boat's 200 lbs. Again, I was faster. I sailed very close hauled, thanks to the Bruce foil. The effect of the foil holding the mast upright could not be measured by me.

I'm convinced of a few things.

1 The unequal hull is fast—perhaps the fastest.
2 Building and tuning are easy.
3 The weight is low.
4 Taking apart takes a short time.

The canoe is too light for two persons so I'll change it for a *Shearwater* hull. The sail area will be 150 sq ft, the weight under 200 lbs. The mainsail and jib will have the same height and both will be loose footed. There will be one boom from the clew of the main sail to the tack of the jib and the clew of the jib will open automatically 9 in at the mast. I will then have only one sheet to turn the whole sail area and mast. There will be four stays to the ends of the cross-arms with the mast standing between them with no forestay. The mast will stand on the gunwale of the *Shearwater* hull at the outrigger side.

Thank you for all the information and the pleasure of reading.

O. Holtman

HISTORICAL FOOTNOTE ON NON-HEELING SAILING CRAFT

by Henry A. Morss, Jr. November 1974

More than once over the years Edmond Bruce mentioned to me that there was a United States patent fifty years ago, more or less, which covered the principle of the non-heeling sail boat. I don't recall discussion of this in any detail.

Recently, in a conversation, Professor W. S. Bradfield told me that there were two articles on the subject in "Yachting" magazine. He gave me the names and dates.

Now I have looked up all of these references and confirmed the statements. An interested reader may wish to turn to an article entitled "The Sailplane—A New Type of Sailboat" by Malcolm and T. A. McIntyre in "Yachting" for November, 1920, an article entitled simply "The Sailplane" by Malcolm McIntyre in "Yachting" for February, 1934, and United States patents 1,356,300 (10/19/20) and 1,670,936 (5/22/28), both entitled "Sailing Craft" and issued to Malcolm McIntyre and Thomas A. McIntyre.

CHAPTER XXVI

STABILIZING AND LIFTING FOILS APPLIED TO CATAMARANS

Reprinted from AYRS 66A, Oct. 1968

By Edmond Bruce

A number of sailors now have had "THE experience". They have found that, in strong winds, heeling really can be stabilized by one or more laterally-canted water-foils. This heeling stabilization is dynamically derived largely from the usually wasted sail side-force on the hull, as distinguished from its driving-force component. In addition, useful speed-producing lift can be provided with certain configurations. It may be that this new type of lift is as important to sailing as the non-heeling feature, both of which can be provided simultaneously by this canted foil.

The writer's correspondence indicates that some catamaran enthusiasts appear disappointed by a mistaken belief that canted foils cannot be usefully applied to catamarans of existing beams. I am writing this extension of my article in Chapter XXV to try to assure them that this is not the case. Existing catamarans can benefit greatly in strong winds. Personally, I much prefer the exciting but greater "critical beam".

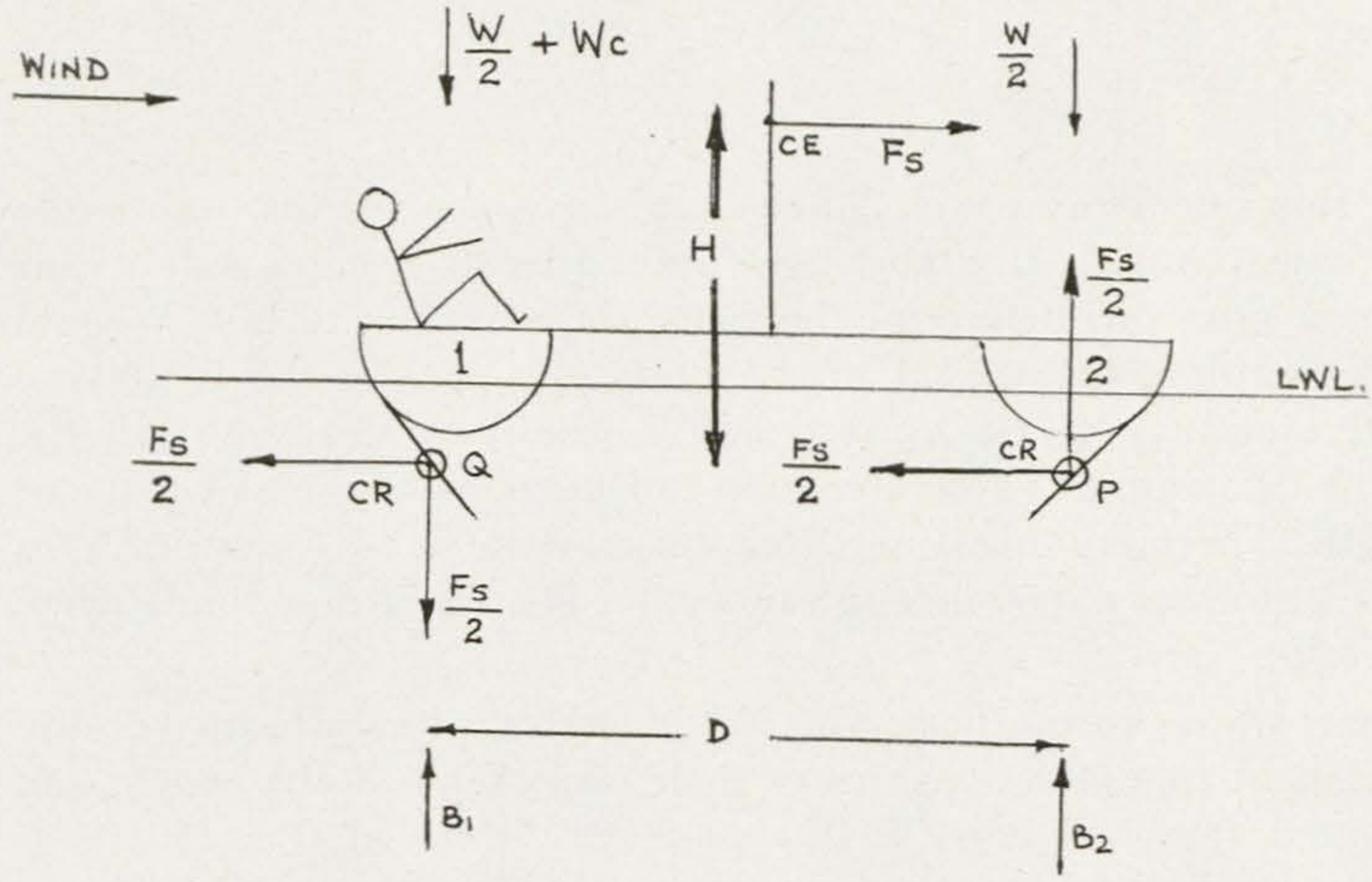
I believe that the previous wrong impressions were created by an incorrect "rule of thumb" of mysterious origin. It stated that an imaginary line perpendicular to the centre of a water-foil must extend through the sail's centre-of-effort. This was only an accidental coincidence in my Chapter XXV article.

Actually, according to the theory of moments, as applied to the non-heeling boat, the sail plan can be placed laterally anywhere without affecting its heeling moment. The magnitude and direction of the total sail force would be unchanged if this were done. Also, the effective length of the moment arm would be unchanged. Since such lateral movement would displace the stated alignment with the sails' centre-of-effort, the rule of thumb cannot be correct.

Let us examine Fig. 1 which represents the cross-section of a catamaran with its sail force having an abeam component. The crew is perched on the windward hull. A steady-state condition, without acceleration or deceleration, is assumed. The height of the sails' CE above the centres of resistance CR, of the pair of 45°-canted, flat, thin boards, is H. The separation of the CR of the two canted boards is D. The sketch also shows the two moments and the algebra involved in the calculations of buoyancy for those who are interested.

The distribution of weight between multihulls is highly important to an analysis. My diagram in Chapter XXV was made easy since most of the total weight of the single outrigger and crew was in one hull. This permitted a smaller beam for non-heeling. The present Fig. 1, showing a catamaran, involves weight and buoyancy distributions between two hulls. Two moments are now required for a solution since two unknowns are involved. As shown on the sketch, the buoyancies required by the hulls for equilibrium are stated in terms of the weights of the catamaran and crew, the side-force of the sail and the ratio of the dimensions H over D

When the windward hull 1 is lifted just clear of the water so that its



W IS BOAT WEIGHT. Wc IS CREW WEIGHT. Fs IS SAIL SIDE-FORCE.

MOMENTS ABOUT P & Q:

$$M_P = F_S \cdot H - \frac{W}{2} \cdot D - W_C \cdot D + B_1 \cdot D - \frac{F_S}{2} \cdot D = 0$$

$$M_Q = F_S \cdot H + \frac{W}{2} \cdot D - B_2 \cdot D - \frac{F_S}{2} \cdot D = 0$$

REQUIRED BUOYANCIES:

$$B_1 \cdot D = \frac{W}{2} \cdot D + W_C \cdot D + \frac{F_S}{2} \cdot D - F_S \cdot H$$

$$B_2 \cdot D = \frac{W}{2} \cdot D - \frac{F_S}{2} \cdot D + F_S \cdot H.$$

$$B_1 = \frac{W}{2} + W_C + \frac{F_S}{2} - F_S \cdot \frac{H}{D}.$$

$$B_2 = \frac{W}{2} - \frac{F_S}{2} + F_S \cdot \frac{H}{D}.$$

Fig. 1

buoyancy is $B_1 = 0$, capsize is imminent. The limit of sail force for stability is then, from the Fig. 1 equations,

$$F_S \left(\frac{H}{D} - \frac{1}{2}\right) = \frac{W}{2} + W_C$$

So far as heeling is concerned, it is seen that the sail force F_S can be infinite if

$$\frac{H}{D} = \frac{1}{2}, \text{ or } D = 2H$$

Actually, this catamaran could "pitch-pole" in violent winds, unless the main-sheet were released. It is no longer limited by its heeling stability, as is the common situation. Before this happens, the buoyancy of hull 1 would be, without variation, the weight of the crew plus half of the catamaran weight. The buoyancy of the leeward hull 2 would be steady at half the weight of the catamaran. These are quite independent of the sail force or wind strength. There is no real need for the crew to sit to windward as is shown. It is a glorious experience to sail such a boat in strong winds when other boats falter.

There seem always to be those who would prefer a lesser beam because of a measurement rule or for reasons of their own. While some benefit can still be obtained, they will miss "THE experience". If we let $D = H$ or half the above, the limit of sail force before capsize or main-sheet release is,

$$F_S = 2\left(\frac{W}{2} + W_C\right)$$

This is exactly twice the stability we would get if we re-worked the whole problem for a conventional pair of vertical boards. This reduced beam, canted board boat could still win strong wind races over the conventional catamaran.

While the first mentioned wide beam, canted double-board configuration describes a safe structure for very strong winds, we can be more adventurous and faster if we introduce our lift simply by pulling up the windward board. This case is shown in Fig. 2. The remaining leeward board should have ample area available so that the leeway angle can be again adjusted to the optimum of about 5° (see writer's article in Chapter IV). It now has double the water force it experienced when paired with the windward board.

A new situation now presents itself. In Fig. 1, where two boards are used, if one adds the required buoyancies of the two hulls, they become simply,

$$B_1 + B_2 = W + W_C$$

This is therefore independent of the sail force but experiences no lift.

For the situation of the single leeward board in Fig. 2, the sum of the buoyancies is,

$$B_1 + B_2 = W + W_C - F_S$$

This is quite independent of the ratio $\frac{H}{D}$. Therefore, we get a lift equal to the sail side-force regardless of any hull spacing we choose. However, the spacing does control how much lift each hull gets and therefore the heeling. For example, if $D = 2H$ in Fig. 2,

$$B_1 = \frac{W}{2} + W_C - \frac{F_S}{2}$$

$$B_2 = \frac{W}{2} - \frac{F_S}{2}$$

Therefore both hulls experience equal speed-producing lifts from the wind and there is still no heeling with this preferred structure.

Now if one compromises and uses a hull spacing where $D = H$,

$$B_1 = \frac{W}{2} + W_C - F_S$$

$$B_2 = \frac{W}{2}$$

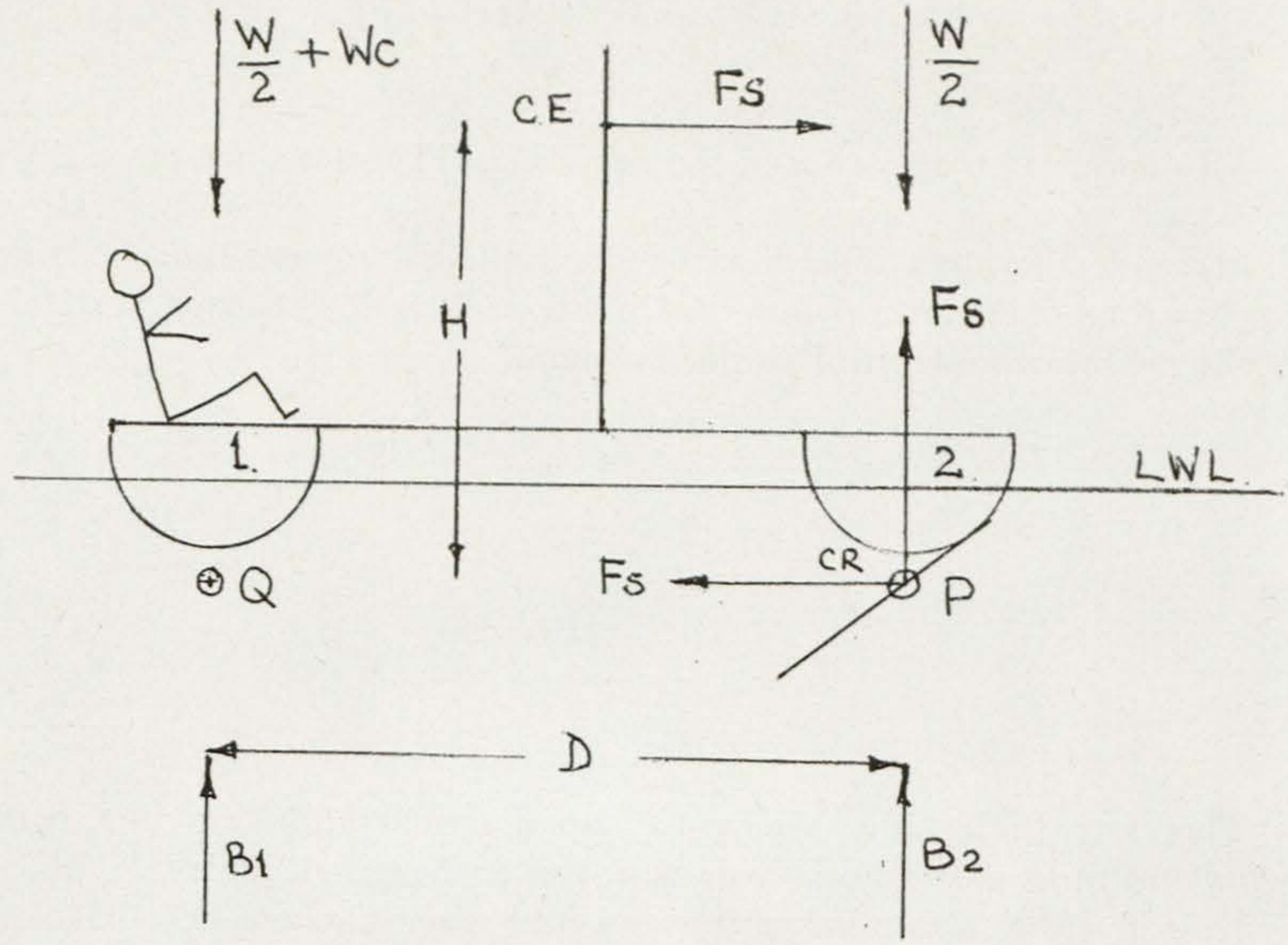
It is important to note that, while the leeward hull gets no lift from the wind, its buoyancy has to support only its own weight in any wind strength. There is no degree of burying of the leeward hull as is usual if vertical boards are used in strong winds or weak.

The limit of sail force for heeling stability now becomes, for $B_1 = 0$,

$$F_S = \frac{W}{2} + W_C$$

This is the same stability as if a pair of vertical boards were used. However, the overall lift and the lack of any lee hull burying, with the windward hull lifted, will give a large dividend in increased speed. Catamarans of conventional beam can use laterally canted boards to advantage.

Let us sum up the predictions about the windward comparisons between a conventional catamaran and catamarans of each of the two beams which use canted-boards, as described. Equal sail areas and weight are assumed.



MOVEMENTS ABOUT P & Q :

$$M_P = F_S \cdot H - \frac{W}{2} \cdot D - W_C \cdot D + B_1 \cdot D = 0.$$

$$M_Q = F_S \cdot H + \frac{W}{2} \cdot D - B_2 \cdot D - F_S \cdot D = 0.$$

REQUIRED BUOYANCIES:

$$B_1 \cdot D = \frac{W}{2} \cdot D + W_C \cdot D - F_S \cdot H.$$

$$B_2 \cdot D = \frac{W}{2} \cdot D - F_S \cdot D + F_S \cdot H.$$

$$B_1 = \frac{W}{2} + W_C - F_S \cdot \frac{H}{D}.$$

$$B_2 = \frac{W}{2} - F_S + F_S \cdot \frac{H}{D}.$$

Fig. 2

In light air, no appreciable heeling is involved in any of the three catamarans. Both of the canted-board boats would use only their leeward board. Little or no speed difference over the conventional catamaran will be experienced. While there is a small lift equal to the sails' side-force, the resulting slightly reduced hull drag may be compensated by the slightly increased overall friction due to a 40 per cent larger area required by the canted board.

As the wind picks up, the conventional catamaran will transfer some of its weight from the windward hull to the leeward hull with a consequent lee hull depression.

The narrower beam, canted-board boat will have neither lift nor depression in its leeward hull. Its windward hull buoyancy will be decreased. Consequently, with less displacement, the canted-board, narrower beam boat will be faster than the conventional boat. There will be only a small degree of heeling.

The broader beam, canted-board boat will have about the same speed as its narrower beam counterpart. However, there will be an equal lift on both its hulls and therefore still no heeling.

In winds that are still stronger, the conventional catamaran will be on the verge of capsizing when

$$F_S = \frac{W}{2} + W_C$$

Due to lee hull burying, its comparative speed will be poorer.

The narrower beam, canted-board boat will also be on the verge of capsize but its speed will be very much greater as its displacement will be only half the weight of the boat without a crew. Whereas the conventional boat is about to pass out of contention, by lowering the windward board, the narrower beam, canted-board boat can continue sailing until the sail force becomes twice as great. The displacement of the lee hull will be still half of the weight of the boat without crew. In still stronger winds, it will also pass out of contention unless it eases the main sheet.

The broader-beam canted-board boat will be perfectly happy in these strong winds. The lift will be equal on both hulls and therefore no heeling will exist. When the narrower beam, canted-board boat passes out of contention, the broader beam version will still be displacing half its weight without a crew. It can continue with its leeward board alone until the whole structure leaves the water. It can then save itself by lowering the windward board to neutralize the lift. The next step upward in wind strength may now result in "pitch-poling", "porpoising" or just plain disintegration. Crash-helmets are in order!

For my trimaran friends, if they can sail with the windward float and board out of water, a leeward, canted-board analysis would be the same as for the outrigger discussed in Chapter XXV. We need a practical invention as to how to fold up or otherwise avoid the spread of that windward float which is doing nothing for us on a given tack. I begrudge this excess spread.

The critical spread for the remaining two hulls is H rather than 2H as required by a catamaran. A favourable weight distribution accomplishes this on one tack only, in the case of the single outrigger, if both non-heeling and lift are to be simultaneous.

If the trimaran's total beam were half its critical beam, while it would get greater speed, due to the sail force lift, it would capsize when the sail force was half the total weight. This assumes that the crew weight is in the main hull. If the crew moved out to the windward float, its point of capsize would be the same as the above conventional catamaran having the same beam and a similar positioned crew. I must again recommend the critical non-heeling beam. I hope for the above invention which could cut the beam to about half.

An Application

Reprinted from AYRS-AIRS 1, Dec. 1971

Letter from Edmond Bruce to John Morwood

May 13, 1971

Dear John,

Congratulations on the big, fat AYRS issue No. 74. Your stated policy of reproducing past articles by subject, in book form, rather than by particular issues, strikes me as being excellent for all concerned and should make AYRS better known in the world of sailing.

I am writing this to be sure that you are aware of a recent situation. My mail indicates great excitement among catamaraners about my article on canted foils as applied to catamarans which appeared in AYRS No. 66A. Several people have tried this with even greater success than I expected. The main point is the elimination of the usual lee hull burying at speed for catamarans of normal dimensions. My correspondents claim that, in strong winds, they now run away from the conventional vertical board catamarans.

I am asking a Canadian, Brian T. King of PO Box 14, Kamloops, B.C., to write to you about his experiences. He wishes he were in a personal position so that he could challenge for the "Little America Cup". I do not completely approve of the flat bottoms on his hulls, however. I believe that they will slightly harm his low-speed performance.

The above mentioned AYRS No. 66A article does not appear in No. 74. I do believe that it contains a more complete analysis of the distributions of the total lift as a function of the H/D ratio than my original article in AYRS No. 51.

EDMOND BRUCE

Letter to John Morwood from Brian T. King

PO Box 14, Kamloops, BC

Dear Dr. Morwood,

Thanks for your letter re publishing details of my "Canted Board Cat".

I would be glad to have it done if you consider it significant enough. I hope the letter (photostat) from Mr. Bruce is coherent.

I would have liked to present wind speed/boat speed figures, but until someone perfects cheap instruments to measure this, it's impossible, I'm afraid. I have a wind speed meter and attempted to install a "speedo" but couldn't get the Pilot Head placed correctly—was getting readings of 6 knots as I passed powerboats pulling skiers!

The boat is being re-rigged to 300 ft (from 260) and a rotating aluminium mast this winter, by the way.

I know the boat should go in all winds, but I was somewhat surprised it went as well as it did—let's face it, it is somewhat a departure from convention. I personally am sure that the standard Cat configuration, as in 'C'-class for instance, hasn't much speed increase to look forward to except maybe a knot or two, so some basic reconsiderations seemed in order.

Mr. Bruce seems to feel that the planing hull of high aspect ratio isn't worth the drag involved. His only comment to my letter was that all useful lift came from the board. Of course this is the very premise on which I based the design—that all the lee hull had to plane was about $\frac{1}{2}$ boat's weight, in this case 150 lbs. All I can say in reply is that at speed this boat has extremely low wetted surface, and that the lee hull is 3 in to 4 in above its static waterline, with the weather hull just skimming, and this drastic reduction in both wetted surface and wave making has to be worthwhile to a pronounced degree. I should be interested in your comments on this.

I am seriously considering building a "proa" type boat with all foils sloped up to lee later on, so will be writing in probably for suggested foil dimensions.

Thanks for a darn good Society and publications.

B. T. King

Letter from Brian T. King to Edmond Bruce

May 4, 1971

Dear Mr. Bruce,

I am writing to you to describe an application of your Canted Boards which I have not seen duplicated in any AYRS publication to date.

On reading of the Canted Board idea applied to a Catamaran, it struck me that if the lee hull had only to support half the boat weight with the crew to windward—it would be pretty easy to design a boat to plane that weight. The windward hull plus crew weight would under most conditions be lifted by the heeling force to board so that it appeared that both hulls, suitably designed, could plane successfully. I thought that by using about 13ft beam and a lowish rig of 260 sq ft the non heeling board to windward would be mostly unnecessary; thereby eliminating the "fight" between that board's downward force and the hull's desire to plane, I'm not certain the two things are fully incompatible, even yet, however.

I have to report that the boat does exactly as predicted and is exceptionally fast. It is difficult to estimate or even measure speeds accurately but suffice it to say in a *wind of about* 12–14+ mph, the displacement of the boat is, due to planing, as near to nil as it's possible to imagine. It will plane fully to windward also and even at high speed (20+ knots) it instantly registers the slightest variation in wind speed (increase) which seems to indicate to me that none of the "peaking out" in performance is taking place that one notices in all normal cats. The boat can be made to travel on only the back 10–12 ft of the lee hull by trimming crew weight aft and this "boat to water" contact is right on the surface, i.e. the flat bottom of the hull in contact only.

Since, even in a strong wind, the boat is over-stable and could use earlier "heeling lift" of the weather hull, I haven't played around with the non-heeling or weather board.

Specifications are as follows:

LOA 22 ft
LWL 16 ft
D = Maximum beam 13 ft
Sailing weight 300 lbs (boat without crew)
Sail area 260 sq ft
Maximum hull beam 14 in
Each board has 5 ft of projected area

$$\frac{L}{B} = \frac{16}{1{\cdot}17} = 13{\cdot}7$$

H by scaling photo to CE is about 11 ft or $\frac{H}{D} = 0{\cdot}7$

$$B_2 = \frac{W}{2} - F_S + 0{\cdot}7\ F_S$$

$$B_2 = \frac{W}{2} - 0{\cdot}3\ F_S$$

The box section hull has a long "scow" bow which does *not* pound to windward or otherwise and doesn't seem to pitch either: this being due to the even flatter and wider sections aft and the way the hulls ride high "on" the water as much as in. The bows, while at first sight perhaps appearing garish or impractical on a cat, are in fact a natural development of the whole concept and I find them hard to fault, having sailed all last year on the thing in all conditions.

The boat has almost unbelievable speed in what can only be described as flat calm—i.e. no ripples whatever on the water (less than 2 mph wind). In this strength, the slab sided hulls suffice and no board at all is necessary: the ratio of wetted surface to sail area is then about 48:260 or 0·185. She appears to do 4 knots in *no* apparent wind on a reach. I know it sounds ridiculous but I've sailed for years on the best light air monohulls and this boat is twice as fast in these conditions. In conditions light to moderate, the scow bows and flat bottomed "entrance" seem to do no harm at all, even at fair speed in pre-planing attitude the unusual hull form seems to do no harm—

perhaps the low wetted surface even with one board down overcomes the extra resistance to be expected from a "bluntish" entrance.

The limitation at present is of course the low AR rig. I was amazed when blowing the jib out at about 20+ knots to see that the boat slowed only a knot or two with a 60 sq ft jib flogging like a machine gun. It should all be in the mainsail obviously, and that higher. As I say, I need a degree more heeling force anyway (how's that for a turnaround?) to get the boat up on one hull easier.

Tacking is as good as any 16 LWL cat, i.e. slowish but pretty positive.

An interesting feature is the lack of surging vibration etc., as is usually felt at speed in a conventional cat with the lee hull running deep and throwing water back. These hulls throw no water at all—it all goes under to lift the hull.

Altogether a success I think, especially since, while I have a fair background in conventional sailboat design, in something this radical I was guessing a lot as to hull beam for dynamic lift etc. Your boards get much of the credit of course—I regard them as highly significant and can't help feeling that with them applied to a more scientifically designed hull along similar lines to my effort outlined here—allied with a rig (wingmast, I'm afraid) able to develop maximum power in its "permanently closehauled" attitude—the 'C'-class cats could be beaten. I can't stress enough that thoroughbred feel and general speed—with no apparent penalties—that even this first rather heavy handed effort gives. Admittedly, with the Non Dimensional Power/Weight ratio this boat has—it could hardly help but go, but to see those hull bottoms no more than skating on the water surface is pretty impressive after you've sailed cats that appear to be trying to "crashdive" to about 30ft below the surface, in any kind of a wind.

Would it not be possible to apply a more mathematical approach to the hull design itself and perhaps tank test it? I would say to 'C'-class specifications. It seems that since the lee hull only has to support (plane) half the boat weight it could be towed for planing etc., with almost no other consideration. I don't think the 250 lbs extra that a 'C'-class type wingmast would add would help much, but perhaps the rig elaboration seen in 'C'-class is partly due to the fact that hull drag on normal displacement type hulls (even, or perhaps especially, in 'C'-class) cannot be lessened any further by fiddling with shape etc. Perhaps, with the shorter water line possible with a planing hull configuration, due to the fact that above a certain speed the hulls rise *out* **of the water, and the decrease in wetted surface due to the short w.l., an overall compromise can be developed to do the trick** without great rig elaboration. As usual there are an immense number of things to consider but without going into the thing any further I would like to ask your opinion on the matter, particularly with regard to the mathematical design of a planing cat hull to suit.

I would be glad to pay any moderate cost for this, should it be a viable idea in your opinion to develop this thing. Of course, I would like to know the approximate costs in advance.

I intend to write this up for the AYRS later—perhaps if you agree that the thing with development, has possibilities, I could exercise a long held whimsy of mine that the Society should "put its knowledge where its mouth is" and persuade it (with appropriate funding from members) to take a crack at something like the Little America's Cup. I don't think it's so fantastic at all.

I would like to have been more scientific with my windspeeds/boatspeeds etc., but at this stage cannot manage it.

BRIAN T. KING

CHAPTER XXVII

THE URGENT YACHT RESEARCH — HULL AND SAIL DRAG ANGLES

Reprinted from AYRS 62, Oct. 1967

by John Morwood

At this stage in the development of the yacht, every yacht test tank and wind tunnel and all amateurs who regard themselves as scientific men should be studying hull and sail drag angles to find the minimum. Not that it is very likely that the minimum angles would ever be used on a yacht but the hull and keel shape and sail rig which produce them must be known.

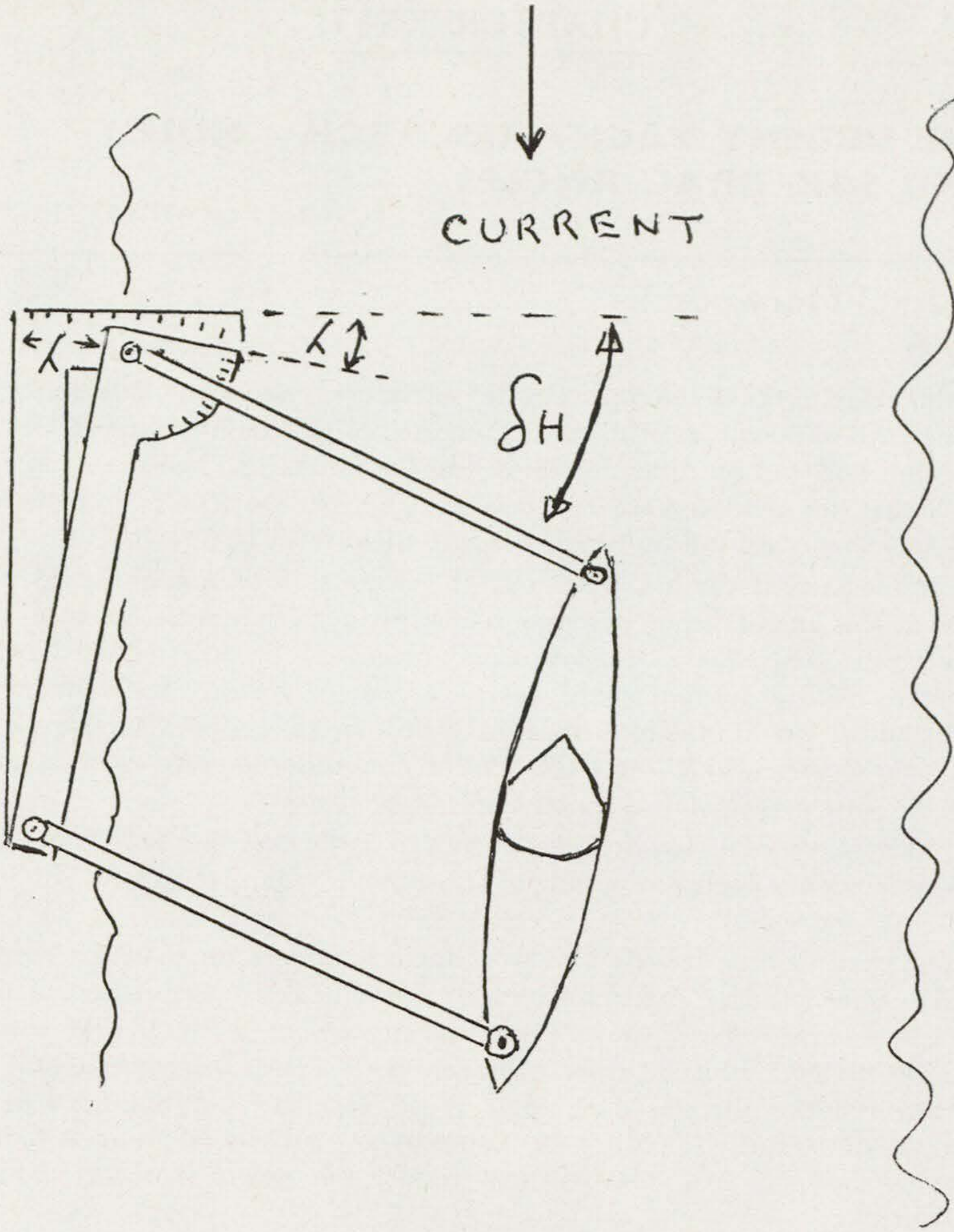
For instance, if the hull shape which produced a drag angle of 5° were known, this might be of a semi-circular main section with either a high aspect ratio centreboard or a low aspect ratio keel, like that of the Norfolk Wherry. Such a section would not have enough stability for a monohull yacht and it would obviously be worth while to have, say, a 4:1 ellipse for the main section with a drag angle of 6° or 7° in order to carry extra sail area. *But the least possible hull drag angle should be known.*

Similarly, very low sail drag angles may give the best speeds to windward. But sails with a higher drag angle will undoubtedly give greater drive on reaching courses.

The need to improve the hull drag angle is far greater than the need to improve the sail drag angle as shown by Edmond Bruce and myself. This is because it is the worse of the two, so the improvement in overall performance will be greater. Indeed, Austin Farrar, with *Lady Helmsman's* sail has already reduced the sail drag angle to an excellent but unknown figure and we will be lucky to reduce this figure by any substantial amount, though General Parham's bent mast rig may reduce the weight if it can be made seaworthy.

It is perhaps fortunate that sail efficiency has already been brought to such a high level because its study really needs a wind tunnel (though full size tethered tests are fairly easy). But hull drag angles can easily be studied by amateurs in a tidal stream or a fast-flowing river. Owing to water gradients and eddies, as measured by John Hogg, the figure obtained might not be absolutely accurate, but it will be relatively accurate, and be of great value. "Bottom effect", which reduces the drag at certain speeds, will also complicate the picture for low aspect ratio keels, like those of the 5·5-meter boats. *But none of these things invalidates the comparative value of such tests.*

A simple apparatus is shown in the drawing for taking hull drag angles at various amounts of leeway. The fixed plank is aligned to the water flow by means of two light poles of the same length stretching out over the water. To the end of the upstream pole is tied a line which should drift down in the



current and the plank is adjusted so that the line comes under the end of the downstream pole.

The "Leeway plank" swivels on the fixed plank and is calibrated to give leeway angles of 3, 4, 5, 6 and 7 degrees. Two pivots are placed on the "Leeway plank" (and these can be round nails) at a distance apart exactly equal to the length of the boat being tested (or rather similar pivots on the boat) and both the upstream and downstream pivots are connected by light rods of equal length such as bamboo poles with bearings at both ends. A quarter circle attached to the "Leeway plank" with its centre at the pivot is calibrated in degrees.

When all is set up, the hull drag angle is the sum of the leeway angle and that on the quarter circle. It will vary slightly with the speed of the current due to wave-making.

The Testing

A paddling canoe is shown in the drawing because these are common and cheap but a skiff, scull or Canadian Canoe could be used. The reason why a canoe sterned boat has been chosen is that the head resistance will be less within the usual range of testing and thus the drag angle is likely to be less. I suggest that a 2 in by 1 in plank be glued along the keel of such a craft and various keels be fitted onto this with dowels.

As shown by Edmond Bruce, the ideal leeway angle is 5°. If, therefore, the minimum drag angle occurs at a leeway angle less than 5°, the keel is too big. If it occurs at a greater angle than 5°, it is too small. However, in the Southampton University tests, the minimum drag angles occurred at 7° of leeway for the best keel tested and 9° for the worst. However, we are looking for a very much more efficient keel than that of the 5·5 meters which were being tested—the drag angle was 22°, as stated in AYRS No. 61.

Having written the previous paragraph, I am appalled by the anomalies and by our ignorances. Surely this emphasises the importance of such a study as is suggested here. Every one of us should start bullying the test tank workers to start action or by an apparatus such as we show, to start action himself.

λ = angle of attack or leeway.

δ_H = drag angle of hull.

CHAPTER XXVIII

SURFACE-PIERCING HYDROFOILS FOR HEELING PREVENTION AND LIFT

Reprinted from AYRS 66A, Oct. 1968
and AYRS 74, Oct. 1970

by Edmond Bruce

Air-ventilation

In Chapter XXV, the present writer stated the critical dimensions for the locations of canted hydrofoils which would achieve dynamic neutralisation of heeling. The dinghy, pictured therein, originally was provided with a foil of high aspect ratio. Above certain speeds to windward, it was troubled with a loss of lateral lift. From observation of the water, it was quite apparent that this was due to "air-ventilation", from the water surface, down the negative pressure side of the canted hydrofoil.

The dinghy was next equipped with a lower aspect ratio foil of larger area, as best shown by the model pictured in Fig. 4 of Chapter XXV. As a result, the air-ventilation troubles disappeared, regardless of the boat speed achieved. Evidently, one cannot be guided by the teachings of aeronautical handbooks when designing surface-piercing hydrofoils or even submerged foils which are close enough to the water surface to cause any degree of wave-making or surface turbulence.

To gain more insight into the problems of surface-penetrating foils, a series of tests were performed in the author's laminar-flow towing tank. These will now be described.

Test arrangement

When the towing tank was originally built, it employed an overhead towing carriage on a track. When it became evident that towing by means of a single long cord, attached to a point equivalent to the sail's centre of effort, produced more accurate results, the overhead railway was put aside but kept intact. This was fortunate as we shall see.

John Morwood, in the previous chapter, suggested an experimental arrangement for quickly measuring hull drag angles at various amounts of leeway, for a stated boat speed. This writer was so impressed with the labour-saving possibilities of this arrangement that he reactivated the former overhead railway and equipped it with the Morwood suggestion. It was arranged so that its pair of arms was attached to both the floating model and the carriage through universal joints located at the height of the centre of effort of the sails, chosen as L/2 for the model. This permitted simulating any heeling which would occur under natural conditions, also any lift.

A constant model speed was obtained since the towing carriage was operated from a properly geared synchronous motor. This produced a violent starting yank on the model but, fortunately, its progress was stabilized by the time it reached the end of the tank where readings were made. Readings were made somewhat difficult by the fact that the scale was moving. The violent means of accelerating the model should be softened for more complete satisfaction. A stationary scale, probably electrical, would also help.

Measurements

We all want to know the optimum for size, aspect ratio and shape for our hydrofoils, whether vertical or canted, for best windward performance. We have learned that the criterion, for best windward performance, is the lowest possible drag angle for the particular hull employed.

The number of experiments required to determine the grand optimum foil would be the *product* of all the variations of size, aspect ratio, canting, curvature, shape, arm length, windward or leeward position, etc. This seemed overwhelming to a lazy individual. Thus, for an initial educational insight, only rectangular, thin, flat foils were studied.

The model hull chosen was a 15-in long, Model No. 8 with a high metacentre as discussed in Chapter XXII. It was connected to a single outrigged foil, without a float. The outrigger arm lengths were initially adjusted to one-quarter of the length of the model. This corresponds to many trimarans when sailing with the windward float out of the water. A small rudder and an out-of-water counterweight for the foil were provided.

Vertical foils were tested and also canted foils. The vertical foils were first positioned to leeward. The best combination was then placed to windward to obtain a comparison. The constant speed of the model was 0·65 ft per sec. This is equivalent to the low speed of $V_B/\sqrt{L} = 0{\cdot}35$ in order to avoid the complications of appreciable wave-making, with its increase in drag angle.

The canted foils were always to leeward so that, in addition to heeling compensation, vertical lift was also provided. A compromise outrigger arm length was studied for comparison with the critical arm length, for heeling neutralisation.

Vertical foils

Table A, for vertical foils, concisely presents the measured inter-relations and the overall optima between six variables. These are:

Variable:	*Optimum:*
1 Hull Drag Angle	12°
2 Leeway Angle	5°
3 Foil Width	$2\frac{1}{2}$ in
4 Foil Depth	$2\frac{1}{2}$ in
5 Foil Area	6·25 sq in
6 Aspect Ratio	1·00

Plotting six variables on two dimensional plotting paper with criss-crossing lines and various labels seems a confusing mess. For this reason, only the

Table A

Model Hull Drag Angles versus Dimensions for Vertical, Flat, Thin, Rectangular Foils. Outrigged to Leeward. Arm Length = L/4. L = 15 in. Speeds = 0·65 ft/sec.

Leeway Angles	Width = $1\frac{1}{4}$ in Depth =					Width = $2\frac{1}{2}$ in Depth =				Width = 5 in Depth =		
	1 in	2 in	3 in	*4 in	5 in	1 in	$1\frac{1}{2}$ in	2 in	†$2\frac{1}{2}$ in	$\frac{3}{4}$ in	1 in	*$1\frac{1}{4}$in
0°	49°	37°	38°	28°	25°	47°	32°	27°	27°	43°	38°	34°
$2\frac{1}{2}$°	40	24	22	18	15	32	21	15	15	35	27	23
†5°	27	16	14	*13	15	22	18	14	†12	23	20	*16
$7\frac{1}{2}$°	20	17	16	16	17	18	17	14	14	19	19	17
10°	22	21	19	18	18	22	19	18	18	22	20	19
$12\frac{1}{2}$°	24	22	20	20	20	25	21	20	20	23	20	20
15°	29	24	23	22	22	26	24	22	22	23	23	22
Foil area sq in	1·25	2·50	3·75	*5·00	6·25	2·50	3·75	5·00	†6·25	3·75	5·00	*6·25

*Best of group.

†Best overall.

Note: The drag angle at 0° leeway is not 90° because the single outrigger is asymmetrical.

tabular form for data will be presented here. The reader may want to plot any pair of variables which may interest him.

The much discussed optimum leeway angle of about 5° has appeared again. An optimum 5° leeway for the model in laminar flow may well be 4° for full size in turbulent flow. The advantage of high aspect ratio for surface piercing foils apparently has been disproved since a unity ratio seems best. Both the width and depth of the vertical foil, for a hull equal to this one's high merit, is about one-sixth of the water-line length. A poorer hull probably would have different values except the tank optimum leeway of about 5° might still prevail.

The question arises as to what the result would be if the best foil of Table A were placed to windward, rather than to leeward. Table B shows the measured data. A foil to windward, rather than to leeward, would give greater directional steering stability. This is because the sail force is away from the centre of water resistance, not toward it. However, the table's optimum shows that no appreciable difference would result in their abilities to sail to windward.

Table B

Model Hull Drag Angles for Leeward versus Windward Placement of Foil $2\frac{1}{2}''$ Wide by $2\frac{1}{2}''$ Deep. Arm Length = L/4.

Leeway Angles	0°	$2\frac{1}{2}$°	*5°	$7\frac{1}{2}$°	10°	$12\frac{1}{2}$°	15°
Foil to Leeward	27°	15°	*12°	14°	18°	20°	22°
Foil to Windward	21°	14°	*12°	14°	16°	—	—

Canted foils

Now we will take up the question as to how a 45° canted foil to leeward, which is used additionally for heeling compensation and also vertical lift, would affect the windward performance. The measured data is presented in Table C.

TABLE C

Model Hull Drag Angles versus Dimensions for 45° Canted, Flat, Thin, Rectangular Foils. Outrigged to Leeward. Width 2½ in throughout. Arm Length Varied. Speed = 0·65 ft/sec.

Horizontal Leeway Angles	Arm = L/4 Depth = 2½ in	3 in	3½ in		Critical Arm = L/2 Depth = 2½ in	3½ in	4½ in	
0°	38°	33°	31°	Some	39°	39°	41°	Heeling
2½°	27	23	20	Heeling	31	26	32	Dynamically
5°	19	18	17		17	17	15	Neutralized
7½°	18	17	*16		14	*12	13	
10°	21	19	18		17	*12	14	
12½°	22	20	19		17	14	14	
15°	22	22	22		17	16	15	
Foil Area sq in	6·25	7·50	8·75		6·25	8·75	11·25	

*Best of group.

Here we find that, for the 45° canted foil, the critical length of the outrigged arm of L/2, producing non-heeling, is far superior to the compromise arm length of L/4. While the best drag angle is the same as the best achieved with the vertical foils, a dynamic lift has been created also. Its advantage at still higher speeds than tested should be outstanding. The vertical lift will greatly reduce the parasitic resistance of the main hull.

Note that the optimum size of the canted foil is now approximately 8·75 sq in rather than 6·25 sq in for the previous vertical foil. The latter is nearly 0·7 times the area of the former. This is precisely what one would expect. The projection, on a vertical plane, of the optimum 45° canted foil area should equal the area of the optimum vertical foil. The sine or cosine of 45° is nearly 0·7, therefore this does occur.

It is interesting to note that the optimum leeway angle of some 7° or more, which was measured in the horizontal plane of the water surface, represents only about a 5° angle of attack to the canted foil. This results because an angle of attack must be measured in a plane perpendicular to the 45° canted foil. This plane must also contain the line of motion. So our convenient "rule of thumb" of a 5° optimum angle of attack has been further supported by the canted foil data in spite of the added complications.

A Curved Canted Foil

While this completes the series of measurements made on thin, flat, rectangular foils, there is no doubt that swept-back shapes and curved foils also should be studied by someone. For curiosity, one "stab in the dark" will be made with one curved thin foil. There is no reason to believe that its curvature is an optimum.

Table D shows the result of a formed circular segment, deflected by 7 per cent of the chord, concave to leeward, for the best canted foil of Table C. It has a $2\frac{1}{2}$ in chord, a span of $3\frac{1}{2}$ in and employs the critical arm length of L/2 to leeward. In a full size boat, a separate foil would be employed for each tack because opposite curvatures are required. The single curved foil in use would always be to leeward. Thus a trimaran-like structure may be called for.

TABLE D

Model Hull Drag Angle Comparison for Flat versus Circular-Segment, Curved Foil of Same Dimensions and Leeward Placement. $2\frac{1}{2}$ in Wide by $3\frac{1}{2}$ in Span. Arm Length = L/2. Curved Foil Deflection = 7 per cent of Chord.

Leeway Angles	0°	$2\frac{1}{2}$°	5°	$7\frac{1}{2}$°	10°	$12\frac{1}{2}$°	15°
Flat Foil	39°	26°	17°	*12°	*12°	14°	16°
Curved Foil	23°	13°	*10°	*10°	12°	15°	17°

Table D indicates that we still have a lot of scope for improvement. The resulting drag angle of 10° is greater by only 1° than the best configuration ever measured by the writer. I can highly recommend canted foils which produce heeling compensation and lift, both horizontally and vertically.

CHAPTER XXIX

STEERING

by Edmond Bruce

January 1973

Conventional Rudders

The preface of this book stated that this compilation of articles was not a text book. Instead, it is restricted to discussions of sailing theory and experiment not readily found elsewhere. For this reason, I recommend the beautiful and exhaustive chapter on steering by conventional rudders contained in Chapter IV of "Principles of Naval Architecture", Volume II, by Rossell and Chapman. This has been a standard text at the Massachusetts Institute of Technology for many years.

In the above chapter are experimentally measured confirmations of theory for such characteristics of rudders as: Size, Shape, Aspect-Ratio, Thickness, Cross-Sections. Also discussed are: Rudder Depth, Leading Skegs, Hull Inclinations and Turning Circles, Bow versus Stern Locations, etc. Much of this material can be applied to other hydrofoils with benefit. My recommendations of thin foils with an aspect ratio of 1 are fully confirmed. These are highly effective over a broad angular range without stalling. This avoids sensitivity.

In spite of all of this information, anyone who has tested bare hulls in a towing tank and then systematically added appendages, one at a time, such as rudders, etc., knows the high penalty in running speed, for a given drive, that must be paid. A rudder has far above the frictional resistance of the added wetted surface, which is sometimes assumed.

A Dipping Rudder

In a suitably designed boat, there may be no need of a rudder when centred. Yet, in this position, the rudder may have frictional and vortex drag as great as 10 to 20 per cent of the hull's total drag. Why not have a rudder that is in the water only when turning is required? Also, the greater the turn, the more rudder area would become useful to avoid stalling. Such a rudder is shown in Fig. 1. (Drawing reprinted from page 96 of AYRS No. 76).

Fig. 1 proposes a simple tiller to rudder linkage. It automatically removes the rudder from the water when the tiller is centred. The rudder is progressively immersed as the angle of the tiller becomes greater.

Sail-Steering

I would like to discuss this proposition, "Why use rudders at all in sailing craft?". One can use variable sail-balance or variable hydrofoil-balance for steering, thus avoiding rudder resistance.

Rudders require forward motion of a boat before they are effective at all.

This is not true of steering by sail-balance. Most sailors are aware that the best way to leave a mooring, after casting off, is to back the jib. It turns the boat when it is stationary thus filling the sails with wind, after which normal sail trim is used.

Sail-steering is effected by initially having perfect balance on a straight course. This is a large advantage as one is forced to sail most efficiently. If a main and jib are used on a single mast, easing the jib causes the centre of the total sail effort to move aft of the centre of hull resistance. The craft will then turn into the wind. If, instead, the main is eased, the centre of total sail effort moves forward and the craft turns away from the wind. Thus, a sheet in each hand can both trim the sails and steer. It adds much interest to sailing.

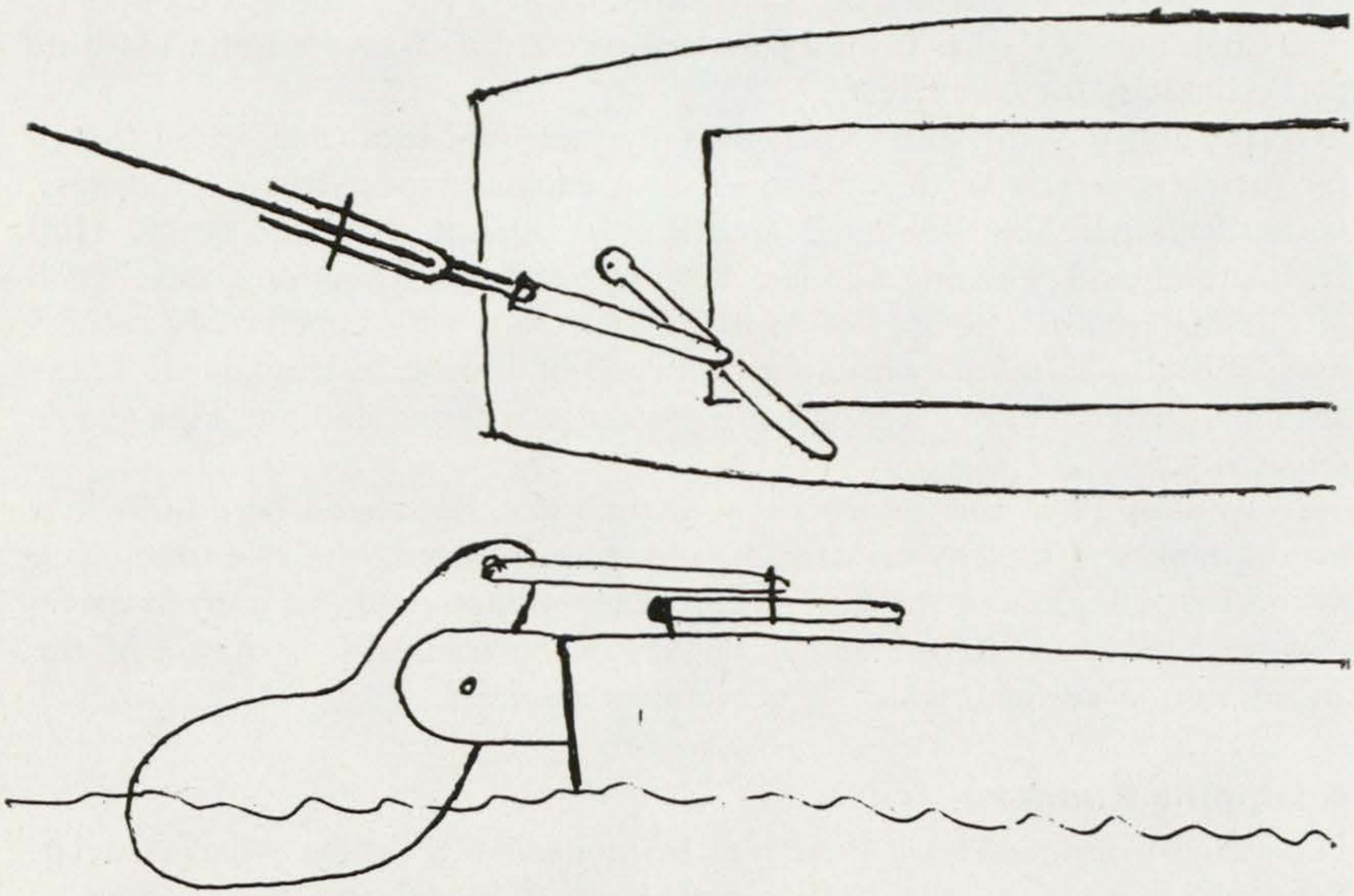


Fig. 1.

Sail-steering also works well when only a boomed jib is adjusted. It is eased or over-trimmed to turn both ways. This method has been used for over 50 years in the shallow but broad bays on the South Shore of Long Island, New York. Those who use this method there like it so much that they even put it on their ice-boats. This is helped by having "rocker" on their ice-boat runners.

An efficient, two-way proa design might use two identical masts with a boomed, identical sail on each. This not only achieves powerful sail-steering but solves the problems of two-way "shunt" sailing and of tack sailing completely and simply. It seems best to use 360-degree rotating masts without stays interfering with the booms.

Board-Steering

Instead of sail-steering, one might prefer steering by hydrofoil or board balance, either vertical or canted. Fig. 2 shows one of many possibilities. It is a plan view of a two-way proa with two canted foils, although one can be used, if desired. These are mounted on a simple pantograph with strong hinges. The foils are moved fore or aft by lines leading to the out-board structure or by tiller-like side extensions of the lateral arms, as shown.

A double canted-board structure is advantageous in improving directional stability in all three mutually perpendicular planes, in other words in yaw, pitch and roll. Down-wind tacking is faster for these boats. For this reason, there is always some side force on the sails, thus down-wind steering problems need not occur.

Folding of the pantograph structure can be useful in narrow channels or where wide beam is objectionable. The foils can be brought near to the side of the main hull. Sail area would be used only at that end of the boat to achieve near balance. Under these conditions, since board steering has been discontinued, a dipping rudder would be desirable for steering.

Monohulls can achieve steering with two centreboards. These are simply raised and lowered in various combinations. Also, a variable total board area is provided. In running dead before the wind, some side-force in the sails is desirable.

Self-Steering

Several members of AYRS have commented in their writings on the inherent self-steering properties of proas and foilers, also their sailing models. How this comes about may appear to be a mystery. It need not be so. The explanation which follows may be timely in view of a growing interest in this subject.

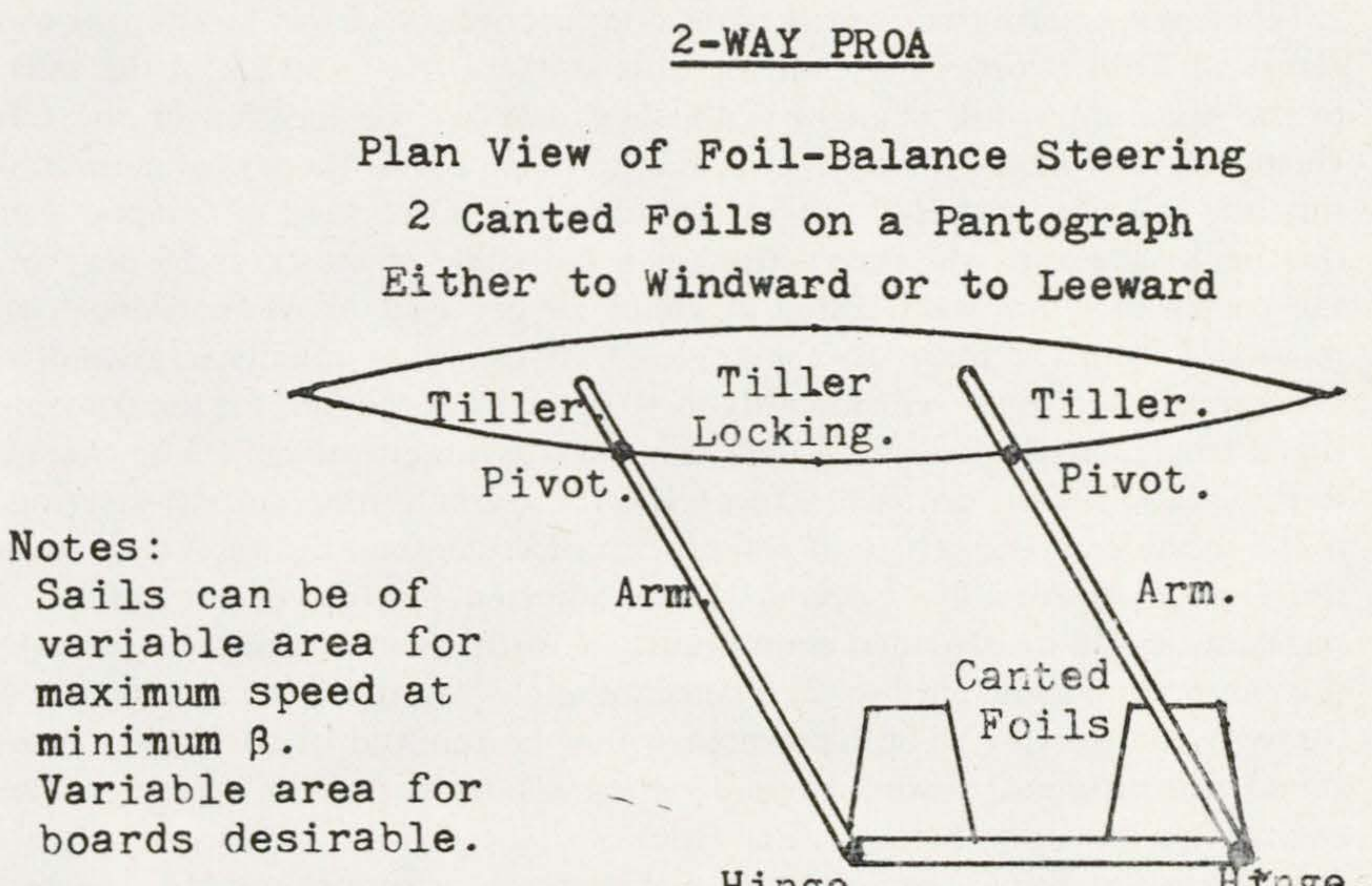


Fig. 2.

First, it is well to point out that there are two basic methods for self-steering. One is the auto-pilot controlled by a selected compass course. The other is directed by a chosen course angle "β" to the apparent wind. It is the latter that will be discussed in this writing.

Non-electrical wind-vane steering attachments are, of course, well known. Also, a wind-vane directed electrical auto-pilot, such as described by Henry Morss in Chapter XIII of this book, is highly satisfactory. However, it is possible to design a sailing craft so that it will inherently follow selected course angles to the apparent wind without resorting to any accessory attachments whatsoever. These now will be discussed.

Inherent Self-Steering

In operation, an inherently self-steering boat is first directionally balanced by adjusting sails and boards for a selected course angle β to the apparent wind so that it will follow a straight course. If the wind direction changes, this boat will chase the wind to re-establish the initial balance. It will also re-establish the previous course angle β and the previous desirable trim of the sails. At some later period, if there are directional wind shifts, the navigator may have to revise his original course plan so as to arrive at the desired destination. The way that the craft self-steers may be as follows:

A good proa or a foiler has a high length to beam ratio hull that does not make appreciable waves. They are designed so that there is little lateral resistance in the main hull. The lateral resistance is concentrated in their foil or foils. This arrangement means that the centre of total resistance is nearly fixed in position in spite of changes in the wind direction or its strength. This resistance always equals and opposes the wind-generated resultant force on the sails.

When self-steering is present, it is due to changes in the location of the centre of wind effort, "CE", on the sails as the angle of attack of the sails, to the apparent wind, changes. Published data on the location of the CE versus angle of attack for cloth sails is scarce. However, the writer measured this in a full size "tethered test" of a dinghy sail as reported in Chapter I of this book. There it was shown that, at a sail angle of attack of 15 degrees, the centre of effort was located at about 20 per cent of its foot-length as measured from the mast. As the angle of attack was gradually increased to 90 degrees, the CE moved smoothly to 40 per cent of the foot for the conventional triangular shaped sail (50 per cent for a symmetrical sail). The change in the location of the centre of effort CE is the secret of inherent self-steering, if the location of the centre of resistance of the dominating water foils does not change appreciably. Locking of the adjusted position of the centre of resistance could be provided continuously if worm-gear steering was used on the pantograph shown in Fig. 2. A constant angle β would then be maintained through self-steering. The helmsman would be relieved of all but an occasional readjustment. I would enjoy sailing a boat with such steering. One could often leave the helm unattended.

Referring to Fig. 3, representing a close reach, a simple, canted, leeward foil of a foiler is shown directly in line with the sail force. The equal and

ONE-WAY
PROA
WITH LEEWARD FOIL.

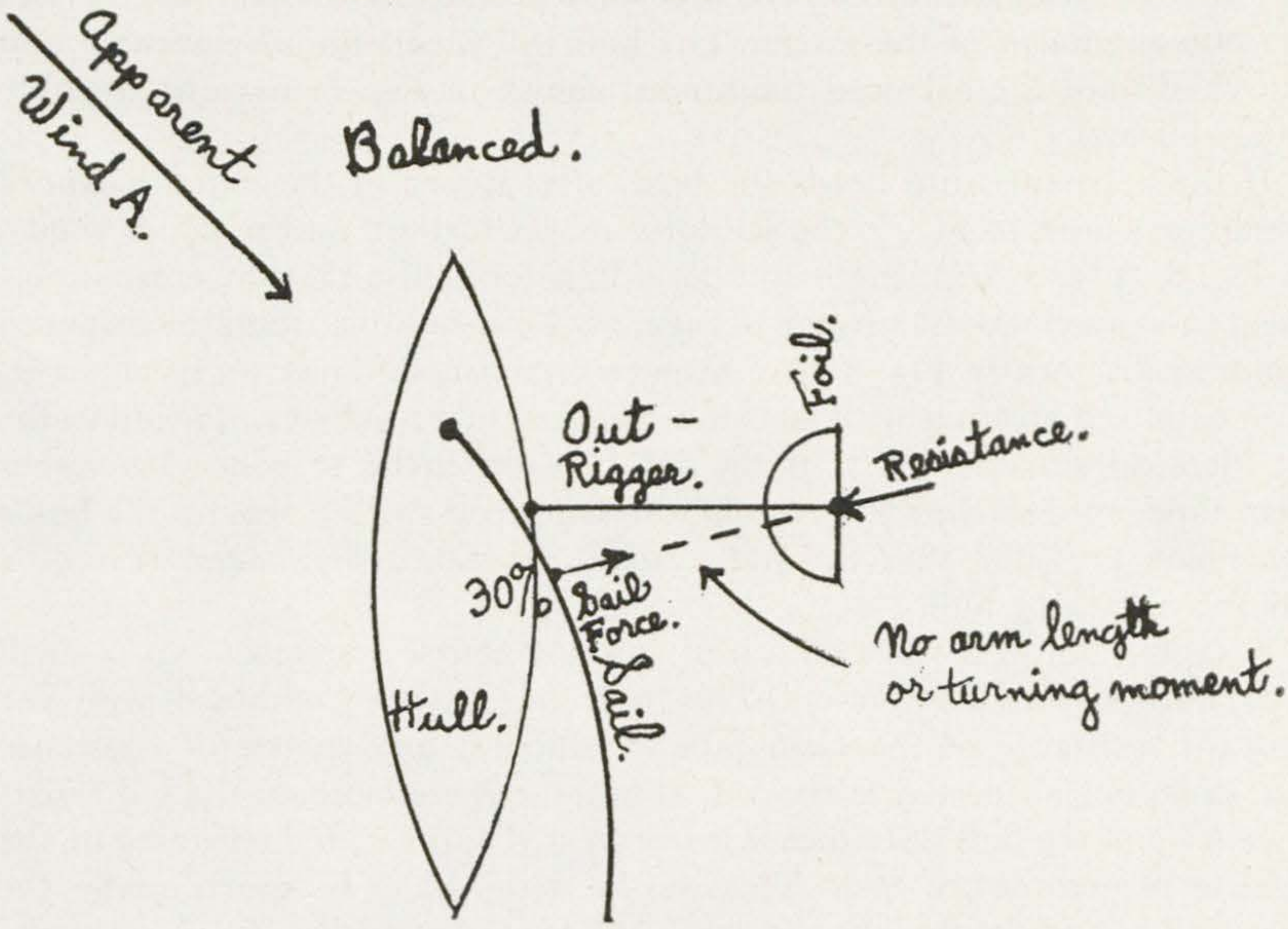


Fig. 3.

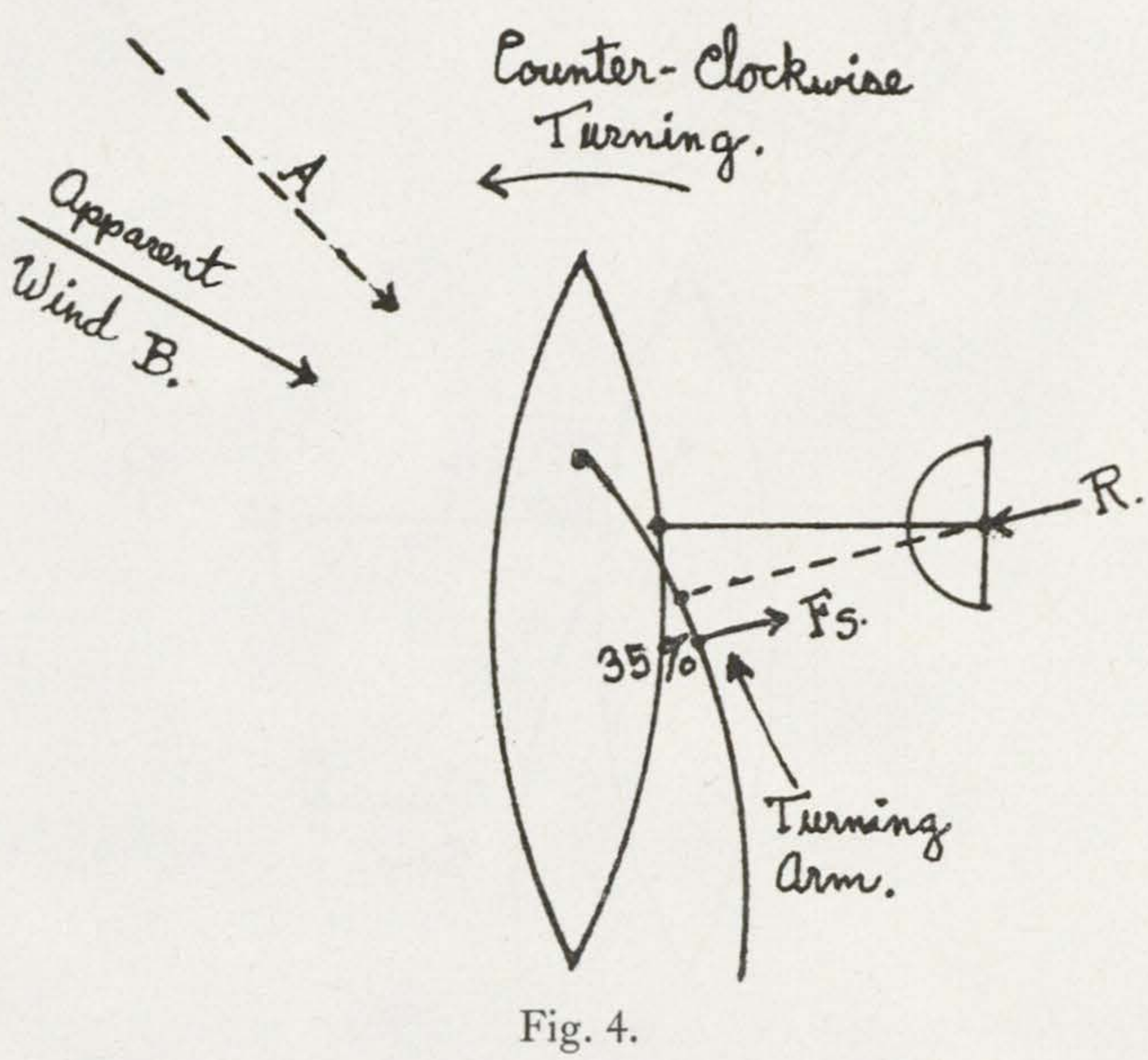


Fig. 4.

opposing sail force and total hull resistance have no length to their moment arm, therefore the hull will not alter its course.

If the apparent wind swings in a fuller direction, as shown in Fig. 4, the sail force moves backward on the sail. This produces a moment arm due to the non-alignment of the forces. The hull will turn counter-clockwise into the wind until the balanced conditions, shown in Fig. 3, have been stably re-established.

If the apparent wind heads the boat, after it was in the initial balanced condition shown in Fig. 3, the sail force moves forward on the sail as shown in Fig. 5. A force-arm length and position is formed so that the created moment causes a clockwise turning of the hull. This continues until the balanced conditions shown in Fig. 3 have been re-established. Thus we have stable, automatic self-steering without wind vanes or other gadgets. Theoretically, an identical situation exists if the foil happens to be to windward rather than to leeward as shown. It would also happen if the foil was on the hull's centreline provided that the foil's lateral resistance dominated that of a non-wave-making hull.

A canted foil of a foiler on a near running course generates only a small resistance to forward motion. This resistance, when combined with the forward resistance of the main hull, produces a total centre of resistance that is no longer located at the foil. It is somewhere between the foil resistance R_F and the hull resistance R_H shown at R_T in Fig. 6, depending on the relative magnitudes of each. This can be designed to be nearly under the centre of sail effort, shown at E, when the boom is positioned normal to the apparent wind. If the apparent wind shifts to a direction marked F or G in

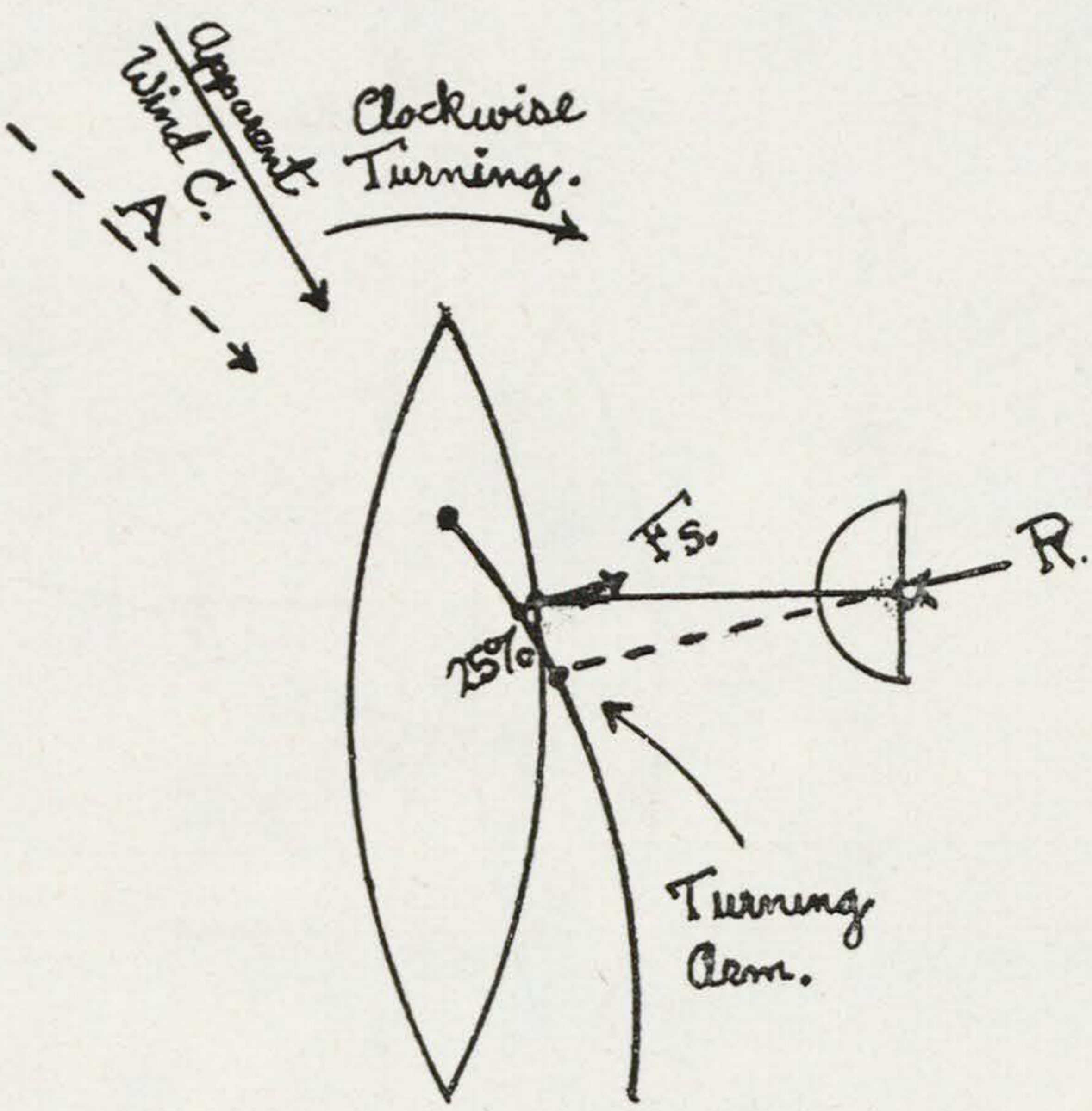
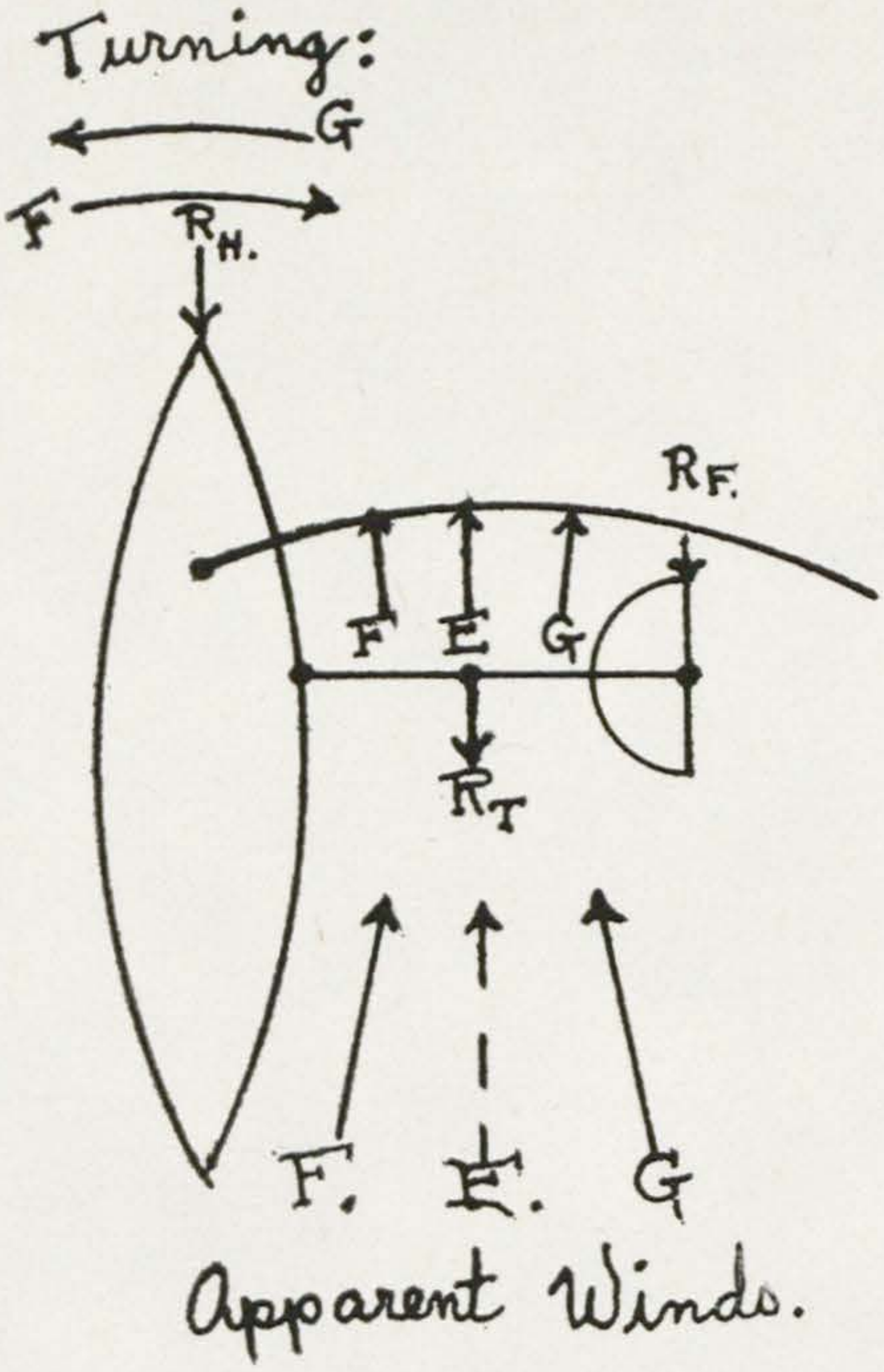


Fig. 5.



Notes for Figs. 3-6*:*
A windward foil or a centre-line foil works similarly. "Dipping" rudder suggested for steering in an emergency

Fig. 6.

Fig. 6, the previous type of force position changes occur in the sail. Restoring turning moments are produced as were described. Thus we have inherent self-steering on all courses for a uni- or bi-directional proa. No external devices are needed and their possible mal-function is avoided.

It was interesting that Dick Newick's two-way proa *Cheers* sailed the Atlantic twice with only Tom Follet aboard in the 1968 "Single-Handed Trans-Atlantic Race" and the voyage to that race. During rest periods, he was glad that he had reliable inherent self-steering with no gadgets to get out of order. There is real elegance in a design which steers itself inherently without a rudder. Let us hope to see many more of these in the future.

In most conventional hulls, having low length-beam ratios, the centre of hull resistance changes with both course and speed due to generated waves. This usually defeats inherent self-steering although a few such mono hulls exist that do self-steer over limited angular ranges, usually to windward. The writer's 1947, mono hull, ocean-cruiser *Aqualure* was deliberately designed in a towing-tank to do this with the help of two centre-boards and a specially shaped hull form. This was discussed in Chapter XXIII in connection with hull models.

Catamarans and trimarans have centre of resistance location changes. These are due to the variable relative immersions of their several hulls with changes in wind strength and direction. These make inherent self-steering more difficult to achieve since the direction of these movements is usually unfavourable.

PART SEVEN

FUTURE DESIGN, RESEARCH, AND DEVELOPMENT

CHAPTER XXX

DESIGNING FOR FAST SAILING

by Edmond Bruce and Henry A. Morss, Jr.

July 1973

Several of the chapters of this book give information which can be put together in the design of fast sailing craft. The essential theory has been set forth. Experiments have shown a direction for meeting every element of the theory.

The Essential Criteria

The route to high-speed sailing involves three steps:

1 Eliminate the "hull-speed" or "wave-making" barrier.

2 Increase sail carrying capacity.

3 Reduce drag angles of rig and hull and hull force coefficient; increase sail force coefficient.

This third criterion is a combination of many things. Some people may prefer to express it as several separate criteria, rather than a single comprehensive one. However that may be, the points to be dealt with are the same.

The Canted-Foil Boat

The elimination of the "hull-speed" restriction can be achieved by suitable design of the main hull. As we have seen in Chapter XXII, a long, slender hull makes very slight waves on the surface of the water and can be driven rather easily far beyond the conventional "hull speed" of displacement craft.

With a canted foil on a long arm, the second of the basic criteria can be met, because the boat can be designed to be "non-heeling" with any rig and thus can indulge great sail-carrying capacity. This is expounded in Chapter XXV. There will be no reduction of driving force due to heeling. If the foil is to leeward and canted at 45°, there will be a reduction of effective displacement in amount equal to the side force of the sails.

We are in position, then, to look into the details and refinements called for in the third major criterion, through reduction of the drag angles and the hull force coefficient and increase of the sail force coefficient.

The outline in the next few paragraphs will not be limited to the canted-foil boats. We shall come back to those as a special case after setting down the basic rules. It is vital to remember, in applying the formulae, to use values of all the parameters appropriate to the particular sailing craft and situation of each calculation which is made.

The Drag Angles

The primary requirement of reducing the drag angles is evident in the theoretical, or purely geometrical, limits to speed which have been reviewed in detail in Chapter VIII. There we see the relationships between possible speed and beta, the angle between the course and the apparent wind. Small beta is essential to high speed. That beta is the sum of the drag angles of the hull and the rig (the entire underbody and everything above water exposed to the moving air) is elucidated in Chapter III. Thus both drag angles must be low for fast sailing.

Highly efficient sailing craft on the water are known to sail well at beta of 22° (see Chapter X). Perhaps even slightly lower values can be achieved. In any case, at 22°, beta is not the limiting factor today in designing for speed. We know that we are not yet at the point of reaching the theoretical limits for beta equal to 22°. Thus we turn to the more difficult study of the force coefficients in our search for improvement.

The Force Coefficients for Sail and Hull

Now we recall the relationship between the coefficients, the sail area, the weight, and the ratio of boat speed to apparent wind speed, first given as formula (A) in Chapter IV:

$$\frac{V_B}{V_A} = 0{\cdot}585 \; \frac{\sqrt{A_S}}{\sqrt[3]{W}} \sqrt{\frac{C_S}{K_H}} \tag{A}$$

Since usually we are more interested in the ratio V_B/V_T, we look to the form of this given as equation (D) of Chapter IX:

$$\frac{V_B}{V_T} = \frac{\sin\gamma}{\sin\beta} \times 0{\cdot}585 \; \frac{\sqrt{A_S}}{\sqrt[3]{W}} \sqrt{\frac{C_S}{K_H}} \tag{B}$$

or

$$\frac{C_S}{K_H} = 2{\cdot}92 \; \frac{W^{2/3}}{A_S} \left(\frac{V_B \sin\beta}{V_T \sin\gamma}\right)^2 \tag{C}$$

and

$$A_S = 2{\cdot}92 \, W^{2/3} \left(\frac{V_B \sin\beta}{V_T \sin\gamma}\right)^2 \frac{1}{C_S/K_H} \tag{D}$$

This latter form can be used directly to design for a given speed and angle of sailing. This is now a practical approach, because, as we have seen, we can choose a hull which can be driven easily to very high speeds and can fit it with a canted foil which will enable it to carry any desired amount of sail (within reason) without heeling.

Right here is a wholly new concept of designing for speed. Pile on enough sail to give the desired speed (but without overloading the water foil and causing a "stall").

Our formula (D) is complicated to visualise. If we elect to design for maximum possible speed made good to windward or for maximum possible theoretical boat speed for a given value of beta, we can simplify it by incorporating the appropriate relationships from Chapter VIII. Thus for maximum to windward, we substitute $\cos \gamma/\sin \beta$ for V_B/V_T and $45° + (\beta/2)$ for γ to see that

$$\text{For max. } V_{MG}, \quad A_S = \frac{2{\cdot}92\, W^{2/3}}{\tan^2 [45° + (\beta/2)]} \; \frac{1}{C_S/K_H} \tag{E}$$

An alternative form of this, derived most easily from the expression for max. V_{MG}/V_T, is

$$\text{For max. } V_{MG}, \quad A_S = 2{\cdot}92\, W^{2/3} \frac{(1 - \sin \beta)^2}{\cos^2 \beta} \cdot \frac{1}{C_S/K_H} \tag{E}$$

Similarly, for maximum possible theoretical boat speed, we substitute $1/\sin \beta$ for V_B/V_T and $90° + \beta$ for γ:

$$\text{For theor. max. } \frac{V_B}{V_T}, \quad A_S = 2{\cdot}92\, W^{2/3} \frac{1}{\cos^2 \beta} \; \frac{1}{C_S/K_H} \tag{F}$$

Of course all these formulae show that required sail area will decrease with decreasing weight and hull force coefficient and with increasing sail force coefficient.

It is not proper, however, to take the next step and attempt to deduce the changes in required sail area as beta is varied, because, as beta varies, in most cases the drag angle of the hull, δ_H, will vary, too, and with it K_H. Perhaps also C_S may vary. Until we can estimate these variations with beta, we can't carry this part of the analysis further. (One approach to this which we shall not explore here but shall simply mention is that for rough figuring it may be worth trying the assumption that K_H is proportional to $1/\sin \delta_H$. With this and guesses for δ_H, δ_S, and C_S as beta varies, we can figure numerical examples to see how they behave.)

Both of these formulae call for rapidly increasing sail area as beta decreases. That is no surprise. To get the higher boat speeds, much more power is required and hence more sail. The exact amounts of the increases in sail area can not be stated in general terms, because the variation of K_H with beta is by no means the same from boat to boat.

By comparison of formulae (E) and (F) at a given value of beta, we do see that *much* more sail area is required for maximum theoretical boat speed than for the boat speed needed for best possible speed to windward; for $\beta = 30°$, four times as much; for $\beta = 25°$, three times as much; for $\beta = 20°$, 2·3 times as much; and for $\beta = 15°$, 1·8 times as much. (For that ice boat which sailed very fast at $\beta = 8{\cdot}2°$, about 1·35 times as much.) (These numbers are based on the assumption that C_S and K_H do not vary when beta is *un*changed while speed increases greatly.)

A Fixed Design Goal

As we digest the magnitudes of the sail areas called for on this kind of reasoning, we may react that it is difficult to decide whether to put our effort into lower beta or into the coefficients. One useful way to guide our choice in this is to explore the interrelationship at a fixed value of V_B/V_T. As an example, we choose $V_B/V_T = 2$ and $\sqrt{A_S}/\sqrt[3]{W} = 2$. We then can use formula (A) to find the value of C_S/K_H for each circle of constant ratio V_B/V_A. This has been done in Fig. 1. The numbers in circles beside those constant ratio circles are these values of C_S/K_H.

Now we can pick off corresponding pairs of C_S/K_H and β at the intersections with the circle for $V_B/V_T = 2$. In this way we get the interrelationship between C_S/K_H and beta as plotted in the middle curve in Fig. 2. The upper curve is the same thing for $\sqrt{A_S}/\sqrt[3]{W} = 1{\cdot}75$ and the lower, for $\sqrt{A_S}/\sqrt[3]{W} = 2{\cdot}25$, both still for $V_B/V_T = 2$. The corresponding values of gamma are noted. (This can be done from the formulae rather than from the graph and has been done that way for Fig. 2 to assure reasonable accuracy.)

We must remember that for each of these three curves there is one value of sail area, since each corresponds to a fixed ratio $\sqrt{A_S}/\sqrt[3]{W}$. To figure those areas, we can write $A_S = (\sqrt{A_S}/\sqrt[3]{W})^2 \times W^{2/3}$. For a boat weighing 1,000 lbs, this will be 310 sq ft for the top curve, 400 for the central curve, and 510 for the bottom one.

These curves point to something we have not seen before so directly. They throw into question the perhaps premature statement above that "In any case, at 22°, beta is not the limiting factor today in designing for speed". The curves show us that very high values of C_S/K_H are required. While we are not in a position to be didactic about the numbers, it does seem likely that the values of C_S/K_H which must be met if V_B/V_T is to reach 2 are much more likely to be possible in the range of beta from 20° to 25°, more or less, than at 30°. As beta approaches 30°, these curves become very steep and reach values of C_S/K_H which are probably unattainable at the present time.

Surely this is another valuable point for consideration in designing for speed. If a fixed value for V_B/V_T is set as the objective, very careful estimates will have to be made of each of the drag angles separately and of the values of the corresponding force coefficients at each value of each drag angle as a part of the process of working out a practical design in which the sail area is something less than astronomical.

Maximum Speed versus Sail Area

It is tempting to wonder if there exists a direct relationship between the maximum possible speed of a craft sailing on the water and her sail area or her ratio $\sqrt{A_S}/\sqrt[3]{W}$. The merest glance at the formulae shows that there is no *unique* relationship. The following reasoning leads to the conclusion that there is a close connection.

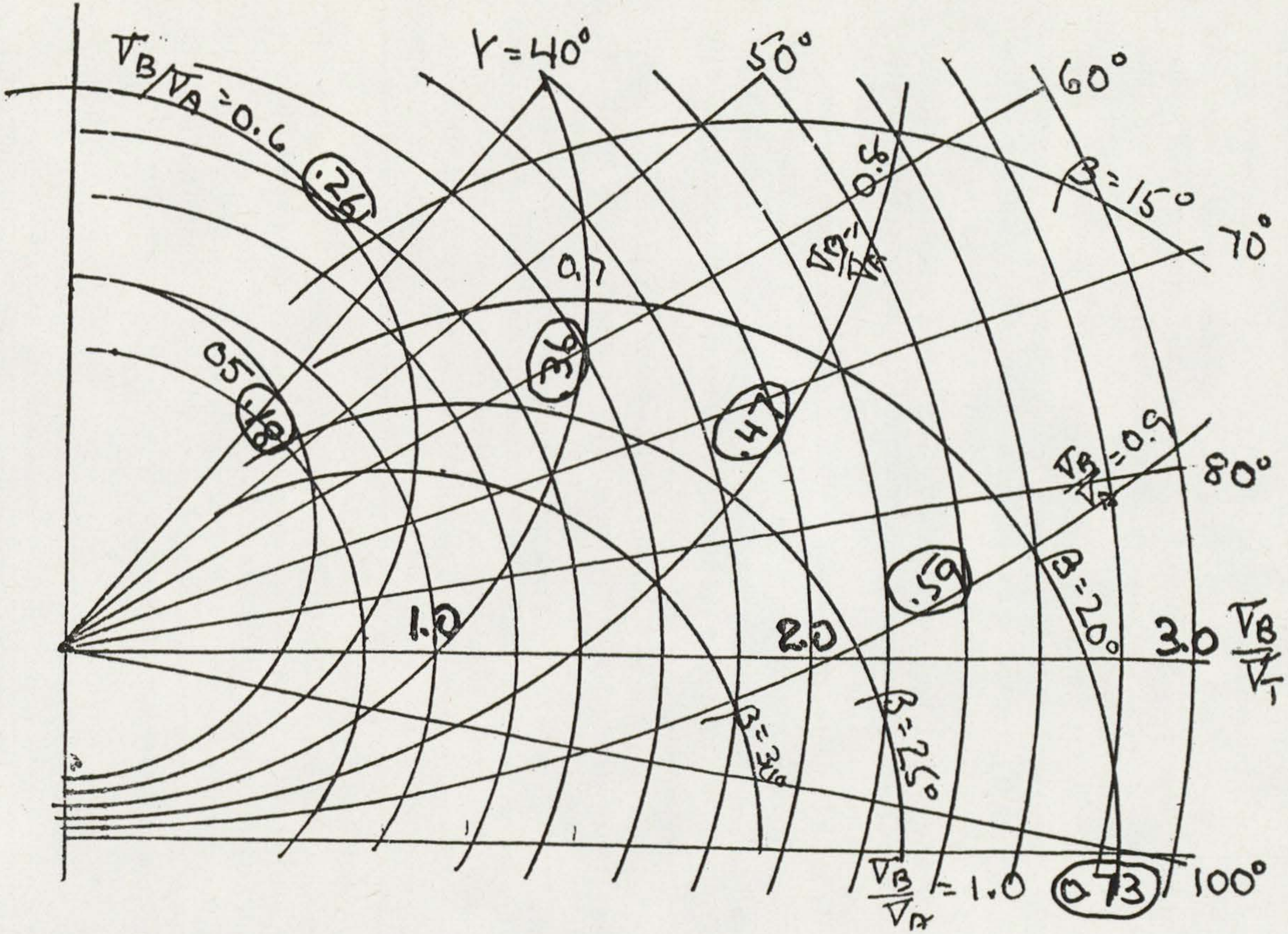


Fig. 1. C_S/K_H plotted on the orthogonal circles (figures in circles) for the case $\sqrt{A_S}/\sqrt[3]{W} = 2$

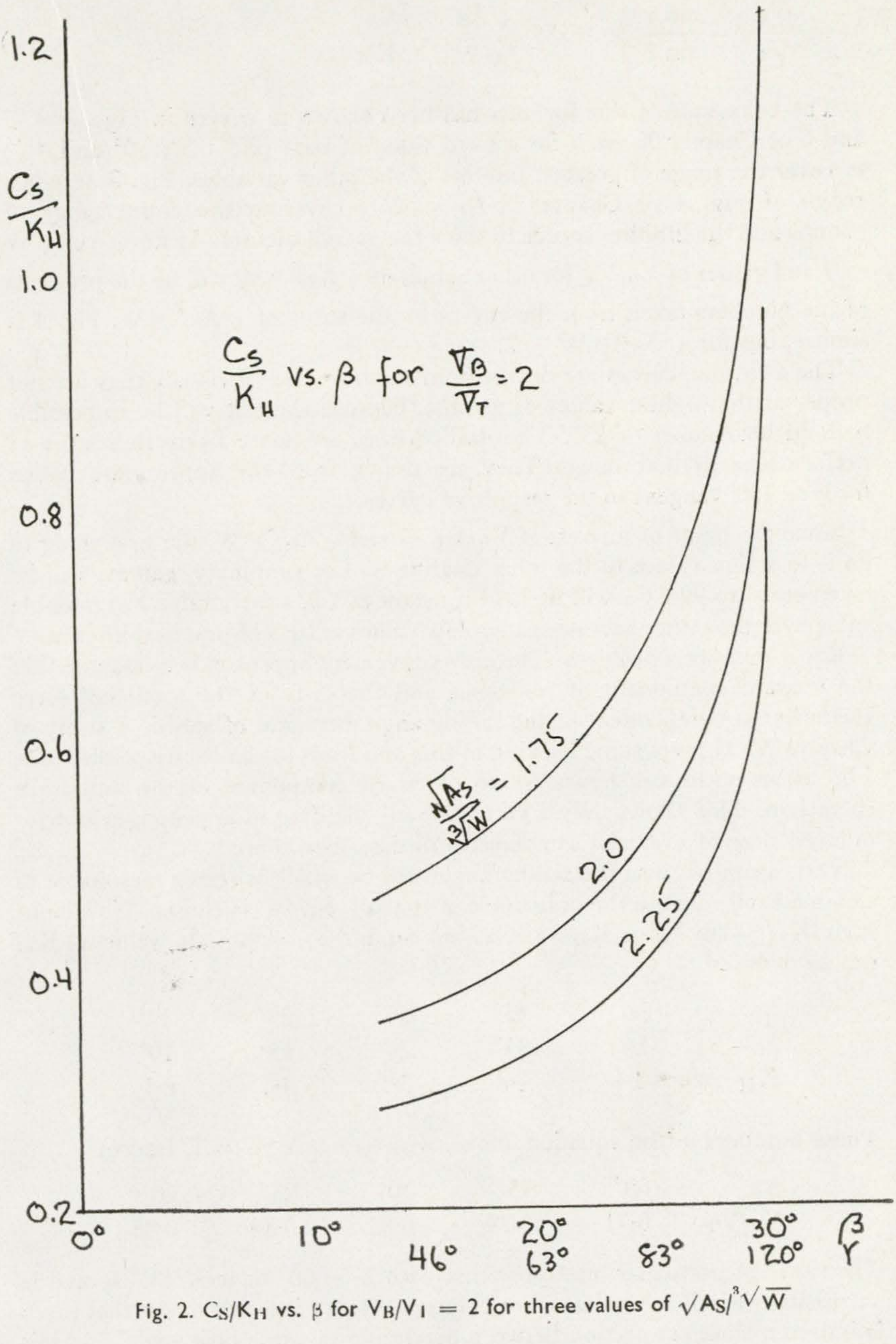


Fig. 2. C_S/K_H vs. β for $V_B/V_I = 2$ for three values of $\sqrt{A_S}/\sqrt[3]{W}$

For this, the useful form of the basic equation is

$$\frac{V_B}{V_T} = \frac{\sin\gamma}{\sin\beta} \times 0{\cdot}585 \; \frac{\sqrt{A_S}}{\sqrt[3]{W}} \sqrt{\frac{C_S}{K_H}} \qquad \text{(B)}$$

The behaviour of this formula has been shown in curves in Figs. 3, 4, 5 and 6 of Chapter X, each for a fixed value of beta (20°, 25°, 30° and 40°) to cover the range of greatest interest of the other variables. Fig. 3 here is a replot of Fig. 4 of Chapter X ($\beta = 25°$) covering the entire range of gamma and the limiting speeds to show the overall picture. Again $\sqrt{A_S}/\sqrt[3]{W} = 1$ and values of V_B/V_T for other values of $\sqrt{A_S}/\sqrt[3]{W}$ will be the products of the numbers taken from the curves by the value of $\sqrt{A_S}/\sqrt[3]{W}$. Fig. 4 is similar, but for $\sqrt{A_S}/\sqrt[3]{W} = 2$.

The solid line curves are drawn from the formula. Obviously they are not proper at the highest values of gamma, because there it will be impossible to hold beta down to 25°. The dashed lines are more likely indicators of performance in that range. They are drawn from the appropriate points for $\gamma = 180°$ tangent to the respective curves.

Since the point of interest is V_B/V_T versus $\sqrt{A_S}/\sqrt[3]{W}$, the first thing to do is to assign values to the other quantities. For simplicity, gamma will be taken equal to 90°. C_S will be held constant at 1·5, a favourable but possible value over the rather narrow span of low values of beta of practical interest.

K_H is more of a problem. The only convenient approach is to assume that the forward component of resistance and therefore of the total hull force coefficient is independent of the sailing angle beta and of speed. A study of Chapter XXII gives some backing to this and leads to the choice of the value 1·05 as an optimistic figure for the forward component of the hull force coefficient. This allows only a very little for the drag of appendages and for induced drag of even the slenderest hull described there.

Next, again because the sailing angle will be small, it seems reasonable to assign a fixed value to the drag angle of the sail, δ_S. 10° is chosen. Now since $K_{HF}/K_H = \sin\delta_H$ or $K_H = K_{HF}/\sin\delta_H$ and $\delta_H = \beta - \delta_S$, values of K_H can be deduced.

β	60°	45°	30°	25°	20°
$\beta - \delta_S$	50°	35°	20°	15°	10°
K_H	1·4	1·8	3·1	4·1	6·1

These numbers in the equation above, with $\sqrt{A_S}/\sqrt[3]{W} = 1$, lead to

β	60°	45°	30°	25°	20°
V_B/V_T	0·71	0·74	0·82	0·84	0·85

The range of particular interest is that with $\beta = 30°$ or less. The spread is surprisingly small in the last three columns. Hence it is fair to say that there is indeed a close connection between maximum possible boat speed and sail area, almost independent of β.

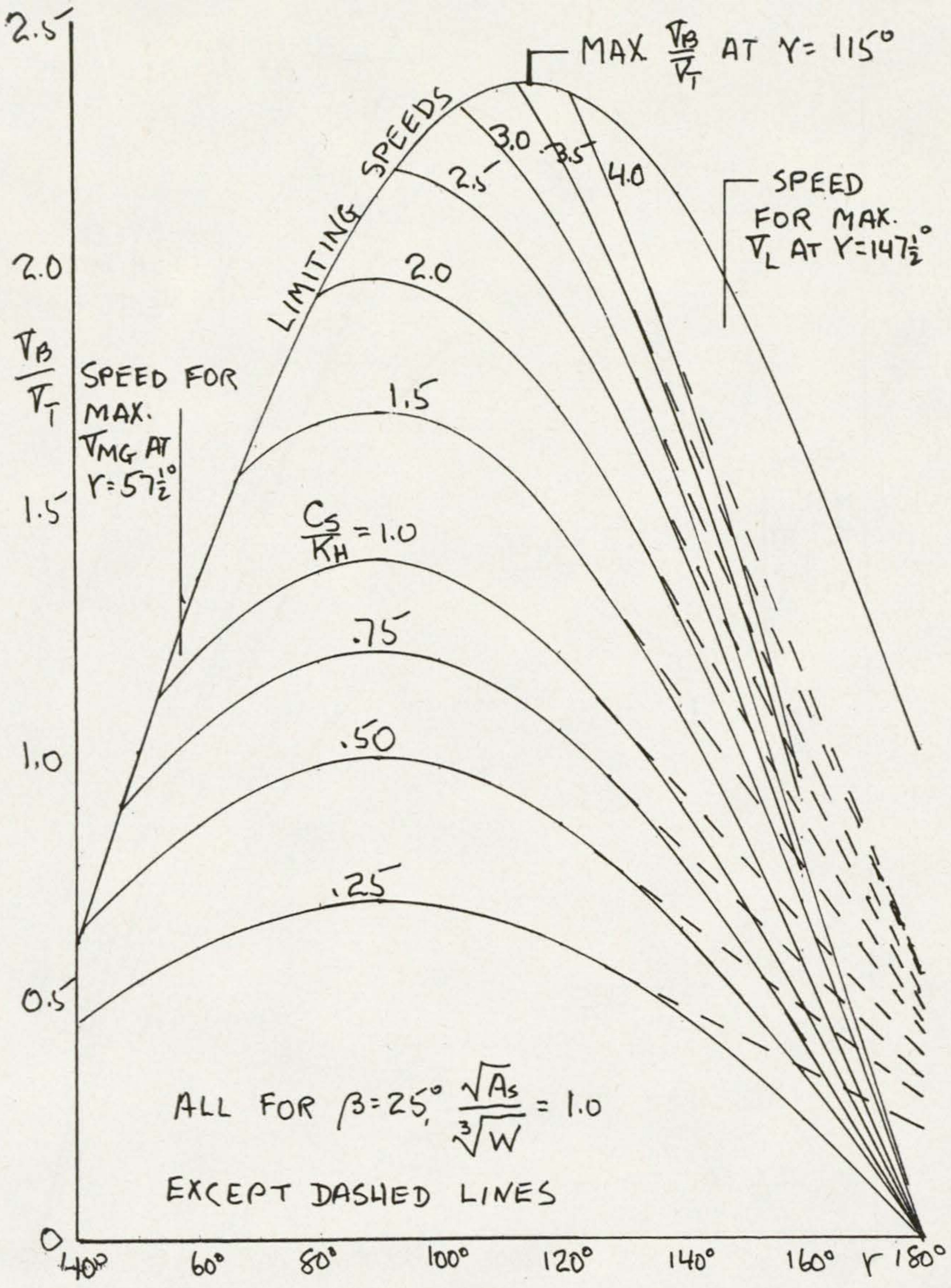


Fig. 3. V_B/V_T vs. γ for $\beta = 25°$, $\sqrt{As}/\sqrt[3]{W} = 1$

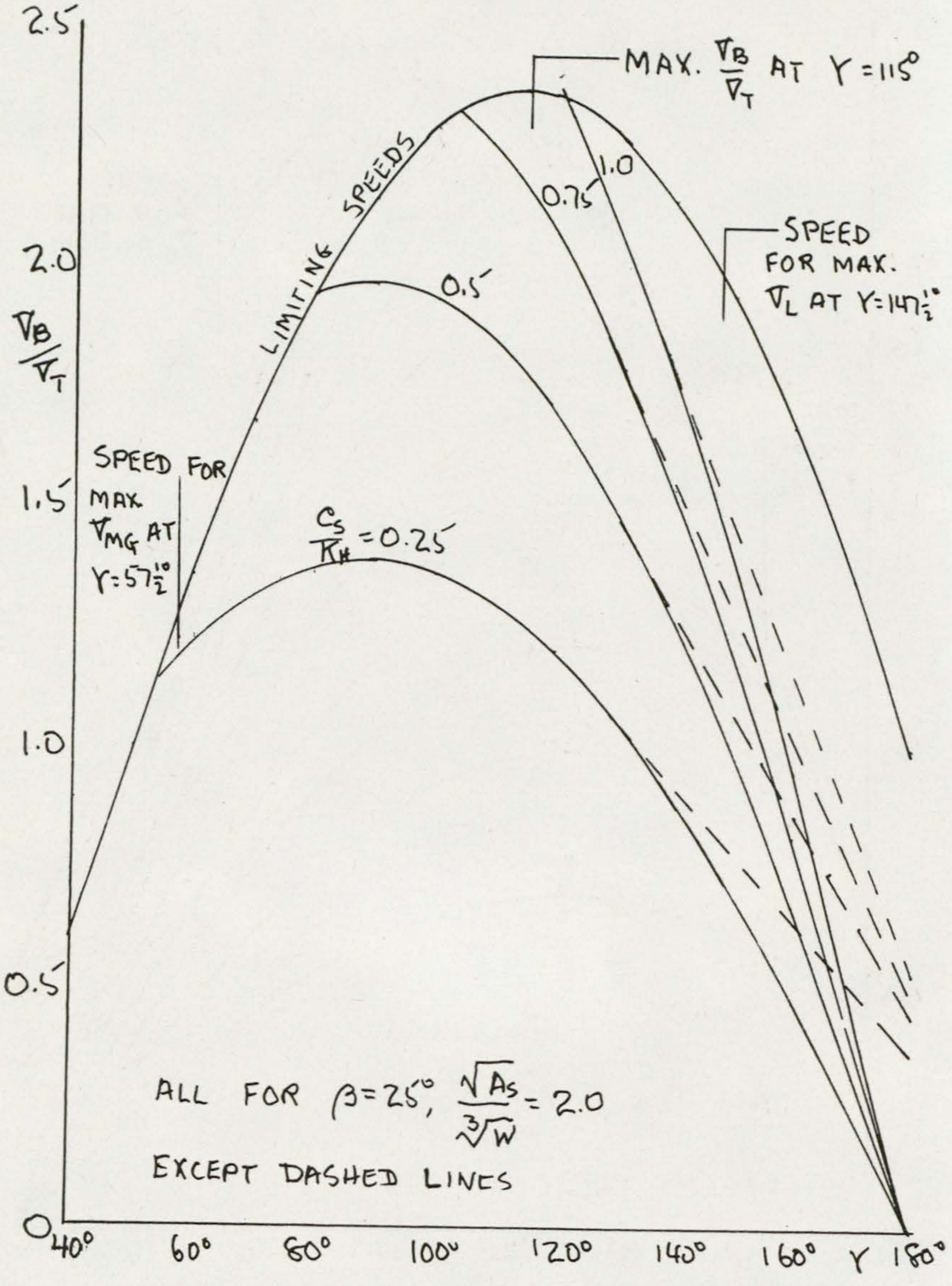


Fig. 4. V_B/V_Γ vs. γ for $\beta = 25°$, $\sqrt{A_S}/\sqrt[3]{W} = 2$

These figures are for $\sqrt{A_S}/\sqrt[3]{W} = 1$. The formula shows V_B/V_T proportional to that ratio. Thus a straightforward calculation gives us that "close connection". The value $V_B/V_T = 0{\cdot}84$ at $\beta = 25°$ is taken as a representative starting point.

$\sqrt{A_S}/\sqrt[3]{W}$	1·0	1·25	1·5	1·75	2·0	2·25	2·5
Max V_B/V_T	0·84	1·05	1·3	1·5	1·7	1·9	2·1

The result is plotted in Fig. 5.

For this study, everything has been taken at its most favourable—the form of hull and the likely values of the drag angles and the force coefficients. In practical cases these values are not likely to be exceeded significantly. (It is safest to exclude "flying hydrofoil" boats from this reasoning for lack of knowledge of their "hull" force coefficients and in the face of some doubt that they can yet sail well at beta angles as low as 30°, not to mention 25° or 20°.)

A rough check is easily made by taking figures from Chapter X or Appendix D:

Boat	$\sqrt{A_S}/\sqrt[3]{W}$	Highest reported V_B/V_T	Value from above
Tornado and other fast cats	1·8	1·4–1·5	1·5
Crossbow	2·3	2·0	1·9

This is a good fit in view of the rough estimates which entered the calculations.

The Many Refinements

These several equations and graphs give us the background for working rather specifically toward a desired goal. They give us precise numbers which must be met in a given situation. In effect, they restate the problem in the form "Improve the design in every possible way in order to reduce the needed sail area to the lowest possible figure". Some practical or possible values of these parameters are tabulated in Appendix D and its antecedents. The further refinements will be discussed briefly in the next chapter in terms of experimental and theoretical work which is needed for future improvements in sailing speeds.

Other Interrelated Factors

The reasoning above relates to boats sailing on smooth water in ideal conditions. As more experiments along the lines just described are carried out, especially those with boats having very large sail rigs, attention will have to be given to many other factors. At some point, stern-over-bow capsize will become a real worry. Will waves from various directions create unexpected problems for craft of these extreme types? etc., etc.

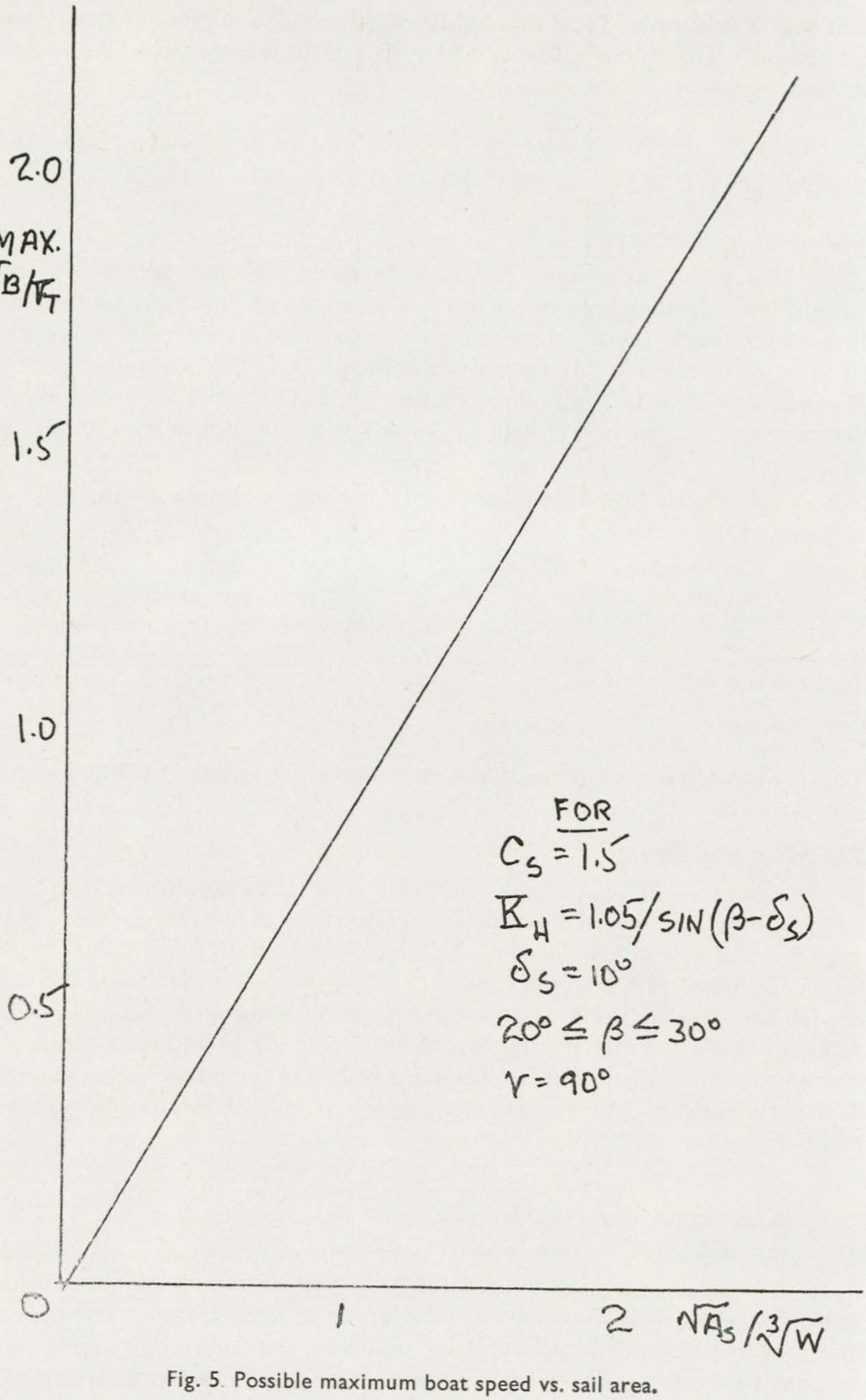


Fig. 5. Possible maximum boat speed vs. sail area.

Applicability

These considerations are applicable to any boat, so long as correct values of the several parameters are used in each and every calculation, as was pointed out just ahead of the paragraph entitled "The Drag Angles".

However, they may not be very broadly useful. For instance, it is hard to imagine applying them to heavily-ballasted displacement boats. Such boats can not reasonably be driven at the high speeds implied here. Presumably no one knows what their hull force coefficients would be at extreme speeds.

One may ask about the applicability of our rules to planing boats and flying hydrofoil boats. The answer is that there will be no problem if the hull force coefficients properly reflect the performance of the hull in each case, as is required anyway.

Back to the Canted-Foil Boats

Among others, of course, we may apply this theory to the canted-foil boats. If in doing this we overlook the dynamic lift provided by the leeward, canted foil and the consequent reduction of actual displacement of water by the entire structure, we should expect to find values of sail area larger than those which will be needed for a desired speed.

The simple theory suggests that we should reduce W in the formula by the product of the side force of the rig and the cotangent of the cant angle (measured from the horizontal). This would raise the necessity of a separate calculation for each wind strength.

Tests of this in the towing tank or at full size have not yet been comprehensive enough to tell us how far we can carry this idea. Until there are more data, the authors suggest caution. There are, needless to say, imaginable complications which may blur the picture. In some degree at least, the necessary amounts of sail area will not be quite so extreme. Here lies one of the great excitements and challenges in pressing forward with this type of design.

Other Possible Forms

A reader may infer from the preceding sections of this chapter that the non-heeling type of boat with very slender hull is the only way to get maximum sailing speed on the water. Can no other form of craft match it? At the present time and in the present state of their knowledge, the authors believe that the canted-foil boat has the most promise.

While they do not look on a "flying hydrofoil" sailboat as likely to be faster, they can not exclude the possibility. Their view involves two principal thoughts:

1 There is doubt that flying hydrofoils can sail effectively close enough to the apparent wind (small enough beta).

2 The force which lifts the hull or hulls out of the water is a part of the precious driving force component of the total sail force. Thus the force left to develop forward speed is less for the flying hydrofoil than for the

non-heeling boat (with the same sail area). This loss of driving power seems likely not to be wholly offset by higher efficiency looked for in the underwater parts of the flying hydrofoil.

Admittedly these remarks are made at what may prove to be a very early stage in the development of foil systems for flying hydrofoil boats. Innovations not yet conceived may change the picture, in the face of the sizable complications and great range of possibilities which obviously exist.

What is in the Record?

Let us review very briefly the history of the fastest sailing craft.

a The Fast Racing Catamarans. These boats have reached V_B/V_T of 1·4 or a little higher in light and moderate winds. Within their sail area limitations, the only hope for better speed is in reducing weight and improving the force coefficients. Only modest further improvement seems likely.

b Flying Hydrofoil Boats. One of these, the *Icarus*, was second in the Players competition of October 1972. At her maximum speed, her V_B/V_T was only 1·14. She probably never sailed at beta as low as 35°. She did not match the fastest reported speed of a D-Class catamaran. Great further improvement does not seem imminent.

c "Non-heeling" craft. While several of these have been built and sailed in recent years and have demonstrated the correctness of the concept, none has had enough sail area (high enough ratio $\sqrt{A_S}/\sqrt[3]{W}$) to attain very high speeds, as far as we know. We look to the day when there will be a real test.

d Outriggers. The *Crossbow* sailed fast in 1972, even though she was probably then at an early stage in her development. More than likely she will be improved in many ways to give better performance. A canted foil to leeward seems to be a natural for her. Before long we may see her go much faster.

e Others. At the moment it is not obvious that other types are in the running.

The Future

Perhaps the key message of this book is that significant additions to the knowledge and understanding of sailing have been made in *very* recent years and are still being made. We recognise as a real possibility, therefore, the development of new ideas which will extend our present knowledge into new areas and open whole new vistas for speed and comfort in sailing.

Recapitulation

Designing for speed in sailing on the water has made great strides in the past few years and can now be examined in a relatively comprehensive way. The "hull-speed" or "wave-making" barrier can be circumvented by the choice of light, long, slender hulls. Limitation on sail-carrying capacity can be removed by adoption of the non-heeling configuration. Drag angles can be made small enough today to put the limitation over into the sail and hull forces. In effect, a desired goal can be met by providing enough sail area to overcome the resistance force of the hull at the desired speed.

This is not to say that various detailed problems will not be troublesome as people push for higher speeds. Obviously they will. There is plenty of room yet for research—for refinements at every point. Nonetheless, the total picture begins to unfold. It could touch off a new era in sailing.

CHAPTER XXXI

NEEDS FOR THE FUTURE

by Henry A. Morss, Jr.

May 1973

A principal lesson from this compilation is that the day of innovation in sailing is still very much with us. No one can say what fundamentally new concepts will emerge, or when. He can predict with some confidence that they will, especially in view of the surprisingly important things which have come to light in very recent years.

For the future, then, the greatest need is to stimulate most especially people who will discover these new concepts. Since the identity of those people can not be known in advance, this implies the encouragement of anyone who is interested to try his hand at it. That is a job which the Amateur Yacht Research Society can do probably more effectively than any other group. It can publish work of many kinds. It can be a forum for discussing and assessing new ideas. It can encourage people to pick up the ideas of others and put them to the test.

Since the founding of the society a couple of decades ago, this has been its major success, largely through the work of John Morwood. We strongly hope that he and the society will continue this valuable contribution.

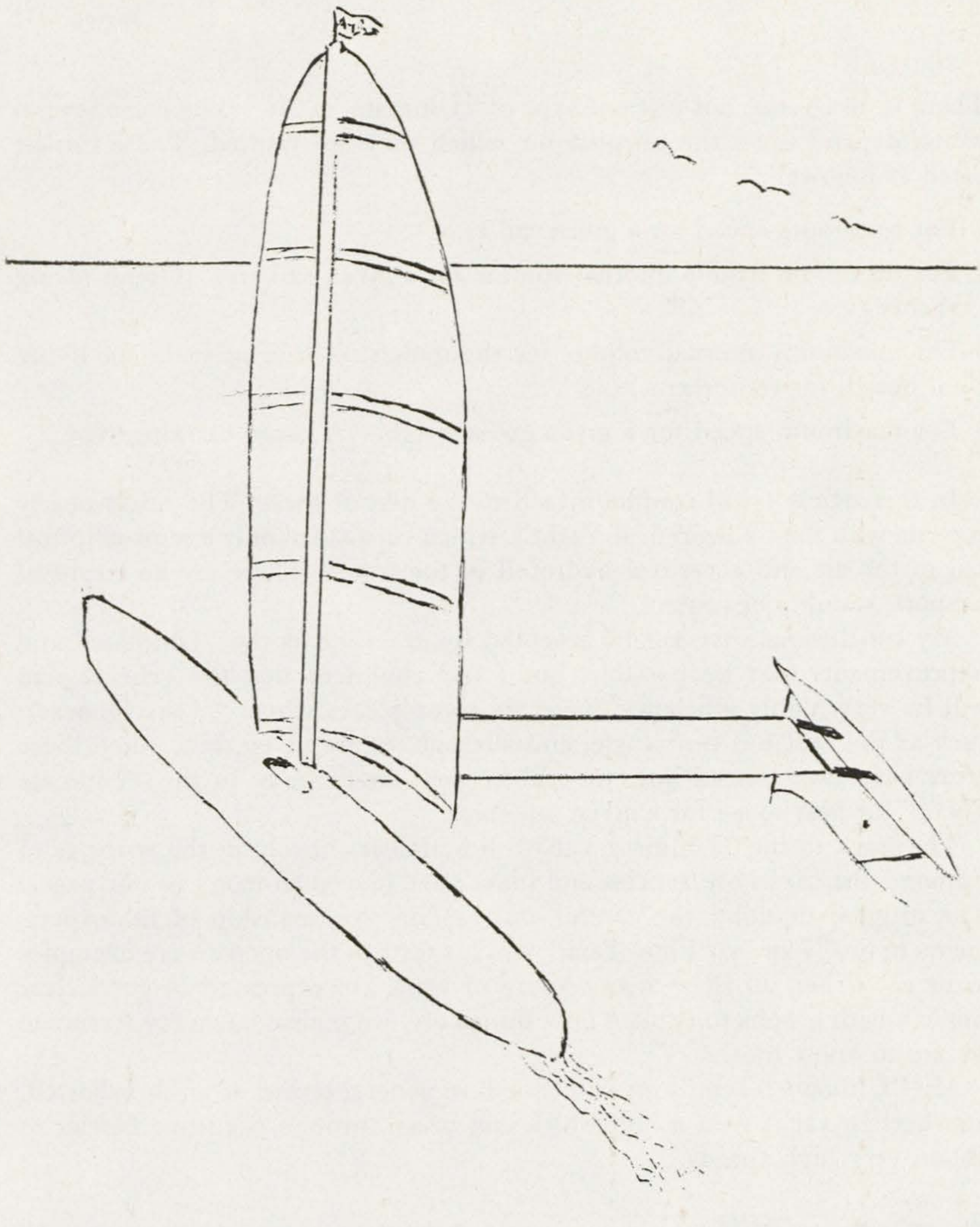
Surely one class of work which is very much needed is to extend and bolster our understanding of the fundamentals of sailing. This implies more thorough and detailed experimentation on sails, hulls, and related things. "Foils" are obviously a key element. Development of theory must go hand in hand and at times must precede practical tests.

Within this class falls also a great range of experiments and theoretical studies of all aspects of flying hydrofoil boats in the very real expectation of exploiting possibilities not yet realised.

Also here lies much needed work on other aspects of the performance of sailing craft, such as sea-keeping and course-holding qualities, basic stability, inherent self-steering, safety, new materials, and many others. Every one of these has been touched upon in the AYRS publications. We hope to see much more in the future.

A third important area, and one in which the AYRS has great strength, is for various people to try out and evaluate the ideas of others. There are many ideas in this book which have been proved by such tests, others which have been tested so far only inadequately, and still others which have not yet been subjected to such analysis and trial.

The AYRS has proved the rather surprising and unlikely proposition that non-professional people with very limited time at their disposal but unlimited enthusiasm and encouragement can make tremendous contributions to this science. Knowing this, let us build on it.



CHAPTER XXXII

THE QUEST FOR THE "ULTIMATE YACHT"

by John Morwood

Spring 1973

There is, of course, not just one type of "Ultimate Yacht". There are several which depend upon the purpose for which they are wanted. These can be listed as follows:

1 For maximum speed for a given sail area.
2 For maximum livable internal volume for a given sail area. (Ocean racing yachts.)
3 For maximum internal volume for the money. (Cruising yacht for living on board, for retirement.)
4 For maximum speed for a given gross weight. (A cargo-carrying type.)

In this article I will confine myself to the first of these. The result nearly accords with the "Theoretical Yacht", which consists of only a semi-elliptical sail in the air and a vertical hydrofoil in the water. There are no means of support, stability or control.

My conclusions may not be accepted by everyone as the "Ultimate" and improvements may be possible, but I feel confident that the general plan will be very highly efficient. There are some places where we are ignorant, such as the best foil cant angle, and alternatives are given, but, when these areas have been sorted out, we will be well on the way to the "Ultimate Yacht" for best speed for a given sail area.

The track to the "Ultimate Yacht" lies almost entirely in the writings of Edmond Bruce, whose articles and ideas have graced so many of our pages. The original thought, the careful and precise workmanship of his experiments in his "Laminar Flow Tank" and his tests in the open air are examples to us all. When all these many hours of work are expressed in good clear English with graphs to explain how things are, we realise how very fortunate we are to know him.

My "Ultimate Yacht" can be defined, in general terms, as an unballasted, non-heeling yacht with a hull which can break through the wave barrier to obtain very high speeds.

The Configuration

My "Ultimate Yacht" is a "proa" with the hull to windward and a canted foil to lee. As such, putting about is not normal, the process being called "shunting". The proa is allowed to stop or is stopped beam-on to the wind. Then, by sail adjustment, it is made to sail off in the opposite direction to which it had been sailing before. Our members find this process enjoyable for casual sailing.

However, not only is our boat a proa but it can also be sailed normally with a fixed bow and stern, putting about through the wind. The foil then lifts up the lee side when it is to lee and pulls down the same side when it is to weather. As such, it is called a "Bruce Foil", because the configuration was invented and first made by Edmond Bruce.

The Hull

From Edmond's article "The Running Resistance versus Speed of Sailing Multihulls" (Chapter XXII of this book), we have no hesitation in selecting his "16" hull, whose length to beam ratio is 16:1. It has less resistance than all the others from a $V_B/\sqrt{L}$ of 0·7 to 3·0. This hull appears to make negligible surface waves during this speed range and thus would not be improved by any "trick" such as (a) a transom, (b) shifting the greatest sectional area aft, or (c) raising the centre of the hull semi-circle above the LWL and dropping the ends.

The speed trials at Weymouth, England, run by Players in October 1972, showed that the 60-ft *Crossbow*, a single outrigger, could sail at more than double the windspeed as measured at a level considerably below the centre of area of her sails. If our yacht should come up to expectations, we should hope to reach double windspeed in light winds. A zephy of 3·5 knots should give us a speed of more than 7 knots and thus again the "16" hull is indicated.

In general, too, the faster catamarans approximate the "16" hull. For instance, the beamiest catamaran hull is the *Shearwater* with a length to beam ratio of 14. The *Tornado* and 'C' class are slimmer than this. The Australian catamarans, designed by the Cunninghams, are almost the "16" hull and have shown superiority over the broad sterns of the English and American craft.

Displacement

Having selected the main hull type, we now have to choose the size for the load we wish to carry. If we want to build our boat robustly and carry a crew of two, we must have a larger boat than for a lightly-built, one-man boat. The larger boat will, of course, have a greater top speed than the smaller one but will not be faster in light winds.

In the present state of our knowledge, departure from the Bruce "16" hull is not advised. However, a Bruce "20" hull might have a higher top speed at the expense of speed in light weather. On the other hand, using a Bruce "12" hull (length to beam 12:1) will increase the light wind performance but reduce absolute top speed.

The displacements of Bruce "16" hulls of various lengths from model size up to 48 ft are as follows:

Length LWL	Beam LWL	Displacement
4 ft	3 in	3·3 lbs
16 ft	1 ft	215
17 ft 4 in	1 ft 1 in	272
18 ft 8 in	1 ft 2 in	340
20 ft	1 ft 3 in	419
24 ft	1 ft 6 in	724
32 ft	2 ft	1,720
40 ft	2 ft 6 in	3,360
48 ft	3 ft	5,800

The small increments in length from 16 ft up to 24 ft are included to cover the new 10 sq meter (107 sq ft) class. To calculate displacement, multiply the area of the maximum section ($\pi r^2/2$) by the length and by the "Prismatic Coefficient", which Edmond gives as 0·534. This produces the displacement in cubic feet. A cubic foot of salt water weights 64 lbs (fresh water 62 lbs). One long ton of sea water displaces 35 cubic feet. (The prismatic coefficient is defined as the displacement in cubic feet divided by the product of the LWL and the area of the maximum body section underwater).

The Topsides

Topsides have two purposes. Firstly, they keep the water out of the boat. Secondly, they cut through the seas and, hopefully, can actually pierce and come out through them without hindering speed too much. Mainly, however, topsides give wind and water resistance. They should be as low as possible with, preferably, a rounded deck. The best possible topsides consist of a small vertical all around the underwater part, above which is placed a rounded deck similar to the underbody inverted. The Prout brothers have been the only people to have such a hull. It went very well but it was only a marginal improvement for a catamaran.

The Cockpit

This must be, of course, amidships and would essentially be a streamlining for the crew (sitting out tactics are not needed). As a proa, there would have to be room even in the smallest sizes for the crew to turn to face either end. The craft may not be uncapsizable. A hatch which allows exit from the upside-down position should be fitted.

Cant Angle

Though not altogether sure, I believe that the cant angle to produce the minimum hull drag angle should be 60° from the horizontal and not 45°, as often used. The advantages are as follows:

a Smaller foil.

b Less surface waves.

c Smaller reserve buoyancy.

d Edmond Bruce points out that the drive of a conventional ballasted keel yacht falls off by the *square of the cosine of the angle of heel* and not by the simple cosine, as one would expect. This may, at least partly, apply to hydrofoils.

The disadvantages of the 60° cant angle are:

a The 70 per cent extra beam needed with its extra weight and windage. (However, the longer beams need not be of greater scantlings than those for the 45° cant angle.)

b Sail balance will require a greater lengthwise movement of the centre of effort of the sails during "shunting".

c Reduced vertical lift when to leeward compared with 45°.

Plan Form

Edmond Bruce has clearly shown that the aspect ratio of a vertical, surface-piercing foil should be 1:1. This low figure surely means that at least half the force it produces is due to the surface waves it creates. It therefore seems logical to have the plan form of the working part of the foil as a curve related to the sine shape of a wave. Either a sine curve or a versed-sine shape seems worthy of thought to my hydrodynamically untutored mind. A double versed-sine is suggested. Above the working part, the shape can be part of a right triangle. John Shortall points out that most modern designers of single hull yachts no longer shape their hulls, keels and rudders to the surface waves created by the versed-sine trochoid curve of sectional areas which once were used. This is so, but I note that salient keels of keel yachts approach this shape.

In profile, the aspect ratio of the working part of the foil should be 1:1 when it is expressed as span^2/area. The span of the foil will therefore have to be increased by the cosecant of the cant angle.

Area

Here, Edmond's calculations show that the minimum area needed will be variable, depending on the side force of the sails (hence the windspeed). The area of a vertical foil may need to be as much as 3 to 4 per cent of the sail area in light winds and perhaps double that in strong winds. (See Chapter VI.) As mentioned above, canted foils need to be greater in area by the cosecant of the cant angle. A reserve area is needed above the working part, not only to keep the static buoyancy above the waves but also for the accelerating and hove-to states. The exact foil area needed is not yet known, but with a basic 4 per cent or more plus the reserve area above it, there should be ample in moderate wind. Edmond suggests a total of 10% of sail area.

Section

Edmond's tests show that the best section is thin. On a given tack it is advantageous to have the foil curved in an arc with a curve rise of about one-twelfth of the chord. The alignment should be fore and aft, even for a "Double Bruce Foil" using one foil at a time.

Foil Retraction

Bruce foil craft have been around for several years now. One person whom we know who really enjoys his boat is Gerard Horgan. Gerard finds no trouble in sailing his boat with the foil to weather. If it lifts, he lets the sheet go and he has seldom been anywhere near a capsize. However, he has been in trouble once and feels that the problem should be designed out.

One day in 1971, he was returning to base over a sandy bar and ran aground. The foil touched first, of course, and the boat swung around with the foil firmly hooked in the sand to windward. There was too little wind to sail him off. His paddle was too short to pole him off and the water was too deep to go overboard. The tide was rising and the foil stayed hooked with the boat heeling more and more to weather. Finally, he got off but there were a few anxious moments.

Gerard's solution is to have the foil retractable hydraulically. Stops for various cant angles are apparently not needed. This system would also be valuable to immerse the foil more when the sail is reefed and the centre of effort lowered. The cant angle should then be increased.

The Cross Beam

Many different types of cross beam have been used for native and Western trimarans and outriggers, with round poles of wood or alloy being preferred. Only three other types of cross beam have been used to my knowledge:

1 Victor Tchetchet used two planks of wood joined in the flat at the outer ends and sprung apart by struts in the middle. I found this system strong in my 1956 foil boat.

2 Erick Manners used built-up cross beams of angle iron or steel in his Trifoil, with Z struts between, also of angle metal. He used the same system in White Cloud of the 1968 Single-handed Trans-Atlantic race where, unfortunately, they broke as far as we know. The design looked strong, however.

3 Edmond Bruce and I have both used the common alloy ladder, placed flat, and found it good. After all, a ladder is designed to take bending loads. Its torsion resistance is good.

After a great deal of thought on the subject, I now feel that the only logical cross beam is a ladder system. For small boats commercial ladders can be found to be perfectly good and strong with a better strength to weight ratio than the more usual mast section poles. For large craft, the ladder can be built up of angle alloy with the flat at the top. The rungs, also of alloy angle, can presumably be screwed, bolted or welded, or any combination. For very large craft, each rung can have a strut going downwards and the tips of these can be joined by alloy bars in a similar fashion to mast staying to give increased strength both to upward and to torsional strains. The jibs of some cranes are made thus. The whole would have to be streamlined as far as possible to reduce wind resistance.

In order to achieve sail balance on the two shunts, especially with the longer cross beams needed by a 60° cant angle, it may be necessary to have the two cross beams pantographing so that the hydrofoil can be placed in the required position fore and aft. By suitable design, this would not only allow the cross beams to be laid alongside the hull to reduce beam at moorings or a boat park without detaching them, but the boat could actually be steered by moving the foil fore and aft, thus abolishing the rudder at a saving of perhaps 10 per cent of wetted surface and form drag as pointed out by Edmond. Even the complicated angle alloy cross beam with stays could be made to pantograph thus.

The cross beams of our craft have to withstand the following:

a Compression strains from the side force of the sails.

b A vertical force at the end to counteract the heeling moment.

c Drag forces from the foil drag and from hitting the shore and flotsam.

d Torsional strains from the same causes as in the previous item acting at the bottom of the foil.

The Mast

The mast can be of two different placings. It can either be centrally located on a mast step which allows it to turn or the top of the mast can be in a fixed spot which is centrally located and the foot of the mast is placed in a track so that the mast may be moved near the leading edge of the semi-elliptical sail on each shunt. The track will, of course, need to be curved to combine arcs of two circles whose centres are firstly the mast head and secondly the staying point of the weather stays.

In either case, the mast or mast foot track must be firmly allied to the cross beam, appropriately to transfer the stresses on it to the foil. It should, if possible, be placed on it. The mast should also have minimum windage and should, therefore, be an alloy plank either rectangular or lens-shaped in section. Because of factors to be discussed later, its scantlings can be far less than usual for the amount of sail.

The Sail

In theory and in wind tunnel tests it has been demonstrated that the most efficient shape for a sail is a semi-ellipse of aspect ratio 3:1. For best results, the boom eddy should be abolished by bringing the foot of the sail down to the deck.

The sail suggested is a semi-ellipse set on curved yards which are hoisted up the mast. In order to make the sail lose power when the sheet is eased, the leading edge of the sail has to be near the mast. This can be accomplished in two ways, depending on which of the two mast systems above is used. With a central mast step, the sail can be made so that it will slide to bring the leading edge of the sail aft. With the mast step on the above track, the mast can be slid forward for each shunt to achieve the same result. With a 60° cant angle of the foil and the long cross arms which go with it, the fixed centrally placed mast step seems preferable because the more aft position of the sail is the likely one for proper balance. The sliding mast step goes with pantographing cross arms. It has the advantage that the sail can be vertical and not sloped forward.

I have chosen a lug sail arrangement because of efficiency and the ability to alter sail balance while shunting. When the foil is to weather this sail will be inefficient, being curved the wrong way, and may be hard to manage. As an alternative, I have dotted in a conventional sail to be used for short tacking.

This control of sail balance has another value. Either with or without pantographing cross beams which, as has been said, can steer the boat, the sail itself can be used to steer by shifting it fore and aft. This is yet another way of abolishing the rudder with its possible saving of some 10 per cent of resistance.

Sail Area

For these boats, the greater the sail area the faster they will go in winds which do not overpower them either through capsize or "stalling" the lateral resistance. Also, the greater the sail area, the lower will be the beta angle. The parasitic resistance of mast, rigging, hull, cross beam, etc., stays constant within limits so that increase in sail area will lower the sail and windage drag angle, which is part of beta.

Our boats of this article can stand any amount of sail from the ordinary capsize point of view. The limitation may lie in the stern-over-bows capsize ("pitch-poling"), which occurs only when the sheets are eased. It is a condition to avoid and we may do so in three ways, namely:

1 By moving the crew aft, as is done in racing catamarans.

2 By reducing sail area.

3 By greatly *increasing* the sail area on free wind courses so as to make the boat "always sail close-hauled", even with the true wind direction aft of the beam. The concept will be described later as "The Constant Beta Boat".

Selecting the Square Footage of Sail Area

The earlier chapters of this book relate sail area, C_S, the boat weight, and K_H to the maximum V_{MG}/V_T, the maximum V_B/V_T, and the beta angle. This allows us to select sail areas to aim at desired results in performance.

Sail areas for the boats of this series have been considered as follows:

1 Before reading the earlier chapters of this book, I thought to use a sail area $4\frac{1}{2}$ times the area of wetted surface, or 190 sq ft for the 24-ft craft. Harry Morss then gave me the following figures for this sail area. Beta angle for maximum V_{MG} is 23°; max V_B/V_T is 1·3 at a course of 90° from the true wind direction. This ratio was too low for an "Ultimate Yacht" speedster and I had to think again.

2 I next considered the 'C' Class figure of 300 sq ft for the 24-ft craft. Now, the 'C' Class have been measured at a V_B/V_T of 1·5 and, at this speed, they are just flying a hull and have lost about half of their wetted surface. Harry Morss worked out the beta angle for the 24-ft boat for the maximum V_{MG}. It came to 21° and the maximum V_B/V_T came out at 1·6 for a course of 90°. If the weight is the same as the 'C' Class, the figures will be the same. I would hope to make the craft of my series rather lighter than catamarans of the same length.

These two methods of sail area selection will be familiar to readers. They are traditional but must now be considered old-fashioned. We can do better, as in the remaining items:

3 The Morss method consists of first selecting the beta angle at which the boat will be expected to reach the maximum possible V_{MG}. From this and the other figures, one then works out the sail area. For a beta angle of 25° for maximum V_{MG}, the sail area works out at 225 sq ft for the 24-ft boat. The max V_B/V_T at a course of 90° is 1·5.

4 I started this article by hoping for a V_B/V_T of 2·0 without knowing that we can now design directly for any figure for this ratio we wish, within reason. By the formula, a V_B/V_T of 2·0 will be achieved on a course of 90° at a beta of 20° from 460 sq ft of sail area for the 24-ft boat. This area seems large but could be reduced, in common with all the above sail areas, by reducing the weights of the boats of our series, using slimmer hulls. As he says later on, all Harry's calculations assume a sail drag angle of 10° and a sail coefficient of 1·5. If our sail proves to be of great efficiency and parasitic windage can be reduced so that the sail drag angle is 9°, sail areas will be less.

"The Constant Beta Boat"

The title of this article indicates that we want to reach for the "Ultimate Yacht", even if the construction seems at the moment to be an impossibility. We must therefore consider "The Constant Beta Boat" concept devised by Harry Morss where, at all times, the boat is being sailed at the limit of its capabilities. As the title of this section indicates, the beta angle is always kept at the same figure no matter what course is being steered within the possible sailing circle. This involves varying the sail area according to the course steered between that for the maximum V_{MG} and that where V_B is maximum. For the beta angle to be kept constant at 30° between these two courses, the sail area has to be increased some four times. With a constant beta of 20°, much greater sail areas are needed, but there is less increase on going from the course where V_{MG} is maximum to where V_B is maximum.

The mind boggles at the figures of sail areas given by Harry, at least my mind does, and when the sail area varies, the length of cross beam and the size of hydrofoil must vary with it. There is, of course, some latitude if one starts off with a cant angle of 60°. This could be reduced to 45° when the sail area is increased. As will be seen later, however, considerable reductions in sail area can be achieved by reduction in the weights of the boats of our series.

Good ice boats are already almost "Constant Beta Boats" without the complications of varying sail area. The concept, however, allows us to consider the design of a water sailing craft of the utmost efficiency possible.

Harry Morss sets out the concept of the "Constant Beta Boat" for our series of craft as follows:

From earlier parts of this book (Chapters IX, X and XXX) it is seen that for a yacht to sail at a constant beta angle, the sail area must be variable. Close-hauled, the minimum beta angle for effective sailing can be used with the correct sail area, but when the true wind angle widens, more sail area is needed to speed up the boat in order to hold the beta angle down to its best value.

The two formulae which give the sail areas for the best possible V_{MG} and for the highest possible speed are as follows, labelled "Formula V_{MG} max" and "Formula V_B max".

Formulae V_{MG} max

$$A_S = \frac{(1 - \sin \beta)^2\, 2{\cdot}92\, W^{2/3}\, K_H}{\cos^2 \beta\, C_S} \quad \text{when } \gamma = 45° + \frac{\beta}{2}$$

Formulae V_B max

$$A_S = \frac{2{\cdot}92\, W^{2/3}\, K_H}{\cos^2 \beta\, C_S} \quad \text{when } \gamma = 90° + \beta$$

If less sail area is used than is called for by these formulae, the boat will slow up for want of sail. If the sail area is greater than called for, the boat will "stall out" and also slow up.

The sail areas of the nine Bruce "16" hulls already mentioned are given in the following table as worked out by these formulae. Sets of figures are included for $\beta = 20°$ and for $\beta = 30°$. We have assumed that δ_S is 10° in both cases; δ_H will then be 10° and 20° respectively. K_H is taken as 6 for beta of 20° and 3 for beta of 30°. In both cases, C_S is taken to be 1·5.

The wetted surface is also given for an old-fashioned comparison and with it the sail area at $4\frac{1}{2}$ times the wetted surface. (A good approximation for the wetted surface of the Bruce hulls is $\frac{3}{4}$ length multiplied by the wetted perimeter of the largest underwater section.) The wetted area of the foil is not included.

At $\beta = 20°$, both values are enormously large. Even for best V_{MG}, the rig required on the 48-footer is comparable to that of a 12-meter class yacht, although our boat weighs less than a tenth as much. (Water lines are nearly the same.) Of course their resulting speeds are vastly different.

At $\beta = 30°$, the values of sail areas from the two formulae span the empirical value of $4\frac{1}{2}$ times the wetted surface. Note that the sail area required to hold beta down to 30° at maximum possible boat speed is four times the amount needed for maximum possible V_{MG} for the same value of beta.

Sail Areas

LWL ft	Wetted Surface sq ft	Sail Area at $4\frac{1}{2}\times$ Wetted Surface sq ft	Sail Area Corr. C-Cat	Sail Area Best V_{MG} at $\beta=25°$	$\beta = 20°$ Formula V_{MG} max sq ft	$\beta = 20°$ Formula V_B max sq ft	$\beta = 30°$ Formula V_{MG} max sq ft	$\beta = 30°$ Formula V_B max sq ft
4	1·18	5	8	7	13	30	4·4	17
16	19	85	133	113	205	475	70	280
17·33	22	100	156	133	240	560	82	330
18·67	26	115	180	155	280	645	95	380
20	30	135	210	180	320	740	110	435
24	42	190	300	255	460	1,065	155	630
32	75	340	535	455	820	1,900	280	1,120
40	118	530	835	710	1,280	2,950	435	1,750
48	170	765	1,200	1,020	1,850	4,250	630	2,500

These sail areas in the table from the two formulae are based on the assumption that the effective displacements of the boats are as given in the earlier table. If, instead, we assume that the calculated dynamic lift from the leeward canted foil reduces the effective displacement without altering anything else, then we find that these sail areas can be reduced by the following percentages:

Reduction in Sail Area due to Dynamic Lift of Canted Foil (at 60°)

	$\beta = 20°$		$\beta = 30°$	
	Formula V_{MG} max	Formula V_B max	Formula V_{MG} max	Formula V_B max
In 10-knot true wind	6%	10%	2%	$7\frac{1}{2}$%
In 20-knot true wind	19%	33%	7%	21%

If the cant angle had been set at 45° instead of 60°, the reductions in sail area would have been roughly 50 per cent more. (This would mean a reduction of about a half for V_B max at $\beta = 20°$ in the 20-knot wind.)

These figures illustrate the dilemma and highlight the difficulty of deciding how much sail area to use. An individual will obviously make up his own mind in the knowledge that he must carry as much sail as he dares or as he thinks he can handle or afford.

Reduction in Sail Area due to Reduction in Displacement

John Morwood thinks that, with extreme care, the 24-ft boat of his series could be sailed at half the 724 lbs weight given at the earlier part of this article, or 362 lbs, and the 48-ft one could be built and sailed for a quarter of the 5,800 lbs calculated, or 1,450 lbs. This would, of course, entail slimmer hulls.

With these sailing weights, and without allowance for dynamic lift, the sail areas needed to achieve a "Constant Beta Boat" would be as follows:

	$\beta = 20°$		$\beta = 30°$	
	Formula V_{MG} max	Formula V_B max	Formula V_{MG} max	Formula V_B max
	sq ft	sq ft	sq ft	sq ft
24-ft boat at 362 lbs	290	670	100	400
48-ft boat at 1,450 lbs	735	1,685	250	1,000

In the above examples, only two boats of the series have had their figures worked out. Other boats for the same figures will have sail areas in proportion to the squares of their lengths.

Sail Height

To calculate the sail height, I imagine the sail as a rectangle made up of three equal squares placed one above the other, thus giving an aspect ratio of 3. Dividing the sail area by 3 gives the area of one of these squares and the square root of this will give the vertical height. Three times this height is the height of the sail. If we use the formula $\dfrac{\text{span}^2}{\text{area}}$ for the aspect ratio, it does not matter how the area is disposed to make up the sail—the height will be the same. The system will work for a semi-elliptical sail.

The Centre of Effort of a Semi-ellipse

By drawing a semi-ellipse of aspect ratio 3 and balancing it upon a knife edge, I find that the centre of area is 42 per cent above the foot. The centre of effort will be slightly higher than this, due to the wind velocity gradient, but we do not know how much. Sail twist, if present, on the other hand may lower it a bit. As an approximation, let us take the centre of area for the centre of effort.

The Sail Foot

The area of an ellipse is πab, where a is half the major axis, i.e., the sail height, and b is half the minor axis, i.e., half the sail foot chord. To find the length of the sail foot chord, therefore, twice the sail area (for the full ellipse) is divided by π and the sail height (found as above) and this will give the half chord of the foot of the sail.

Drawing an Ellipse

The most convenient and accurate way to draw an ellipse is as follows:

Two lines are drawn on a piece of paper at right angles to each other (x and y axes). A separate strip of paper is now marked on one edge with three points, which we shall call A, P and B so that AP is a and PB is b. If the strip is now moved so that the point A is always on the y axis and point B is always on the x axis, the point P will describe the ellipse we want.

Mast, Sail, and Beam Calculations

All our series of boats are similar in everything but size. It will only be necessary, therefore, to work out details for one of them and the 48-ft craft is selected. We shall use sail area at $4\frac{1}{2}$ times wetted surface, or 765 sq ft.

$765 \div 3 = 255$. $\sqrt{255} = 16$. $3 \times 16 = 48$. This is the sail height in feet. With the centre of the sail area at 42 per cent of the sail height and with a distance of 10 ft from the foot of the sail to the level of the foil's centre of area, the sail's centre of area lies 30 ft above the foil's centre. Referring to Edmond's geometry in Chapter XXV we find:

Height of sail: 48 ft	Foot/chord: 23 ft
Beam at 45° cant angle: 30 ft	
Beam at 60° cant angle: 52 ft	

(beam measured from centreline of hull to foil centre.)

Sail Construction

The sail consists of panels set between yards (or, the yards may be put in pockets in the sail). Each yard is curved with an arch of one seventh of the chord (more or less, the exact figure is not known for sure) and each one (except for that at the top) has a wire span across it.

Each wire span has a slider on it which can take up any position on the wire. Each slider can slide up and down the mast, as well as having the wire span slide on it.

Sail Handling

When sailing, the sail is held to the wind by a sheet the force on which is much reduced by the balanced nature of the sail. Steering further from the wind is achieved by sliding the sail forward, luffing by sliding it aft. This steers the boat and is only reasonable because of the fact that this kind of foil craft is self-steering and will stay on a course once it has been properly set which adjusting the sail fore and aft does. Shunting is done by steering off the wind and then letting the sheet go until the boat stops. The sail foot is then slid towards what was previously the bow until the sail "fllops" to the other tack. The other sheet is pulled in and the boat sails off on the other shunt.

Short Tacking

The sail as described would produce some progress to windward if the boat were to be put about to bring the foil to windward. A fore and aft rig is, however, dotted in case this is preferred.

Reefing

This must be the handiest sail ever invented for reefing. One simply eases the halliard until one or more of the yards drop down onto the boom. Three to five gaskets tied around the lowered yards would hold them in place.

Alternative Semi-Elliptical Sails

I have drawn out several alternative semi-elliptical sails. The only one which pleases me is one set on a mast which can turn through 360° so that the sail can be fully efficient with the foil to weather. It is shown in Fig.

The Bonuses of Semi-Elliptical Sails

Apart from sail efficiency, the advantages of the sails described are as follows:

1 The mast is shorter than for a triangular sail.

2 The forces on the mast only occur in the direction in which the *Resultant* sail force acts. A conventional mainsail, when closehauled, pulls the mast aft. A staysail produces enormous forces on the mast and hull in directions almost unrelated to the direction in which the sail force acts. For the sails shown here, the mast is pulled in the direction of the resultant sail force by the yards, i.e., forwards and sideways. The mast can therefore have much lighter scantlings.

Efficiency Expectations

Edmond tells us that the lowest water drag angle he has ever had in his tank is 9°, for a catamaran hull with a single vertical foil. We know, too, (also from Edmond) that the 12 metres have a minimum hull drag angle of 10°. I guess that the hull and foil conjectured here are likely to have a minimum drag angle of 10°.

The drag of the sail, which may be very efficient, is affected by the windage of the hull, the cross beam, and the other above-water parts. The sail itself might have a minimum drag angle of 5° or less, especially if the boom eddy were abolished by a cloth running down to the deck. However, the windage of the above-water items will make this worse. My guess here is a minimum drag angle of 7°.

If these guesses of the two drag angles are correct, the minimum course to the apparent wind (minimum beta angle) will be about 17°, which is the sum of the drag angles. At this angle she will be pinched at her highest. Perhaps she will be able to sail best to windward at $\beta = 20°$.

Now the "speed ratio" of a boat on a beam reach to the true wind is the co-tan of the beta angle, which for 20° is about 2·7. If our craft had the enormous sail area required (in the range of 4,000 sq ft for the 48-footer), she should be able to reach a sailing speed of 2·7 times the speed of the true wind in a light breeze. 2,153 sq ft would be needed to produce a speed ratio of 2·0. With a sail area of 765 sq ft, she will only do a speed ratio of 1·2.

An interesting speculation is to consider what would happen if all the yachts conjectured here were to be built and set off to sail a course. Due to the wind velocity gradient, the larger sails will produce relatively more force. However, in low wind speeds, they would all sail at approximately the same speed.

As the wind grew stronger, the model would fall behind at about 6 or so knots. The 16 ft yacht would "stick" at 12 knots, relative to the larger ones. Then, in order of size, they will progressively "stick" up to 21 knots when the 48 ft craft starts to slow relative to the windspeed. Hull-generated water waves will be small. Wind-generated water waves will be speed-restricting.

Finally, the top speeds are achieved in perfect water conditions. The 4 ft model will not, I think, do more than 10 knots, the 24 ft craft 25 knots and the 48 ft one, 35 knots, due to wind gradient, moment of inertia and other factors.

Our Craft as a Flying Foil Craft

It seems likely that our yacht will be so fast that little or no extra speed would be obtained by lifting the hull off the water on hydrofoils. However, for the record, fore and aft foils on the main hull should be tried.

My present opinion is that V foils with 60° of cant angle to the limbs and a short horizontal piece at the apex of the V will be best. A longer horizontal foil can be placed at the top across the upper ends of the V. If, now, the limbs of the V are swept back by some 30° and the whole foil "cart" is mounted on a vertical axis to align with the water flow, we have the system as drawn. Steering off the wind would be done by the forward foil and luffing by the aft one to prevent unloading the side foil. An inverted T aft might be better but would be hard to work out for a proa.

Conclusion

A highly efficient and fast yacht on the speed to sail area basis has been described. Improvement is usually possible in any purely mental design, even one based upon such solid foundations as this one. The final dimensions for several items have yet to be found but, when the design is finalised, a yacht will exist which will satisfy anyone's desire for speed under sail.

This design could not have been devised before 1972. It is true that all the basic information has been lying around in Edmond Bruce's articles for some years but the proa had to become acceptable, the semi-elliptical sail had to be devised to be practical which could only occur as an off-shoot of the proa and a certain period of time had to elapse to let the various items fit together in the brain.

It is very doubtful if any professional yacht designer would have produced this fast design at this moment of time. It needed the amateur approach and open mindedness of our members to achieve success. But even we would have taken many more years to get there if we had not been lucky enough to have the work of Edmond Bruce. It is as a grateful tribute to him that this article has been written.

Finale

It is to be hoped that many of our members will now start working on a model research programme with a view to building at full size. I suggest the name "Bruce Foil Proa" for the configuration.

I have no doubt in my mind that our yacht will perform outstandingly. If this is proved to be so, someone will soon build a large one. I reckon that 144 ft LOA is the limit of length which would be worth while paying for and, if anyone ever makes such a Bruce Foil Proa the top speed should be no less than 60 knots, while, in casual sailing in winds of 15 knots, she should buzz around gently at 40 knots. With her 9 ft of hull beam, she should make a nice charter yacht. It is an idea.

APPENDIX A

TRIGONOMETRICAL RELATIONSHIPS IN CHAPTER VIII

Many of the trigonometrical relationships stated in Chapter VIII can be derived in straightforward fashion, largely with the help of (A) and (B), which are the familiar "sine law" and "cosine law" of trigonometry for a plane triangle. The latter of these can be stated in analogous form with any one of the sides of the triangle at the left.

Only a few of the more complicated derivations will be set forth here.

For (F), formula (C) is written

$$\frac{V_{MG}}{V_T} = \frac{V_T\, V_B \cos\gamma}{\overline{V}_T^2} = \frac{V_B\, V_T \cos\gamma}{\overline{V}_T^2}$$

Now the denominator is found in (B). The numerator is derived from the adjacent Fig. 1, which shows that $(a + V_B)/V_A = \cos\beta$ and $a/V_T = \cos\gamma$, whence $V_T \cos\gamma = V_A \cos\beta - V_B$.

For (G), the clue lies in the fact that for maximum possible V_{MG}, the horizontal line at the top of Fig. 5 of Chapter VIII is tangent to the circle.

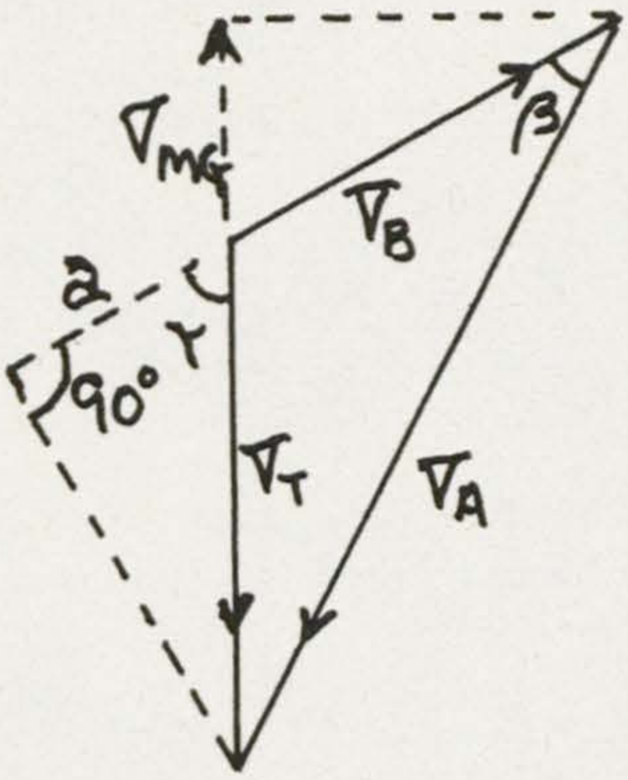


Fig. 1.

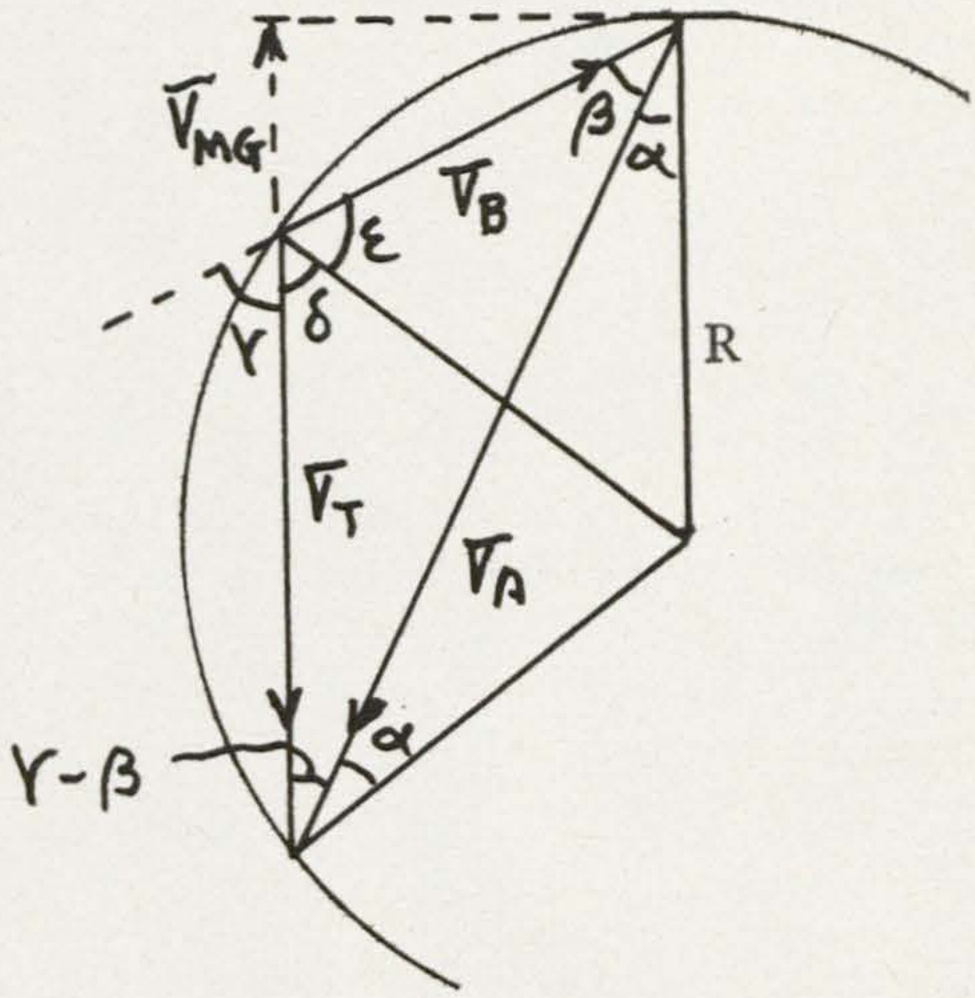


Fig. 2.

Hence it is perpendicular to R, in Fig. 2 adjacent, a radius of the circle. Then $\alpha + \beta = \gamma$. Also by the symmetry of three isosceles triangles in the circle, $\alpha + (\gamma - \beta) = \delta$ and $\alpha + \beta = \varepsilon = \gamma$ and $180° = \gamma + \delta + \varepsilon$. When these are combined, they lead to (G), which states that $\gamma = 45° + \frac{\beta}{2}$ (for the special case, of course).

The other formulae relating to maximum possible V_{MG} come from this and (A) except the last form for max V_{MG}/V_T, which can be found by expanding $\cos^2 (45° + \frac{\beta}{2})$:

$$\cos^2 (45° + \frac{\beta}{2}) = \left[\cos 45° \cos \frac{\beta}{2} - \sin 45° \sin \frac{\beta}{2} \right]^2$$

$$= \left[\frac{1}{\sqrt{2}} (\cos \frac{\beta}{2} - \sin \frac{\beta}{2}) \right]^2$$

$$= \frac{1}{2} \left[\cos^2 \frac{\beta}{2} - 2 \cos \frac{\beta}{2} \sin \frac{\beta}{2} + \sin^2 \frac{\beta}{2} \right]$$

$$= \frac{1}{2} \left[1 - 2 \sin \frac{\beta}{2} \cos \frac{\beta}{2} \right]$$

$$= \frac{1}{2} \left[1 - \sin \beta \right]$$

For (T), a careful comparison with (G) above shows that the angle marked ψ in the adjacent Fig. 3 is $45° + \frac{\beta}{2}$. Then $\phi = 180° - 45° - \frac{\beta}{2} = 135° - \frac{\beta}{2}$. Also $\rho + \phi + \beta = 180°$ and $\rho + \gamma = 180°$. These combine to give $\gamma = 135° + \frac{\beta}{2}$.

For the circles of constant beta and constant ratio V_B/V_A, a rectangular coordinate system may be used as drawn in the adjacent Fig. 4.

$$\beta = \varepsilon_1 - \varepsilon_2$$

$$\tan \varepsilon_1 = \frac{y + V_T}{x} \quad \text{or} \quad \varepsilon_1 = \tan^{-1} \frac{y + V_T}{x}$$

and $$\tan \varepsilon_2 = \frac{y}{x} \quad \text{or} \quad \varepsilon_2 = \tan^{-1} \frac{y}{x}$$

Then $$\beta = \varepsilon_1 - \varepsilon_2 = \tan^{-1} \frac{y + V_T}{x} - \tan^{-1} \frac{y}{x}$$

$$\tan \beta = \tan \left[\tan^{-1} \frac{y + V_T}{x} - \tan^{-1} \frac{y}{x} \right]$$

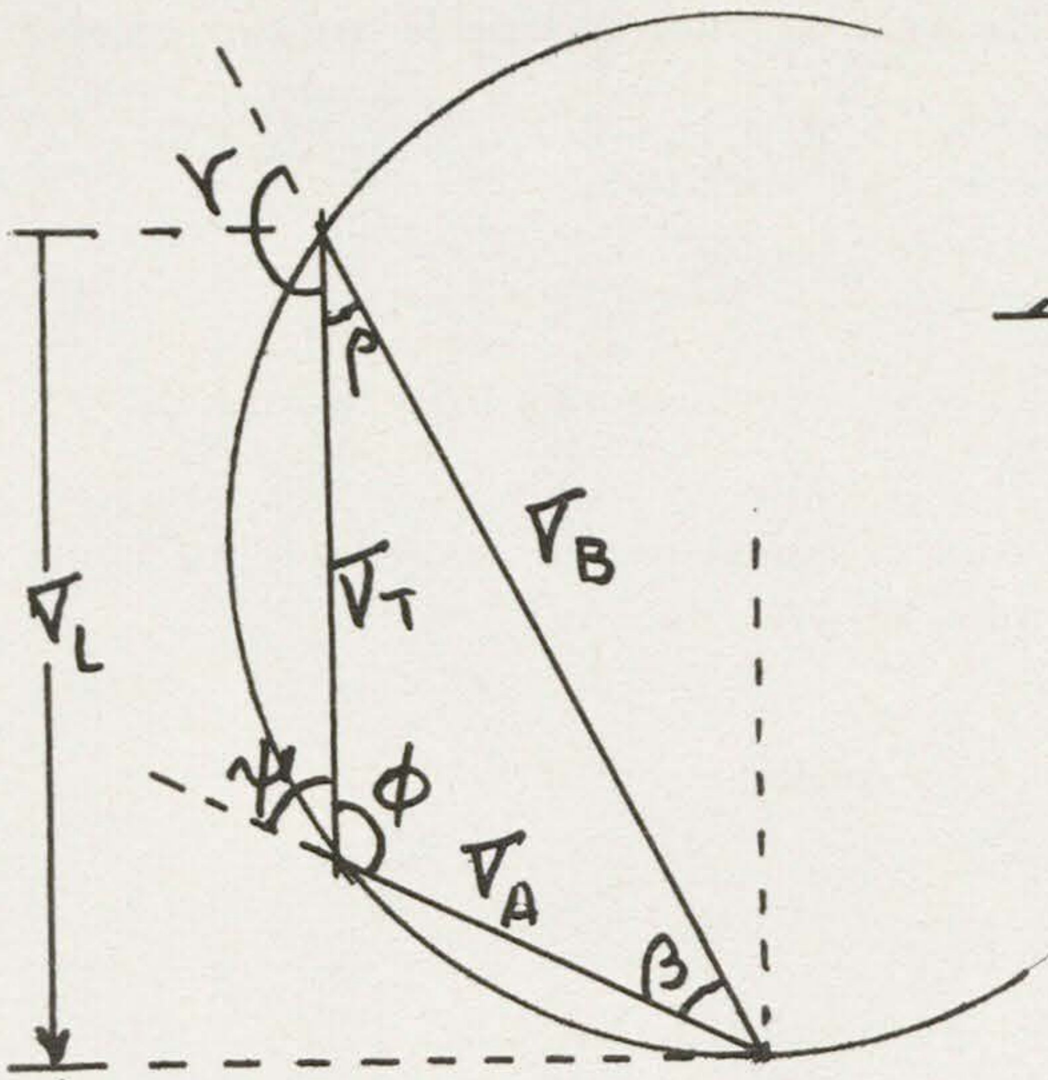


Fig. 3.

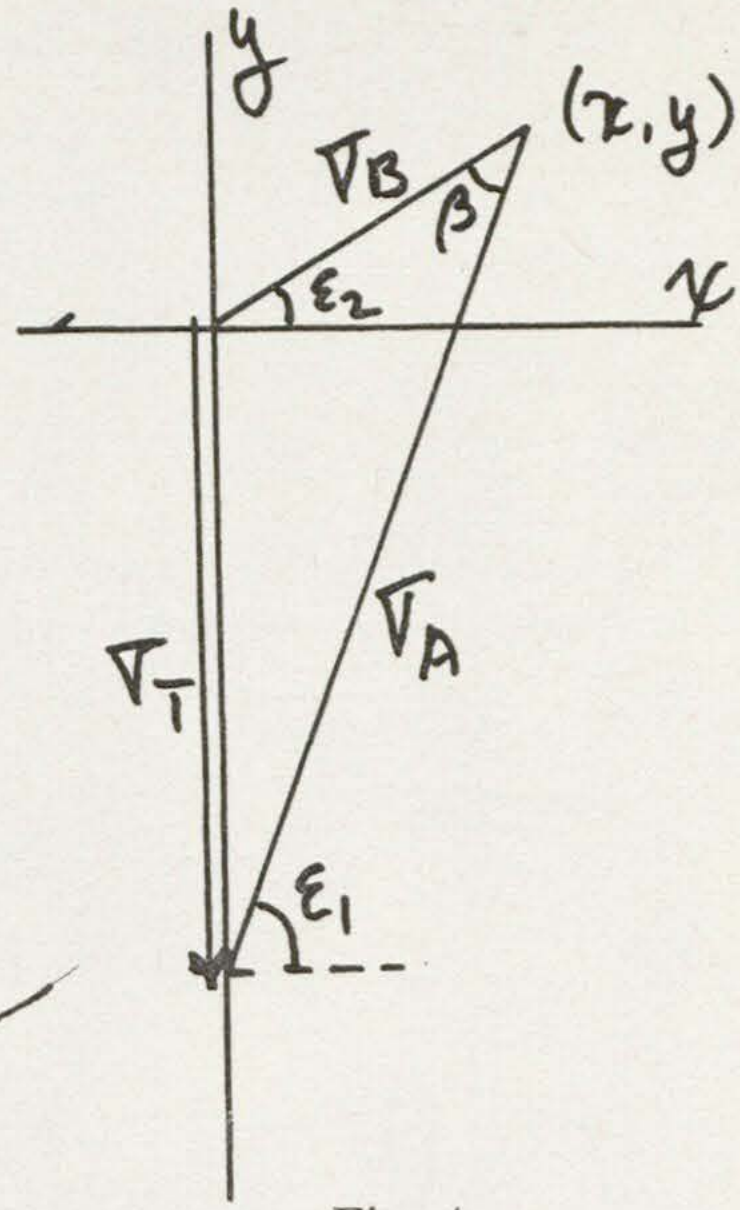


Fig. 4.

Now use the trigonometric identity which can be expressed in the generalised form

$$\tan (a - b) = \frac{\tan a - \tan b}{1 + \tan a \tan b}$$

to find that

$$\tan \beta = \frac{\dfrac{y + V_T}{x} - \dfrac{y}{x}}{1 + \dfrac{y\,(y + V_T)}{x^2}} = \frac{x\, V_T}{x^2 + y^2 + y\, V_T}$$

$$\text{Then } x^2 + y^2 + y\, V_T - \frac{x\, V_T}{\tan \beta} = 0$$

$$x^2 - \frac{V_T}{\tan \beta}\, x + \frac{\overline{V}_T^2}{4 \tan^2 \beta} + y^2 + V_T\, y + \frac{\overline{V}_T^2}{4}$$

$$= \frac{\overline{V}_T^2}{4} \left(1 + \frac{1}{\tan^2 \beta}\right)$$

When V_T and β are fixed, this is the equation of a circle with its centre at

$$x = \frac{V_T}{2 \tan \beta} \text{ and } y = -\frac{V_T}{2} \text{ and with radius } \frac{V_T}{2 \sin \beta}$$

$\left(= \frac{V_T}{2} \sqrt{1 + \frac{1}{\tan^2 \beta}}\right)$. This is the formula for a circle of constant beta.

For constant V_B/V_A we proceed in similar fashion from the same figure. The condition for constant V_B/V_A (abbreviated to C) is

$$\frac{\sqrt{x^2 + y^2}}{\sqrt{x^2 + (y + V_T)^2}} = C, \text{ a constant.}$$

This can be reduced to

$$x^2 + \left(y - \frac{C^2 V_T}{1 - C^2}\right)^2 = \frac{C^2 \overline{V}_T{}^2}{(1 - C^2)^2}$$

With C and V_T constant, this is the equation for a circle centred at $x = 0$, $y = \frac{C^2 V_T}{1 - C^2}$ with radius $\frac{C V_T}{1 - C^2}$. These are the circles of constant V_B/V_A $(= C)$.

Upon careful scrutiny, it is apparent that to produce the circles described in the text V_T must be set equal to unity.

There is another thing that can be done. If V_T is taken to have a value different from 1, different circles are produced. One example of this is the following:

The author has made some on-board sailing performance measurements with an anemometer mounted at the top of the mast. This is not as satisfactory as mounting the anemometer at the height of the centre of effort of the sails but at times is much more convenient. When this is done, the wind speed must be corrected to the value at the height of the centre of effort. The best that can be done is to reduce the wind speed by the ratio of the sixth or seventh roots of the heights of the centre of effort and the top of the mast.

Now if the reciprocal of this ratio (typically about 1·14) is used in the formulae for V_T, and if a new set of curves is then drawn, the resulting circles can be entered with the wind strength as measured at the top of the mast and will, in effect, correct for height in converting a measured point of performance from "apparent wind coordinates" to "true wind coordinates".

APPENDIX B

ANGLE OF ATTACK FOR FLAT PLATE TO PRODUCE OPTIMUM LIFT/DRAG RATIO

By Edmond Bruce — January 1967

The results of this calculation are quoted in Chapter IV.

For Pressure. (Fig. 1). Let C_P be coefficient of pressure normal to plate. Then

$$F_P = C_P \times \frac{\rho}{2} \times A \times v^2 \sin\alpha$$

$$L_P = C_P \times \frac{\rho}{2} \times A \times v^2 \sin\alpha\cos\alpha$$

$$D_P = C_P \times \frac{\rho}{2} \times A \times v^2 \sin^2\alpha$$

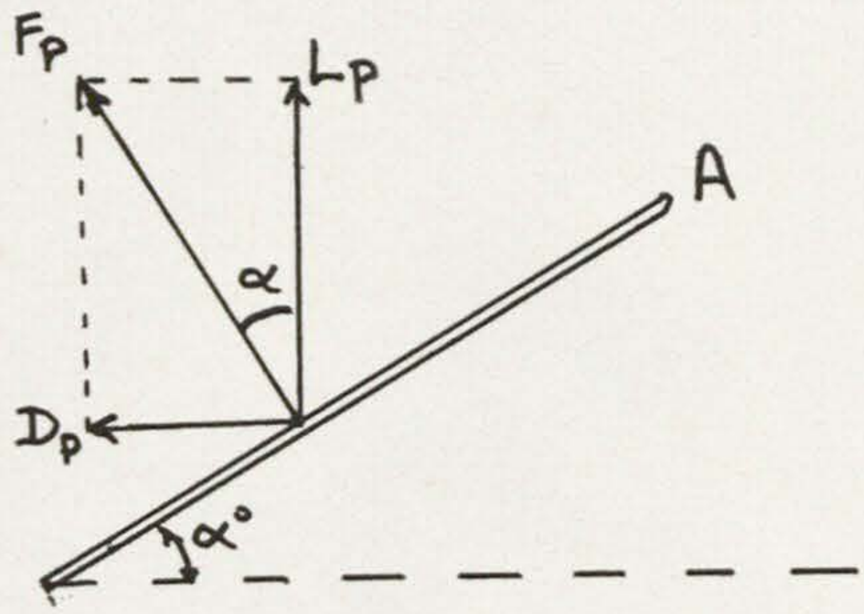


Fig. 1.

Without friction,

$$\frac{L_P}{D_P} = \frac{\sin\alpha\cos\alpha}{\sin^2\alpha} = \frac{1}{\tan\alpha}$$

and $\dfrac{L_P}{D_P}$ = max of ∞ when $\alpha = 0°$.

For Friction. (Fig. 2). Let C_F be coefficient of friction tangent to plate.

Then

$$F_F = C_F \times \frac{\rho}{2} \times A \times v^2 \cos\alpha$$

$$-L_F = -C_F \times \frac{\rho}{2} \times A \times v^2 \cos\alpha \sin\alpha$$

$$D_F = C_F \times \frac{\rho}{2} \times A \times v^2 \cos^2\alpha$$

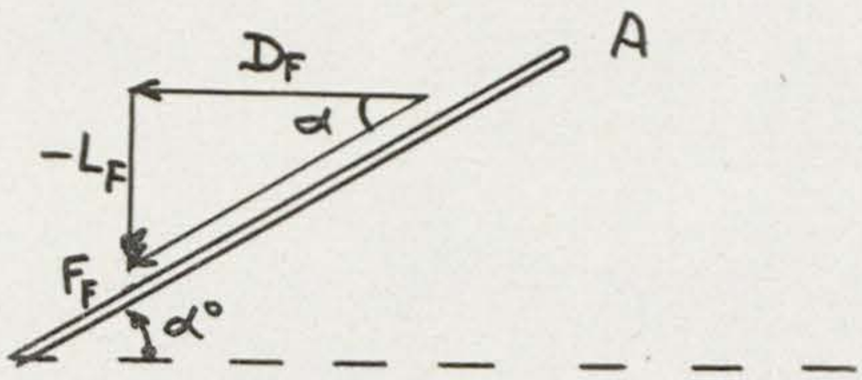


Fig. 2.

Combining pressure and friction,

$$L = L_P - L_F = \frac{\rho}{2} \times A \times v^2 (C_P \sin\alpha\cos\alpha - C_F \sin\alpha\cos\alpha)$$

$$D = D_P + D_F = \frac{\rho}{2} \times A \times v^2 (C_P \sin^2\alpha + C_F \cos^2\alpha)$$

$$\text{whence } \frac{L}{D} = \frac{(C_P - C_F)\sin\alpha\cos\alpha}{C_P \sin^2\alpha + C_F \cos^2\alpha} \qquad \text{(A)}$$

Now $\dfrac{L}{D}$ is a maximum when

$$\frac{d\left(\frac{L}{D}\right)}{d\alpha} = 0 \text{ and } \frac{d^2\left(\frac{L}{D}\right)}{d\alpha^2} \text{ is negative.}$$

$$0 = \frac{d\left(\frac{L}{D}\right)}{d\,\alpha} = \frac{(C_P \sin^2\alpha + C_F \cos^2\alpha)(C_P - C_F)(-\sin^2\alpha + \cos^2\alpha) - (C_P - C_F)\sin\alpha\cos\alpha\,(2C_P \sin\alpha\cos\alpha - 2C_F \sin\alpha\cos\alpha)}{\text{Denominator}^2}$$

$$(C_P \sin^2\alpha + C_F \cos^2\alpha)(C_P - C_F)(-\sin^2\alpha + \cos^2\alpha) =$$
$$= +(C_P - C_F)\sin\alpha\cos\alpha\,(2C_P \sin\alpha\cos\alpha - 2C_F \sin\alpha\cos\alpha)$$

$$-C_P \sin^4\alpha + C_P \sin^2\alpha\cos^2\alpha - C_F \sin^2\alpha\cos^2\alpha + C_F \cos^4\alpha =$$
$$= 2C_P \sin^2\alpha\cos^2\alpha - 2C_F \sin^2\alpha\cos^2\alpha$$

$$C_P(\sin^2\alpha\cos^2\alpha + \sin^4\alpha) = C_F(\sin^2\alpha\cos^2\alpha + \cos^4\alpha)$$

$$C_P \sin^2\alpha = C_F \cos^2\alpha$$

$$\frac{\sin^2\alpha}{\cos^2\alpha} = \tan^2\alpha = \frac{C_F}{C_P}$$

$$\tan\alpha = \sqrt{\frac{C_F}{C_P}} \qquad \text{(B)}$$

This is the condition for optimum $\frac{L}{D}$.

Measured values when flow is:

Normal to plate, front plus back, $C_P = 1{\cdot}25$
Tangent to plate, both sides involved, $C_F = 0{\cdot}006$
(Twice Schoenherr value at
boat's Reynolds' Number)

Then $$\frac{C_P}{C_F} = 209$$

$$\tan\alpha = \frac{1}{\sqrt{209}} = 0{\cdot}069$$

and $$\alpha \doteq 4^\circ$$

Note that $\frac{C_P}{C_F}$ would have to change some 50 per cent for a one degree change in α.

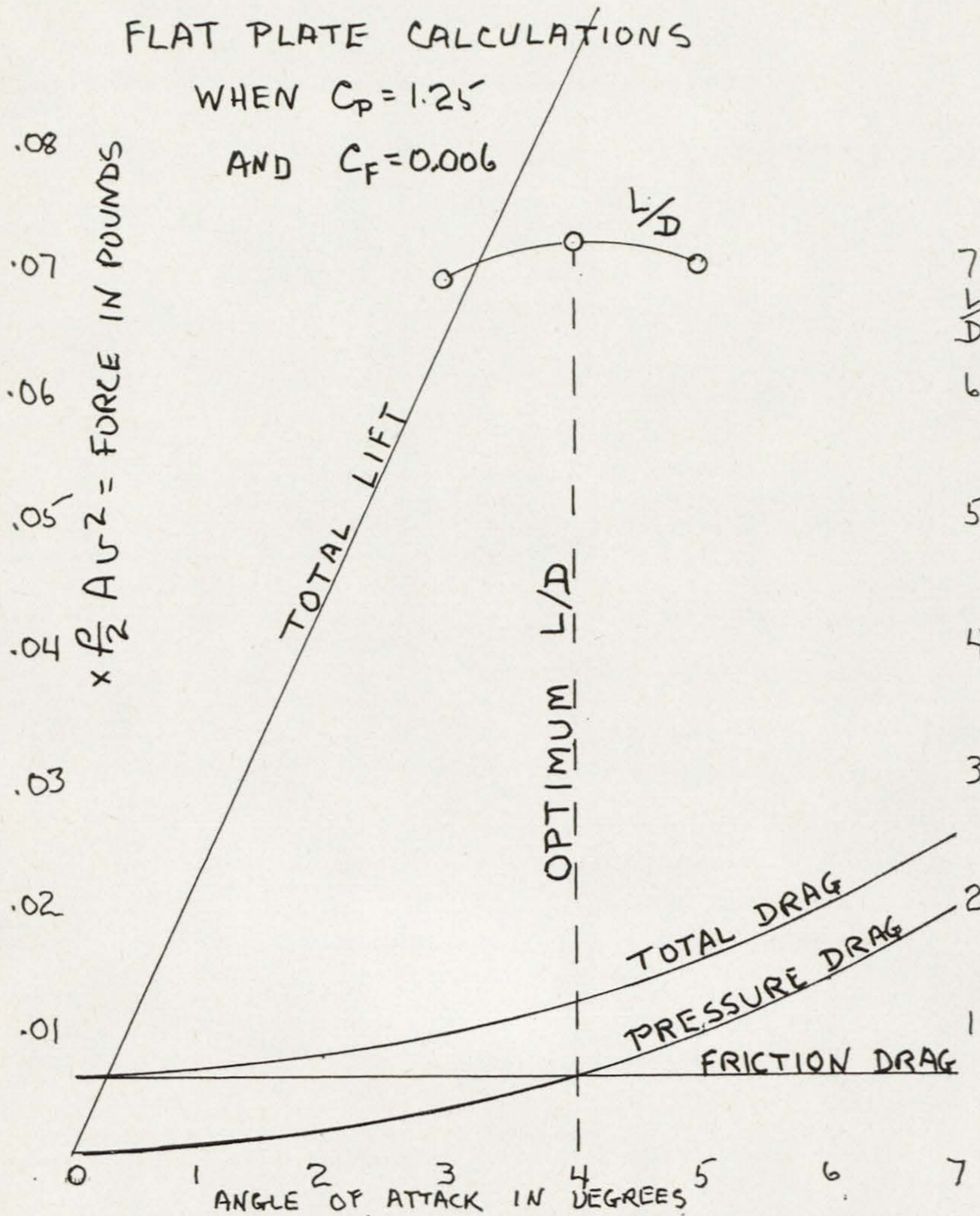

FLAT PLATE CALCULATIONS
WHEN $C_P = 1.25$
AND $C_F = 0.006$
$\times \frac{\rho}{2} A U^2$ = FORCE IN POUNDS
.08
.07
.06
.05
.04
.03
.02
.01
L/D
TOTAL LIFT
OPTIMUM L/D
TOTAL DRAG
PRESSURE DRAG
FRICTION DRAG
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
ANGLE OF ATTACK IN DEGREES

Fig. 3.

By the use of formula A above, we calculate the values of L/D at $\alpha = 4^\circ$ and at values 3° and 5°, just below and just above the optimum we have found.

$$\text{At } \alpha = 3^\circ, \frac{L}{D} = \frac{1{\cdot}24 \times 0{\cdot}0523 \times 0{\cdot}999}{1{\cdot}25 \times 0{\cdot}00274 + 0{\cdot}006 \times 0{\cdot}998} = \frac{0{\cdot}0648}{0{\cdot}00942} = 6{\cdot}88$$

$$\alpha = 4^\circ, \frac{L}{D} = \frac{1{\cdot}24 \times 0{\cdot}0698 \times 0{\cdot}998}{1{\cdot}25 \times 0{\cdot}00488 + 0{\cdot}006 \times 0{\cdot}996} = \frac{0{\cdot}0863}{0{\cdot}0121} = 7{\cdot}13$$

$$\alpha = 5^\circ, \frac{L}{D} = \frac{1{\cdot}24 \times 0{\cdot}0872 \times 0{\cdot}996}{1{\cdot}25 \times 0{\cdot}00760 + 0{\cdot}006 \times 0{\cdot}992} = \frac{0{\cdot}1075}{0{\cdot}01545} = 6{\cdot}96$$

Note that the optimum L/D apparently occurs near $D_P = D_F$. See plot on Fig. 3.

APPENDIX C

PERFORMANCE CHARACTERISTICS OF CRAFT DESCRIBED IN THE BOOK

A large part of Chapter X is devoted to analyses of the performance of several types of sailing yacht to determine likely values of their force coefficients and drag angles. Some material of the same kind is found in other chapters. The table here is a compilation of all those data. It should be read in connection with the following notes and comments, since it contains nearly as much speculation as fact.

In the range of windward sailing, especially for craft which point high, small changes in beta can produce large changes in the other parameters. As an example, if the value of gamma for a 12-metre boat sailing to windward in a 10-knot breeze is held constant while beta is altered by one degree, the resulting V_{MG} for speed to windward is changed by close to 10 per cent.

In most cases in the table the division of beta between the two drag angles of which it is composed is a guess. The inter-relationship of K_H and K_{HF} (the total hull force coefficient and its forward component) plays a role in the guessing.

International Twelve-Foot Dinghy

Source: Chapters I and IV.

Comment: The original data in Chapter I came from "tethered tests" on the sail and rig and towing tests on the hull, all made on the boat itself at full size. The towing test was done with a single line attached at the point of the centre of effort of the sail, as Edmond Bruce does it also in the laminar flow tank.

Only a part of the available data is reflected in the table.

Lightning Class Boat

Source: Chapter XIX.

Comment: Hull tests only, on a small model, at two "towing angles", in the "Bruce Tank".

"*Coquí*"

Source: Chapters XIV and XV and extensive data in the hands of the author.

Comment: The changes between *Coquí* and *Coquí Improved* were changes in the hull only. These figures suggest a big improvement in hull force coefficient and hull drag angle, as would be expected. The rig is not very efficient. If plenty of time, etc., were available, that would be the next area for refinement. Since $\sqrt{A_S}/\sqrt[3]{W}$ is not very high, a first question would be the desirability of increasing the sail area to match the relatively great weight.

In the course of this analysis, some adjustment of the original data has been done to produce a greater internal consistency among the figures in the table. Even so, the numbers do not fit together perfectly.

"*Antiope*"

Source: Report of the tests made on the actual hull in the David Taylor Model Basin.

Comment: As was mentioned in the text in Chapter X, a real difficulty in reading the original report is that there is no way to be sure which of the test conditions most nearly represented sailing to windward. No tests were made with the leeway angle close to that at which the craft sailed to windward in moderate conditions, according to the estimate of those who made and reported the tests.

Ocean Racing Yacht

Source: Report by H. C. Herreshoff of tests of a model in the MIT towing tank.

Comment: Same as for "*Antiope*."

Twelve-Metre Yachts

Source: Report for 1970 of the Race Committee of the New York Yacht Club, many articles in yachting magazines about the America Cup boats and races, and oral conversations with people familiar with the boats and their performance.

Comment: Speeds derived from the data in the Race Committee report are not very consistent, mostly because reported wind speeds are not good averages of what was actually felt by the racers at the height of the centre of effort of their rigs. Hence much trial and error has been needed to get to a half-way consistent set of final figures, and that is the most that has been accomplished. One major element in this has been an effort to estimate reasonable values of sail area for sailing to windward, for broad reaching, and for running before the wind. In the table, the results of this particular effort appear only in the values of $\sqrt{A_S}/\sqrt[3]{W}$.

Also, in some cases, speeds were arrived at by calculating several possibilities rather than by using the ones derived from the Race Committee report. Especially in sailing before the wind, because of the fact that apparent wind speed decreases directly with increase of boat speed, the calculations are very sensitive.

For these reasons and other similar ones, the results in the table are no more than approximations.

Tornado, Class B Catamaran

Source: A polar curve published by Prof. W. S. Bradfield of the State University of New York at Stony Brook.

Comment: At first sight, the original data looked good. Troubles developed, however. The worst of these was that the reading for best windward speed,

V_{MG}, produced what was, by the rules of Chapter VIII, Sec. B (b), an impossible combination. It called for V_{MG}/V_T to be 0·7 at $\beta = 25°$. One or the other must be smaller. The guessing finally adopted here reduced the speed by almost 10 per cent and held beta at 25°.

With this and other adjustments, the figures are still less than a good-looking fit. Should the values for K_{HF} all be alike and other alterations made to suit?

To bring K_H within reason for sailing directly before the wind, C_S was assigned as small a value as conscience would permit, in the thought that the rig may be quite inefficient in that type of sailing. The main boom may be prevented from being set far enough forward by shrouds and the jib may give little help.

"*Icarus*"

Source: Commander George C. Chapman's report of the John Players speed trials in Portland Harbour, England, in October 1972 (AYRS-AIRS 4).

Comment: Very little information available.

"*Crossbow*"

Source: Commander Chapman's report just quoted and published articles in various yachting magazines. Also an estimate of the weight of the boat very kindly supplied by her designer, Mr. J. R. Macalpine-Downie.

Comment: The figures for this craft are intriguing to work with, because she is the fastest or surely one of the fastest waterborne sailing boats (relative to the true wind) and because the relative performance in stronger wind is much inferior to that in light or moderate wind. If her hull force coefficient and her hull drag angle had not risen so much in the increasing wind, she would have been appreciably faster. One wonders, in the light of Edmond Bruce's writings in this book, if that might have been accomplished with a larger centreboard. Or, better yet, make her non-heeling?

A Fast Ice Boat

Source: Edmond Bruce.

Comment: When the high speed is accepted, there is little else about which to be surprised!

ESTIMATED PERFORMANCE CHARACTERISTICS

Boat	V_T	$\sqrt{A_S}/\sqrt[3]{W}$	V_B/V_T	β°	γ°	V_{MG}/V_T	V_B/V_A	C_S/K_H	C_S	K_H	δ_S°	δ_H°	K_{HF}	Figures of Merit		
														β°	V_B	V_{MG}
International	6–10	1·1	0·35	36	48	0·23	0·3	0·2	1·5	8·0	18	18	2·5	36		66
12-ft dinghy			0·55	60	90	—	0·5	0·5	1·6	3·2	21	39	2·0		32	
			0·4	180	180	—	0·7	1·0	2·0	1·9	90	90	1·9			
"Lightning"	6–10									3·5		32	1·8			
										1·7		90	1·7			
"*Coqui*"	6–10	1·3	0·43	37	52	0·26	0·33	0·19	1·25	6·5	19	18	2·0	37		79
			0·54	54	80	—	0·45	0·34	1·25	3·7	21	33	2·0		32	
			0·36	180	180	—	0·56	0·55	1·1	2·0	90	90	2·0			
"*Coqui*"	6–10	1·3	0·49	34	50	0·32	0·36	0·22	1·25	5·8	19	15	1·5	34		80
Improved			0·65	57	90	—	0·54	0·51	1·25	2·5	21	36	1·5		36	
			0·39	180	180	—	0·65	0·73	1·1	1·5	90	90	1·5			
"*Antiope*"	10			32						2·1		18	0·65			
				180	180					0·6		90	0·6			
Ocean Racing	10			30						2·3		14	0·6			
Yacht—1964				180	180					0·55		90	0·55			
12-Metre	10	1·07	0·7	22	37	0·56	0·43	0·49	1·2	2·5	9	13	0·56	22		67
Yacht	20	1·07	0·42	27	38	0·33	0·31	0·25	0·9	3·6	12	15	0·9	27		55
	10	1·20	0·76	86	135	—	1·06	2·3	1·5	0·65	20	66	0·57		28	
	20	1·20	0·50	106	135	—	0·7	0·96	1·25	1·3	20	86	1·3		23	
	10	1·20	0·57	180	180	—	1·33	3·6	1·8	0·5	90	90	0·5			
	20	1·20	0·48	180	180	—	0·92	1·7	1·8	1·05	90	90	1·05			
"Tornado"	5–10	1·9	1·0	25	50	0·64	0·55	0·24	1·3	5·3	12	13	1·2	25		94?
Class 'B'			1·4	38	95	—	0·84	0·6	1·4	2·4	12	26	1·05		59	
Catamaran			1·05	60	125	—	1·1	1·0	1·5	1·5	15	45	1·05			
			0·55	180	180	—	1·22	1·2	1·25	1·05	90	90	1·05			
"*Icarus*"	10–13	1·9	1·5	37	100	—	0·9	0·65	1·4	2·1	12	25	0·9	(37)	(90)	
	19		1·14	45	100	—	0·83	0·56	1·5	2·7	15	30	1·3	(45)	(80)	
"*Crossbow*"	6–10	2·3	2·0	26	87	—	0·88	0·43	1·5	3·5	9	17	1·05	(26)	(88)	
	20		1·31	44	110	—	0·97	0·52	1·3	2·5	14	30	1·25	(44)	(91)	
Ice Boat	15?		7	8·2	98·2	—	1·01				7	1·2		8·2	100	

APPENDIX D

SCHEMATIC WIRING DIAGRAMS FOR ANALOG COMPUTERS IN NEW-GENERATION INSTRUMENTS

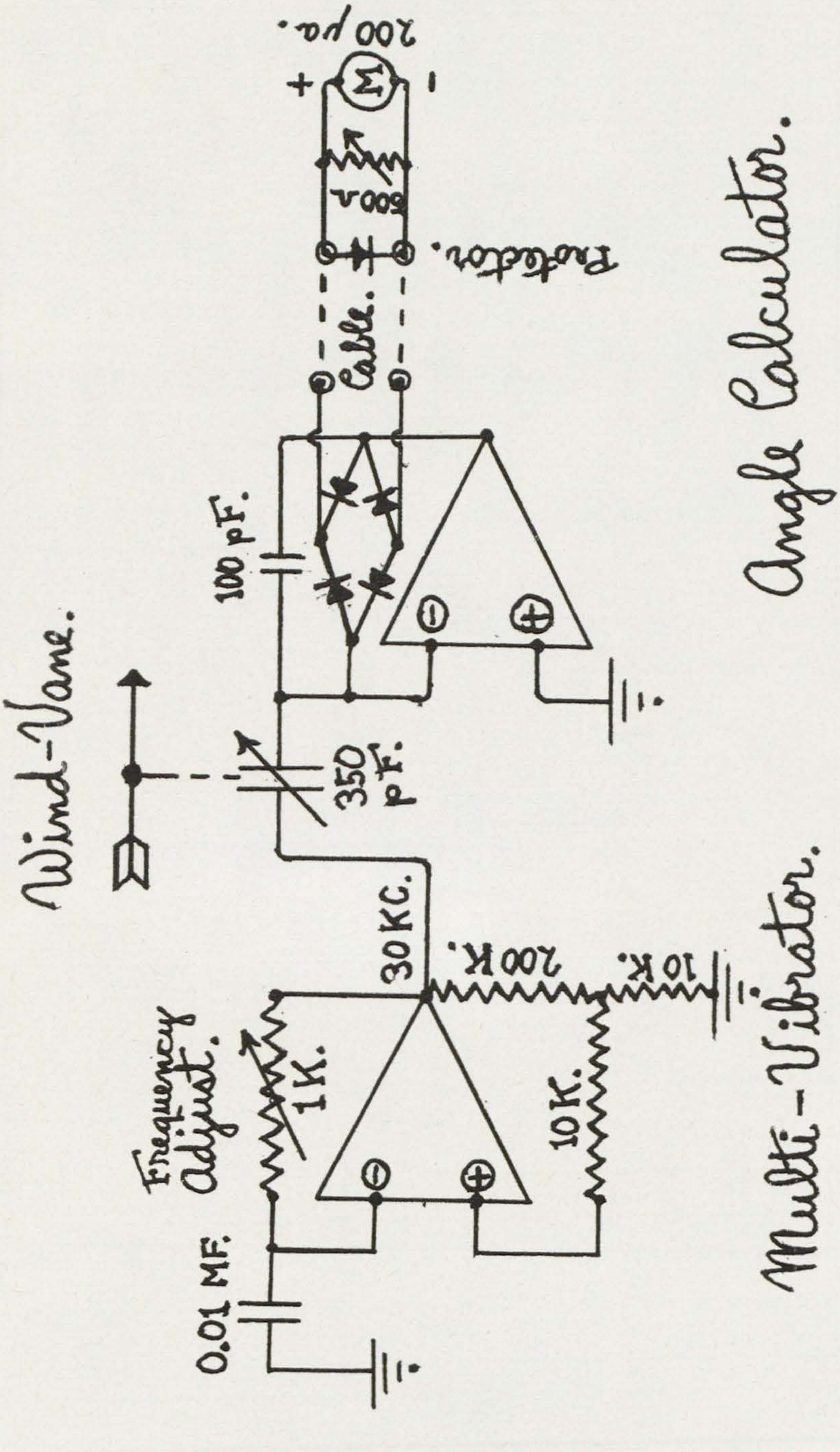


Fig. 1. Wind Direction Indicator

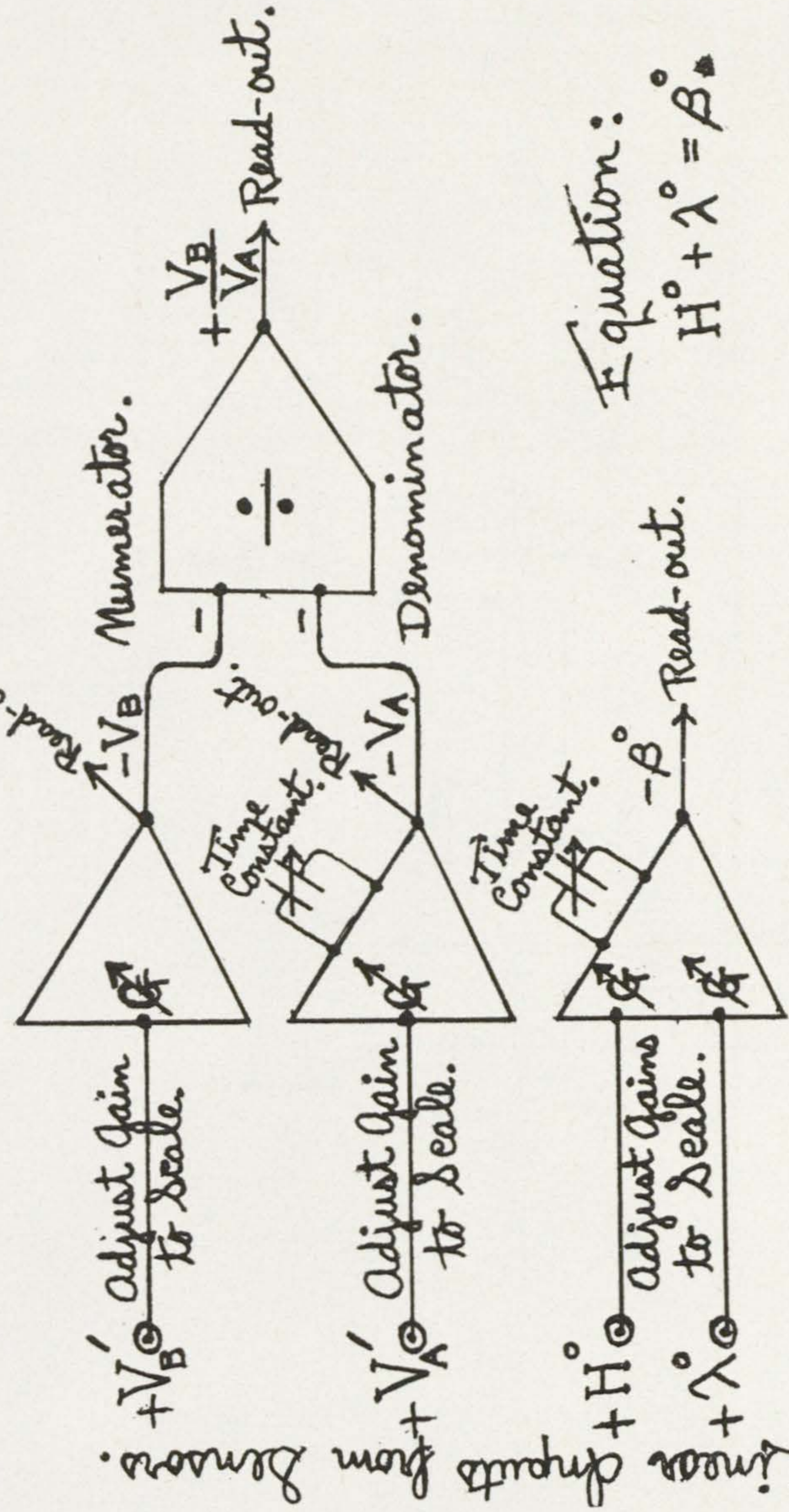


Fig. 2. $\frac{V_B}{V_A} + \beta^\circ$ Analog Computers

Equation: $$\frac{V_{MG}}{V_T} = \frac{\frac{V_B}{V_A}\cos\beta - \left(\frac{V_B}{V_A}\right)^2}{1 - 2\frac{V_B}{V_A}\cos\beta + \left(\frac{V_B}{V_A}\right)^2}.$$

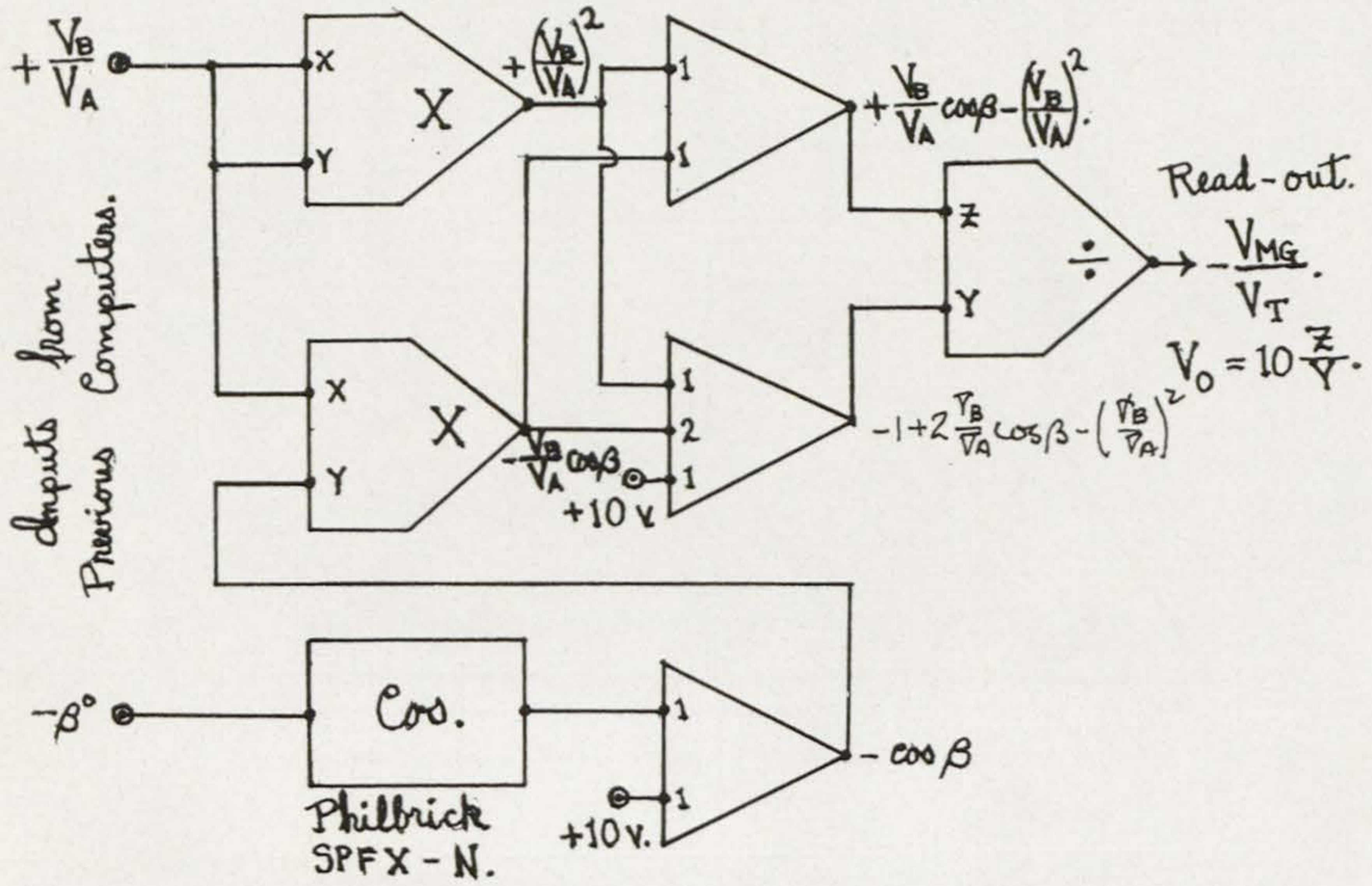


Fig. 3. $\frac{V_{MG}}{V_T}$ Analog Computer

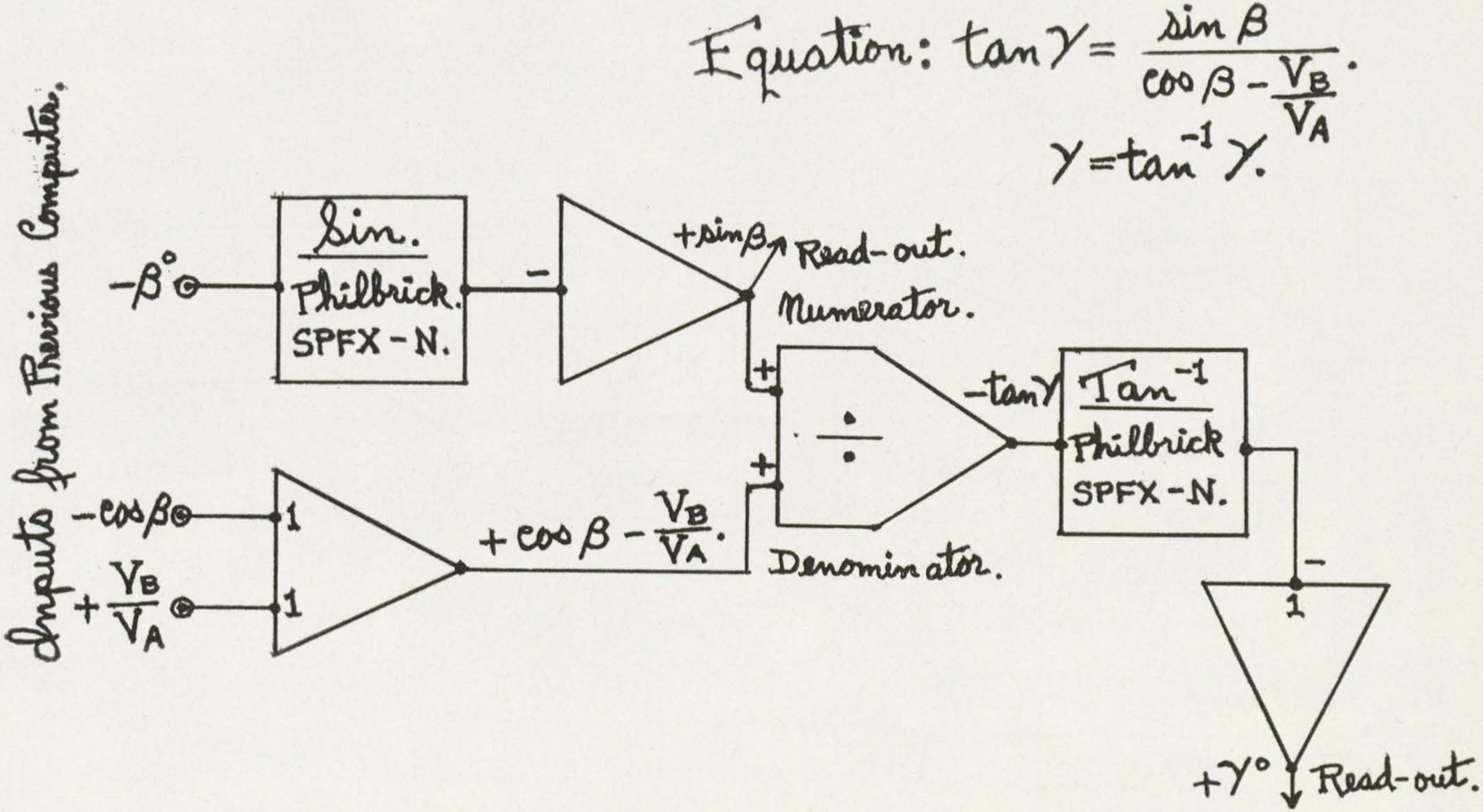


Fig. 4. $\gamma°$ Analog Computer

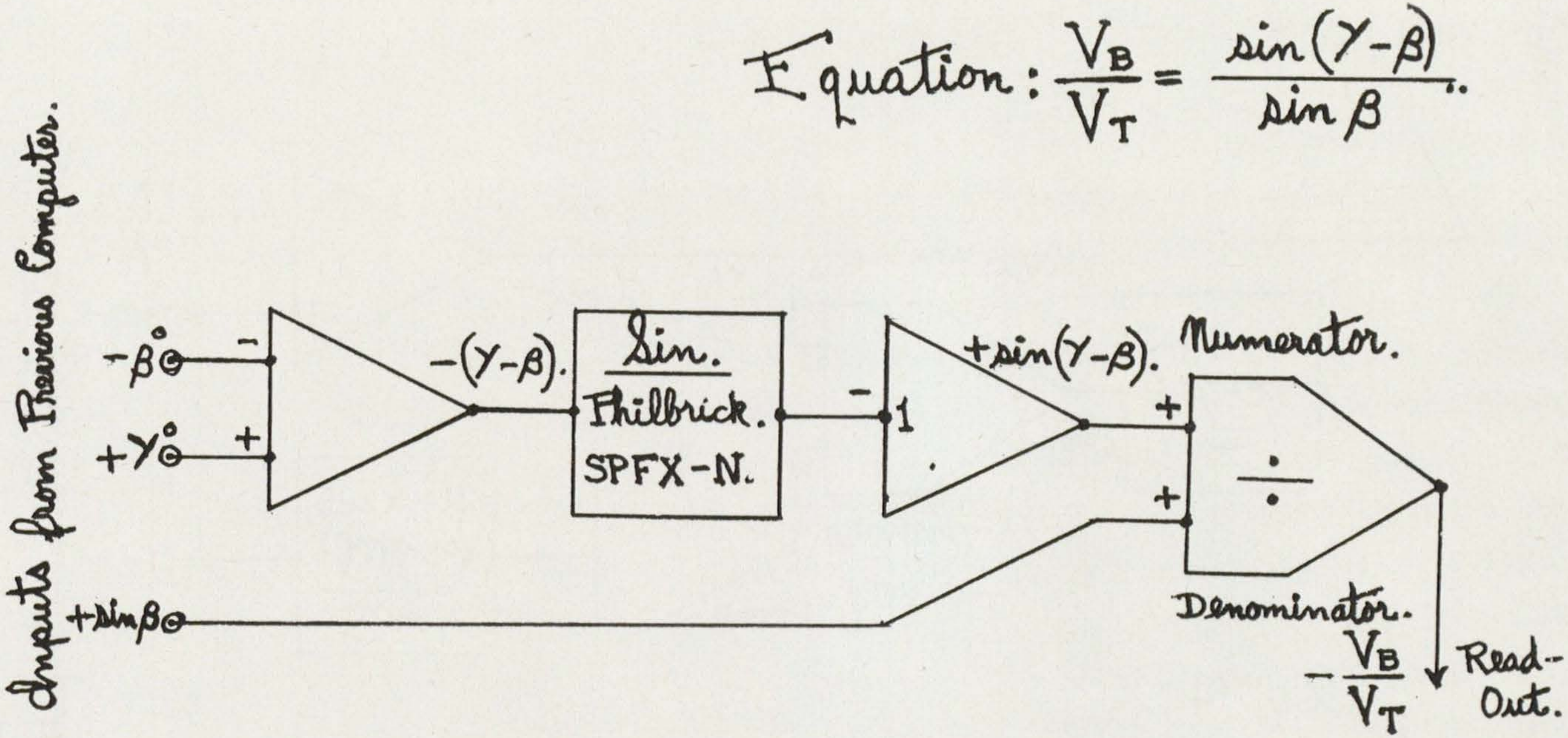


Fig. 5. $\frac{V_B}{V_T}$ Analog Computer

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