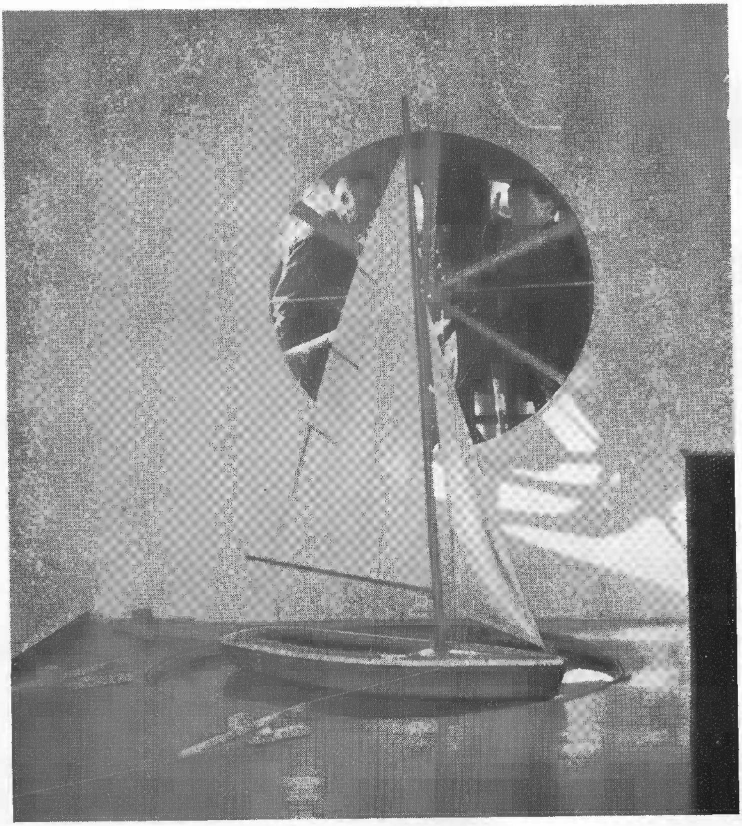
YACHT RESEARCH I

A.Y.R.S. PUBLICATION No. 40



The Model in the Wind Tunnel

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THE AMATEUR YACHT RESEARCH SOCIETY

(Founded June, 1955)

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EDITORIAL

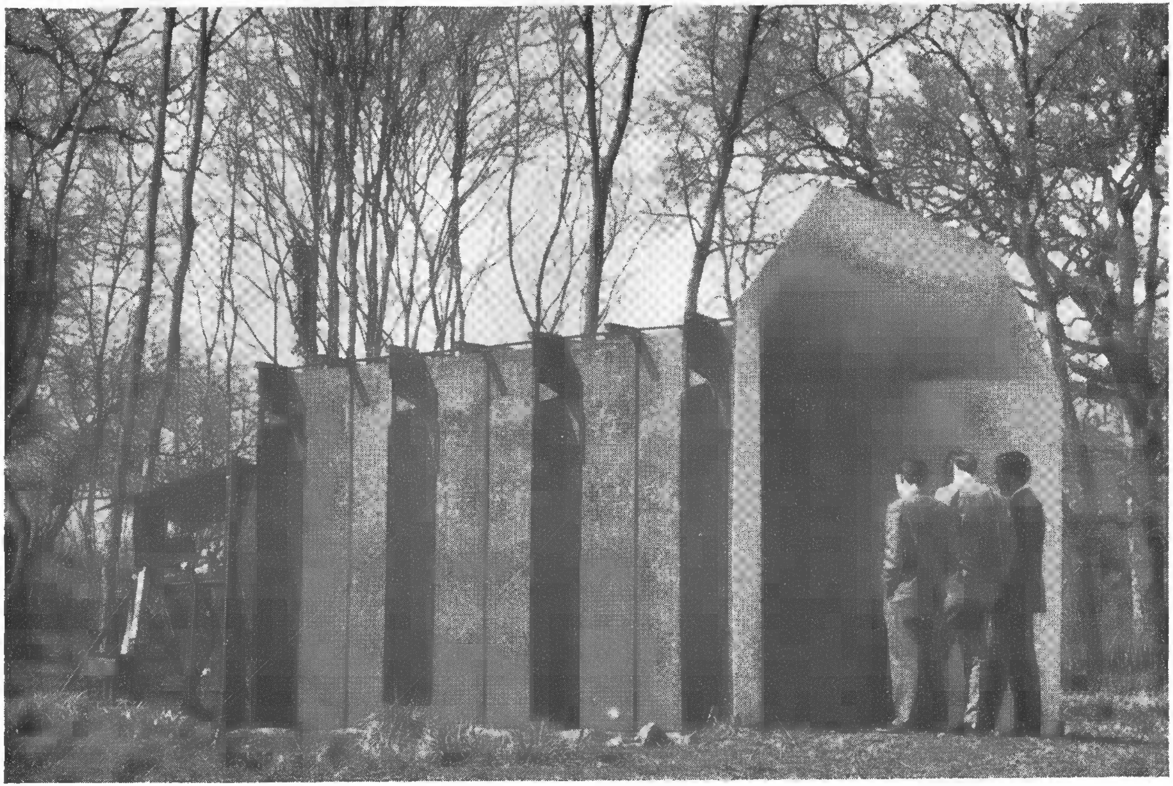
July, 1962

THE A.Y.R.S. YACHT WIND TUNNEL. The completed tunnel was opened by Lord Brabazon on Friday, 13th April. About 50 members attended, many from considerable distances. The engine and fan worked well and Mrs. Evans' beautiful and astutely designed model filled out its sails to the satisfaction of all. The final touches and instrumentation may take up to the end of June to complete but we hope to start serious work in July. Some awkward eddies were shed by the entrance rolls of *Ratsey's* similar tunnel and we trust that this will not happen to ours. The photographs of the tunnel in this publication were most kindly given to us by ALDOUS PHOTOGRAPHIC STUDIOS LTD., Clifton House, 83-117 Euston Road, London, N.W.1.

The New Zealand A.Y.R.S. J. B. Brooke has been made President and T. L. Lane has taken over the Hon. Secretaryship. Regular meetings are now starting in Auckland and members are very enthusiastic. There is a great spirit of drive about the N.Z. A.Y.R.S. and the membership which is now about 70 is increasing rapidly. However, one cannot feel that the A.Y.R.S. will have achieved its proper place in any area until it can provide at least a 4 foot yacht wind tunnel and a laminar flow test tank for the use and instruction of its members.

The Australian A.Y.R.S. Ray Dooris seems to be going ahead with the Australian A.Y.R.S. and membership there is increasing too. The Challenger for the *America's Cup Gretel* seems to be going well against *VIM* and I think we all wish her every success. Should she wrest the stubborn " Cup " from the New York Yacht Club, it will give a great boost to yacht research in both countries.

Southampton University's Yacht Research. As compared to much of the current yacht research which is kept secret, a University must publish everything it discovers. Now, after two years of preliminary work with metal sails in a high speed wind tunnel, Southampton University is starting work on cloth sails in a low speed large wind tunnel and has a test tank comparable to that at the Stevens Institute in New Jersey. If this work can be kept going, in the long run very valuable results will come forth. The University provides the apparatus but the salaries of two research workers are not available from University funds. £3,000 per annum is needed to keep this work going and, if any member is willing to help provide this sum of money, I will send him the necessary forms which must be altered to state that the donation is for yachting research. This is a far more worth while use for money than the £70,000 or even £150,000 spent on *America's Cup* Challengers.



Inspecting the Tunnel Entrance

Aldous Photographic Studios

It may seem odd to some that the A.Y.R.S., which has made its own Yacht Wind Tunnel and does not intend to pay for any work done in it, should wish people to support the Southampton research. The solution lies in what we both want to do. The A.Y.R.S. research both with our present tunnel and with a tunnel which can take full sized yachts which we hope to build someday, is concerned with *finding the best Sails or Sail Rig.* The Southampton research, on the other hand, is aimed at the study of *every Sail and Sail Rig* in every conceivable way. Our aim is much simpler and we hope to get results quickly. The results from the Southampton research may not appear for many years but they will " dot the i's and cross the t's " of our knowledge.

Apology. We don't often make Editorial mistakes other than our opinions about boats which time has proved wrong in some cases. However, in our last publication, we failed to put in the advertisement of THE SHOP, SOUTERGATE, KIRKBY-IN-FURNESS, LANCS., which sells plans of Arthur Piver's boats. I have been watching two *Nuggets* being built by Norman Naish and Derek Musslewhite in Folkestone with great interest. Sixteen *Nugget* sail numbers have been allotted so far and lots of plans have been sold. There will be quite a few trimarans about this summer. I sailed Cox Marine's (Ipswich) *Nimble* recently and found her a delightful craft though the sailing in the extreme conditions of last winter's gales had flattened the sails so that speeds were not maximum. S/Ldr. Clarke, of *Cox Marine* tells me that he has orders for 15 Nimbles, 1 *Victress*, 1 *Medallion* and 3 *Lodestars*.

OBITUARY

Peter H. Coley. Members may remember in the early years of the A.Y.R.S. some clever articles by Peter Coley on a variety of subjects mostly to do with catamarans. It is with regret that we now announce his death in a tragic boating accident. He was out sailing in Auckland Harbour with two young friends when their *Shearwater* capsized. Assistance was not at hand and he tried to swim ashore. One of the boys left aboard the upside down catamaran survived.

J. A. Lawrence. Lawrence, who was on the A.Y.R.S. Committee for several years, did some useful work on sailing hydrofoils. He was a lively and astute personality and we regret to announce his death in a road accident.

Skeezix Walker. Members will remember the catamaran *Marara* built by Skeezix Walker which he later rigged with a bi-pod mast. It is with regret that we have to announce that the craft was lost on Point Pinos on the Californian Coast with Skeezix and his crew of one. There was apparently no fault in the boat as Skeezix was undressed when found and may have been below when they ran ashore.

A.Y.R.S. Policy about Obituaries. It has up to now been the A.Y.R.S. policy not to have obituaries of our members. In the early days of the catamaran it would obviously not have been wise to have published accounts of accidents to them as it might have delayed their acceptance by the yachting public. This need not worry us now and we feel that we may now acknowledge the work of the pioneers of modern boats. However, the views of members in this matter will be welcomed.

THE INAUGURATION OF THE A.Y.R.S. YACHT WIND TUNNEL BY OUR PRESIDENT, LORD BRABAZON OF TARA, G.B.E., M.C., P.C., ON FRIDAY, 13th APRIL, 1962.

OPENING ADDRESS BY LORD BRABAZON

I have come down this afternoon to attend and indeed to open this Wind Tunnel that Doctor Morwood has, with the help of A.Y.R.S. members, constructed. It has long been his ambition to build it and here we are inspecting it. Right at the beginning I would hasten to pay tribute to this man for stimulating so many sailors to think imaginatively on so many matters.

The magazine that he compiles and features I cannot imagine with his multitudinous duties how he ever manages to edit. It is world famous and delights the heart of everyone lucky enough to subscribe to it.

Here I would like to mention his family. Many of us would like to do this or that, but the internal resistance in the home defeats us. Here the enthusiasm of Doctor Morwood is shared by his wife and children, and it is indeed a wonderful and inspiring spectacle to see such an enthusiastic family working creatively together.

The motor starts, air moves, the sail of the model fills and the model boat pulls. How much does it pull ? Would it pull more with a sail cut differently? Is the jib set to get maximum effect on mainsail? What experimental excitement it affords.

It is, of course, pleasant to record that sound work is being done at Southampton University to resolve some of the problems of sailing craft. We wish them well in their pioneer work which is long overdue. Do not for a moment suppose however that this Wind Tunnel is not wanted. We cannot as amateurs all the time butt into the scientific work done by the physicist, but here with Doctor Morwood's help we can try out our pet theories and definitely see whether our ideas are sound or not.

The gathering at the Tunnel entrance Aldous Photographic Studios

Remember the study of sails is a virgin field of great complexity. What a privilege, that due to Doctor Morwood and his friends we can join in.

We thank you from the bottom of our hearts for all that you have done for us, and the excitement that will soon follow.

We bless the Morwood family.

It is a great privilege to me to declare this Wind Tunnel open.

THE A.Y.R.S. YACHT WIND TUNNEL

The tunnel design is based on that by Sir Richard Fairey which he built and used at Hayes, Middlesex, in 1938 and 1939. Sir Richard's tunnel was described for us by M. S. Hooper, the head of Fairey's Aerodynamic Department in publication No. 24 *Yacht Wind Tunnels*, but we have modified it by abolishing the lower roll at the entrance. We are, however, prepared to build one on if it proves to be necessary.

The basic design was then turned into terms of plywood and battens by Owen Dumpleton, with subsequent modifications by us as the work proceeded. For instance, the buttresses were added while Father Fred Redding was helping with the work which gives a faintly Ecclesiastical touch to the job. The roof arches, which are immensely strong, were also made to his suggestion.

In all 19 people have made the tunnel. They are as follows :

Andrew Adams	Robert Seligman
Ernest Collins	C. W. Stainer
Owen Dumpleton	Hetty Tett
P. G. Epps	Roger Waddington
Fred Redding	James Wilmott

and the whole Morwood family of Elizabeth, Maureen and Susan, Dr. and Mrs. Morwood and also Granny Flora Usher.

The fan was made to Owen Dumpleton's design by Leslie Dixon.

Mr. Jarvis of *Martin Walters* made the fan mounting and Messrs. Robert Allin and Charles Richards of the *Ordnance Garage* have adapted the rather reluctant engine to the fan shaft and have got it going.

Norman Naish has given freely of advice about construction matters and has interrupted his work on his *Nugget* trimaran to help with technical advice about the balances.

Mrs. Ruth Evans has made the lovely model shown in the pond whose sails appear to be good replicas of full sized sails. F. W. Bevan has made two hot wire anemometers whose design was discovered

The Engine

Aldous Photographic Studios

by Owen Dumpleton. K. R. May has made a most intricate smoke producing apparatus.

The plywood for the tunnel was bought from Messrs. *Thamesply*. the paint was presented to us free by *International Paints Ltd.* The honeycomb is by *Dufaylite Ltd.*

The A.Y.R.S. Yacht Wind Tunnel has taken some 18 months of part time work to build and the cost has been about £100.

THE PURPOSES OF THE A.Y.R.S. YACHT WIND TUNNEL

Though it has been the ambition of the A.Y.R.S. right from the start to have a yacht wind tunnel, the momentum can be said to have been started by a suggestion from Lord Brabazon in 1957, when he became our President. It was he who contacted Mr. Hooper of *Fairey's* for us and got us the preliminary design of our tunnel.

After our plans had got underway, Southampton University started their work on solid sails in a high speed tunnel and combined it with some information from Saunder-Roe. At last, however, Southampton have a large wind tunnel working in which they are testing cloth sails and a test tank exclusively designed for yacht hulls. We may therefore expect some adequate academic research from them in the course of time. Their recent course on *Yacht Research* was most interesting and instructive.

We can guess that the value of the A.Y.R.S. yacht wind tunnel to yachting will be as follows :

Firstly, it is a test of the wind tunnel itself to see if the design is satisfactory, will produce good windflows and be a suitable instrument for testing yacht sails. If it should prove to be good, we hope to be able to make a yacht wind tunnel no less than four times this size in which full sized dinghies can be tested. This larger wind tunnel would be very valuable for testing Olympic dinghies. It would also be a truer test of yacht sails because model sails, no matter how good, can never quite give us the absolute picture of what goes on at full scale.

Secondly, this yacht wind tunnel will be available to any amateur who has developed a yacht rig and wishes to test its value, as long as he is an A.Y.R.S. member. Ruth Evans has made the model so that the mast can be put in any fore and aft position so that semi-elliptical sails and " mast-aft " and other rigs may be put on it.

Thirdly, Every year, students have to write theses on research projects. We must allow these keen young men to use the tunnel and they will surely increase our knowledge of yachts.

Yachting Research in General. Human knowledge and intelligence can be concentrated among a few highly learned people at a University who will, given the facilities and time, produce an increase in knowledge.

The A.Y.R.S. approach is somewhat different. We believe that the large numbers of our highly intelligent and original membership will also produce an increase in knowledge of a very much wider kind that the more concentrated intelligence of a University. We hope that our *Yacht Wind Tunnel* will be the catalyst which will make this possible.

YACHT RESEARCH 1

The main articles in this publication are by Edmond Bruce and they contain a complete examination of a sailing dinghy from the scientific point of view. From practical tests, he comes up with figures from which he mathematically derives the smooth watei performance of the dinghy for all wind directions and wind speeds. In the 29 pages of his articles, therefore, is to be found the fundamental concept for the scientific study of sailing craft which can be carried out both on the smallest dinghies and the largest yachts.

Because of the public interest, it would be interesting to the yachting public if both Gretel and Vim were to be tested in this way by the Australians and the defenders in America were also tested. By this means, the yachts with the greatest potential performance would be found and, as compared to trial races, the personal factors would be avoided.

I think the methods of deriving the sail and hull forces are most simply and easily described and should present no difficulty in being understood. However, the mathematical marrying up of these forces is to going to present difficulties to many members and we are prepared to devote a good deal of space in future publications to make this clearer. Where there are regular meetings of A.Y.R.S. members, it is hoped that the whole method will be discussed and made clear to all because it is more than likely that this method (or similar ones) will constantly recur in A.Y.R.S. publications. If members, therefore, want some point made clear, I am sure that neither Edmond Bruce nor I will mind supplying an answer.

Now that we have shown a method of analysing a sailing boat's performance, it will be apparent that the value of a yacht wind tunnel will be appreciated because of the time saved in the sail testing. Smooth water is not hard to find and calm conditions are frequent so that towing tests of hulls are relatively easy. However, the natural wind frequently changes its strength and direction due to eddies of large size which may be vertical or horizontal and this makes taking the sail forces in the natural wind difficult and time consuming.

Publication No. 41. We have had such a mass of material on Yacht Research and Theory that we have not been able to use it all in this publication. I had hoped to produce a simple method of analysis of the kind used here for members to appreciate the general idea of what has to be done and there are articles by Col. Bowden and others on sail tests and research equipment. These will be used in our next publication with any letters and questions raised by members on the present one. This publication is therefore called *Yacht Research I* and the next one will be *Yacht Research II.*

THE SEVERN BRIDGE WIND TUNNEL

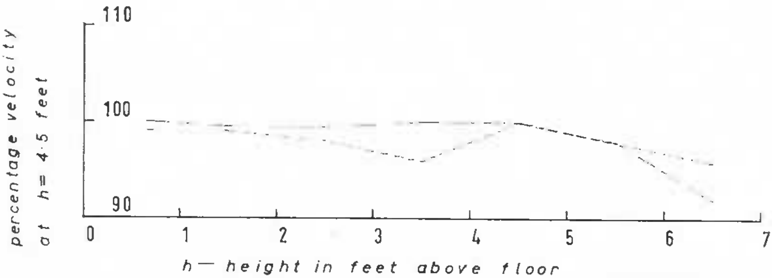
BY JOHN MORWOOD

During Southampton University's recent course on Yacht Research, I took the opportunity to discuss our yacht wind tunnel with several people. For instance, at the Boat Show, there had been conflicting views on what should be put at the entrance by very knowlegeable people indeed. The alternatives were (a) Honeycomb and (b) screens or (c) both. Sir Geoffrey Taylor suggested starting with honeycomb because of its lesser blockage and, as this was the only structure used by Sir Richard Fairey, it seems reasonable. It may even be desirable to have an eddying flow in the tunnel to simulate the natural wind but, of course, it must be straight and of constant velocity.

Professor Richards and others seemed to favour screens to have a smooth airflow. In the course of discussion with Professor Richards, he suggested approaching Mr. C. Scruton of the National Physical Laboratory as regards the vertical velocities in the wind tunnel made to test a large model of the Severn Bridge, which was roughly of the same general design as ours. His reply to my letter follows.

DEAR MR. MORWOOD,

In response to your request for information on the vertical velocity distribution in the large tunnel built for the original Severn Bridge research, I enclose a plot of results obtained at two positions centrally placed in the working chamber. The vertical distributions were equally good at other positions. There is some tendency for the velocity to fall off near the roof of the tunnel, but otherwise we would regard this distribution as adequate for your purpose. We used two screens, one 3 inches behind the other, at the intake end of the



working section. These were intended to give a total resistance coefficient C = 2, which is generally regarded as the optimum for smoothing purposes, but in fact measurements showed that this coefficient was only 1.4. A similar two-mesh screen was placed at the downstream end of the working section, and this may prove necessary for your tunnel also to prevent any " funnelling " of air from the intake end to the smaller fan annulus.

The honeycomb and the mesh screen have somewhat different functions — the honeycomb straightens while the mesh smooths. If you are already committed to a honeycomb, and the honeycomb proves insufficient, I would sggest that you leave the honeycomb in position and add a C = 2 screen to leeward of the honeycomb, and perhaps another screen to windward of it. The windward screen could be a fairly crude nylon mesh, but it is essential that mesh of the leeward screen should be uniform.

You are no doubt aware that the presence of the smoothing screens limits the propagation of the distortions of the flow due to the model under test and, because of this, spurious results may arise if the working section is not large enough in relation to the size of the model. A further factor affecting the permissible size of model is the wake blockage correction to the drag forces. These corrections can become very large indeed for a " bluff " body such as a spinnaker.

If you are not already overburdened with the opinions of experts, and there are any wind-tunnel techniques or details of the aerodynamic design of wind tunnels which you would like to discuss with us, I would be pleased to make the necessary arrangements with the appropriate members of the staff.

Yours sincerely,

C. SCRUTON.

National Physical Laboratory, Teddington, Middlesex.

A LAMINAR FLOW TEST TANK

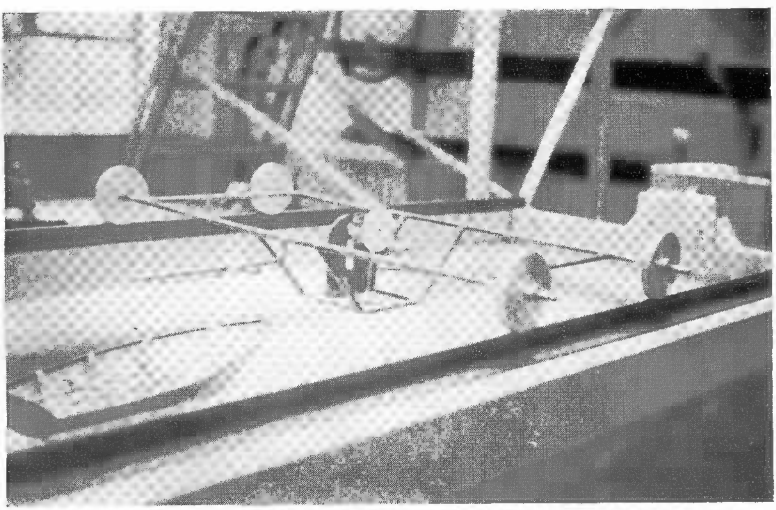
BY A. G. MORSE-BROWN
Summer Place, Swindon Road, Kingswinford, Staffs.

This article is a description of a laminar flow test tank and related full scale tests used in the experimental work for a College Thesis.

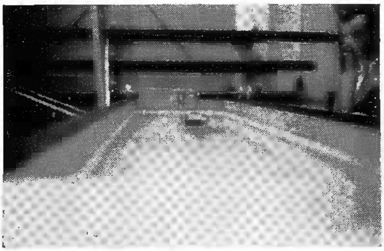
In the first place, the work of Edmond Bruce was studied and it was decided to use similar apparatus to extend his work and try to correlate model and full scale test results.

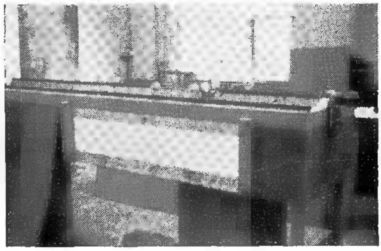
Tank, Towing Apparatus and Models. The tank itself was basically similar to Bruce's and was 10 feet long, 2 feet wide and a foot deep. It was made of polythene sheeting hung in a wooden supporting framework, the whole being mounted on legs to bring the water level to a suitable working height. Initially, Bruce's method of towing was used, incorporating a falling weight, the line passing over a pulley in the roof. However, a great deal of trouble was experienced with pulley friction and the method of towing had to be changed. After numerous methods had been tried, full scale practice was reverted to and a light travelling carriage used. This was made of $\frac{3}{8}$ inch diameter mild steel rod welded into a basket form and running on four aluminium wheels on rails made of 1 inch by 1 inch by $\frac{1}{8}$ inch angle iron, the latter being screwed to the sides of the tank.

The carriage was towed along the tank by a falling weight and to maintain its speed at a uniform value, a line was attached to the rear and then round a stepped drum mounted on the shaft of a clockwork

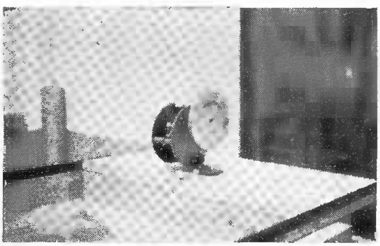


gramophone motor. The required model speeds had previously been worked out and the diameters of the steps on the drum calculated so that when it was driven at the motor speed of 78 R.P.M., the periferal speed at each step would correspond to one of the derived model speeds.





The towing line formed a closed loop over the gramophone motor drum and the two other pulleys. A line was attached at a point between the pulley at the end of the tank and the idler pulley. It then passed over the idler pulley and a weight was hung on the end. The tension in the closed loop was adjusted to prevent slip on the drum by using a sliding line attachment on the carriage. The line used was single core plastic covered electric flex, which proved sufficiently inelastic to prevent undue oscillation.



The timing of the model was done by Bruce's method of a stroboscopic wheel -- the British counterpart of his American pen recorder and amplifier being used, while the photocell circuit was obtained from the Mullard Handbook.

The measurement of the towing force was done by means of a simple pendulum. The unit was made out of a pressure gauge, the pendulum arm being soldered to the curved rack shaft and the Bourdon tube sawn off. Deflections of the pendulum from the vertical were thus recorded by rotation of the pointer, the dial being calibrated in grams. The tip of the pendulum was joined to the bows of the model by a thread. Calibration was done by applying known horizontal forces to the pendulum (suitably weighted) by means of a balanced bell crank. The balance was then mounted on the travelling carriage in a slotted plate to enable the tip of the pendulum to be adjusted to the level of the model.

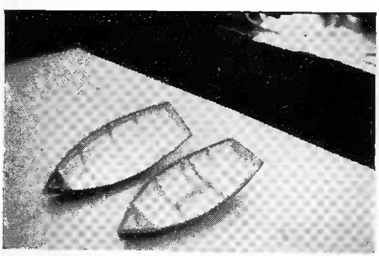
It was found that damping was required and a simple piston type oil damper was fitted. This proved too insensitive and was scrapped. Lack of time prevented further experiments on this but a light vane type damper would doubtless improve the balance.

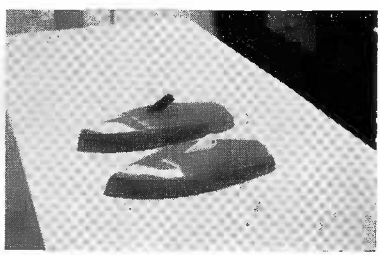
The models were made from $\frac{1}{8}$ inch and $\frac{1}{16}$ inch plywood and the full size methods of construction were copied on the smaller scale. They were finished with filler and four coats of Valspar paint on the outside with varnish inside. The models were of the Yachting World G.P. 14 foot dinghy and the National *Enterprise* dinghy, each model being exactly $\frac{1}{12}$th scale.

The polythene model skins were made in the same manner as Bruce's with a thickness of 5 thousandths of an inch.

The Model Tests. With a $\frac{1}{2}$ lb. weight on the towing line, each hull was run three times at each speed and the speed and balance reading noted. The water temperature was noted at the same time.

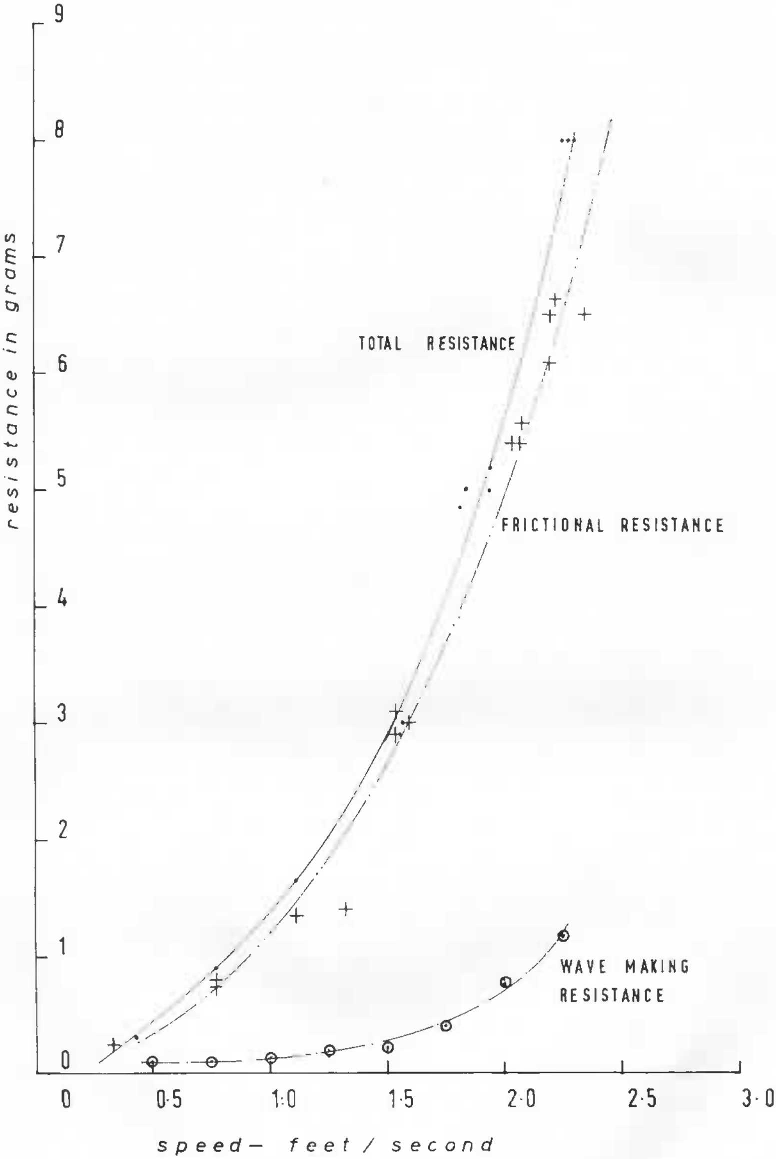
At the higher speeds, oscillation of the balance pointer occurred due to lack of damping on the balance, but this was simply overcome by steadying the model with a piece of wood held against the carriage until the initial acceleration period was over. Removal of the piece of wood then left a steady balance reading for the remainder of the run.





The skins were also tested but no balance oscillation occurred, due to the skins' low inertia.

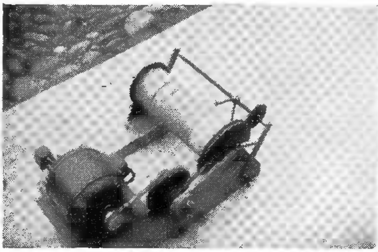
By subtracting the towing force of the skins from that of the models, wave making resistance was then obtained. Graphs of wave

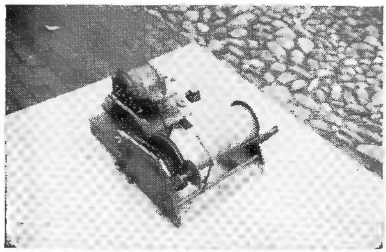


9
8
7
6
5
4
3
2
1
0
resistance in grams
TOTAL RESISTANCE
FRICTIONAL RESISTANCE
WAVE MAKING
RESISTANCE
0
0·5
1·0
1·5
2·0
2·5
3·0
speed— feet / second

making resistance, skin friction and total drag were drawn for each hull. Then using Froude's Law and the Schoenherr curve, the total drags of the full size hulls were calculated.

Full Scale Towing Apparatus. The full scale hull towing was done by means of an electric winch fitted with various sizes of towing drums or rolls. The winch and rolls were made almost entirely of wood and the rolls ran on a shaft made of 1 inch conduit, the ends being mounted in small ball races.





For sufficiently accurate measurement of distance, using a hand stop watch for timing, the error had to be comparable to that of the model tests, which it was hoped would be about 1%. The length of line for each speed was thus calculated to give the required accuracy.

Thus, with a timing accuracy of 1/5th second, if the boat speed is V ft./sec. then the distance travelled in 1/5th second is V/5 feet. For required accuracy, total length of travel is then $\frac{V \times 100}{5} = 20\,V$ ft.

The length of the rolls to accommodate the required length of cord were also calculated. The line was guided onto the rolls by a leadscrew and nut, the nut having an eye for the line to pass through and the leadscrew was driven by a friction disc from one of the pulleys.

The rolls could be driven at two speeds by means of plywood " V " pulleys and this gave, with five rolls, a selection of 7 different speeds from 1 to 7 ft./sec. The winch was powered by a $\frac{1}{4}$ H.P. motor which was later found to be inadequate at the higher speeds, unless some manual assistance was given on the tow line during the acceleration period.

The towing force was measured by a large spring balance attached to the mast at deck level, the towing line being fixed to the hook. The balance was read by the man in the boat.

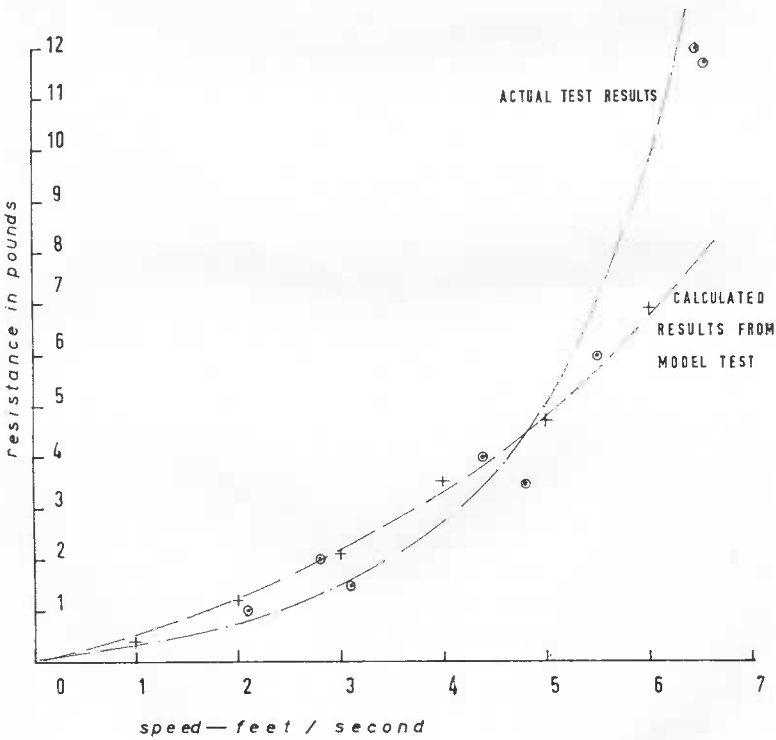
It was found necessary during tests to have the centreboard lowered a certain amount, this being noted and reproduced on the models. Timing of the boat was done by counting paint marks on the line put on at 20 ft. intervals as they passed through the eye of the leadscrew nut.

The G.P. 14 was tested on a local canal and the apparatus proved. However, due to the model being slightly on the heavy side, causing it to ride below the correct water line and, since the correct water line was used on the full scale test, the results did not correlate. Lack of time prevented any rectification of this problem.

By contrast, the *Enterprise* was towed on the sea in Tenby Harbour and the results from this trial were quite good as can be seen in the graph.

Conclusions. The time available for completion of the project was insufficient to gain enough results from which to draw any definite conclusions. However, it was possible to develop apparatus which is now capable of giving useful information.

Doubtless, Bruce's method of towing is equally as good as the one used, but again, lack of time prevented further experiments in this direction and no bearings having a low enough coefficient of friction were available at the time.



As stated earlier, light viscous damping would greatly improve the carriage balance.

The reason for the scattering of the points on the full sized *Enterprise* curve is that conditions were by no means ideal for testing, there being a slight swell running and light winds.

However, the graph does show correlation between scaled up model test results and full scale test results.

This article is printed with the kind permission of the Principal of the Wolverhampton and Staffordshire College of Technology at which college the project was carried out as a Thesis for the Diploma in Technology.

DEAR MR. MORSE-BROWN,

May I congratulate you heartily on the competent job you have done on your thesis, " Hydraulic Models." I received the copy by mail on December 2nd. You were obviously battling against a time dead-line but successfully fulfilled your objective of investigating " scale effect."

I regret that pulley difficulties consumed so much of your time in seeking alternatives. Had I known, I would gladly have sent you a suitable low mass pulley. The Central Scientific Company of Chicago, Illinois, U.S.A. made my pulley. Later it appeared as a regular low cost item in their catalogs of physical scientific apparatus. Incidentally, the photograph of my pulley unit in A.Y.R.S. No. 30 was printed inverted by accident.

I may have caused your pulley troubles by recommending ball-bearings. Actually my home-built sharp needle bearing pulley had less rolling friction but it was delicate and would not stand abuse. My pull calibrations were obtained by measuring the effective pull of the cord through the complete pulley system with a chemist's balance located at the position the model would have been. The balance arm was caused to oscillate to obtain rolling friction rather than static friction. To determine the friction magnitude, this pull was compared with the weight of the experimental weight plus hook minus the thread effect, which had been analyzed. My ball-bearing pulley shows rolling friction of 0.005 gram for a weight plus hook of 5.660 grams. Size A Nylon thread was used, having a diameter of 0.005 inch. It is strong and its weight is negligible. On rare occasions, I supplemented this system with a rearward rising weight at the end of a cord over another pulley. It was arranged so as to give a sternward force on the model hull. The differential weight was then used for pull calculations.

My experiments progressed in the opposite direction to yours. I originally had a floor-level, 18-foot tank with a mono-rail mounted spring scale. The mono-rail could be moved sidewise to permit windward type tests. I had much trouble with oscillations in this mass-elastic combination. Also I had trouble with poor accuracy at low scale readings, travelling scale, acceleration and deceleration problems with the carriage. I became distressed and built my present type of simplified smaller tank with its falling weight over a single pulley. In general, for windward type tests, if a long towing cord and the necessary height is possible, I favour calibrated falling weights as being more accurate than readings of a pointer on a scale. If housing space is limited, a moving carriage with a scale may be best.

Your stated objective does not necessarily need to know boat and model weights. However, to the individual who would like to compare the merit of various hull designs, these must be stated. I would be much interested in knowing the weights of the models and boats as tested. I have found that the full size weight must be accurately scaled to give a valid comparison of model with boat. Fore and aft water-line levels were observed only to check trim and wetted area.

I have a few comments to make on the scale effect curve on page 17. One gets the impression that the scattering of points means considerable experimental error. Actually, this is not the case. I have identified each point and find that the G.P.-14 points all lie below the drawn curve while the Enterprise points lie above. Curves drawn through these respective families of points show far less scattering. Since the areas and average lengths of the two skins are not too different, it would have been interesting, had time permitted, to determine the cause for this shift in these two curve positions. I have experienced similar marked shifts with the growth of algae. This cannot be the cause in your case, however, since you state that all model tests were made on the same day.

I certainly hope that now that your thesis has received high honours, the towing tank and ingenious full size test apparatus are not abandoned. There must exist all kinds of folk anxious to continue testing. Personally, I would like to see both tank and full size arrangements expanded to handle simulated windward tests. To me, this type of testing is the most fascinating of all.

Canterbury University in New Zealand, among others, was building a laminar tank. Mr. Charles Satterthwaite wrote me complaining about the time required to build accurate models. He was delighted with a description of my present method and I am passing this procedure along to you in case further activity is envisioned.

My models are close to the size of the usual drawings of body lines. The modest size conversions required are accurately made with ordinary X-frame proportional dividers. Cross-sections at stations are scribed on rectangular aluminum sheets which, after cutting away interiors and filing on a power jig-saw, are placed in saw cuts within a box. Such cuts are properly spaced for each station location. A concave mold is then made with modelling clay using a flexible batten for fairing to the aluminum cross-section templates. Polyester resin and catalyst reinforced by surgical gauze is then used for model fabrication. This will not adhere to this clay on curing. If care is taken to form smooth surfaces, a gloss finish results. If not, sanding and polishing readily accomplish this.

I wish to thank you for the opportunity of reading your interesting thesis.

Sincerely,

EDMOND BRUCE.

Result of Test on Full Size Enterprise.

Balance Reading in Pounds	Speed in Ft./Sec.
1.0	2.1
1.5	3.12
2.0	2.81
3.5	4.8
4.0	4.39
10.0	5.58
6.0	5.51
11.75	6.55
12.0	6.49

Results Obtained by Calculation from Enterprise Curves.

Model speed ft./sec.	Corresponding boat speed ft./sec.	Total model drag grams.	Model skin resistance grams.	Model wave making resistance grams.	Boat wave making resistance pounds	Boat frictional resistance	Boat total resistance pounds
0.289	1	0.15	0.10	0.05	0.195	0.212	0.407
0.578	2	0.50	0.40	0.10	0.391	0.737	1.128
0.867	3	1.00	0.86	0.14	0.547	1.540	2.087
1.156	4	1.72	1.52	0.20	0.781	2.360	3.341
1.445	5	2.65	2.41	0.24	0.939	3.930	4.869
1.735	6	3.95	3.59	0.36	1.140	5.50	6.910

Results for Enterprise Hull and Skin Models.

Model Enterprise Hull		Model Enterprise Skin	
Force in grams.	Model speed in ft./sec.	Force in grams.	Skin speed ft./sec.
8.0	2.275	6.5	2.34
8.0	2.27	6.1	2.19
8.0	2.28	6.5	2.2
5.0	1.95	6.6	2.22
5.2	1.95	6.5	2.2
4.5	1.85	5.55	2.085
5.0	1.86	5.35	2.02
5.0	1.86	5.4	2.03
3.0	1.585	5.4	2.07
2.9	1.568	3.1	1.54
3.0	1.585	3.0	1.55
1.65	1.125	2.9	1.52
1.65	1.125	1.4	1.34
1.6	1.125	1.4	1.34
0.9	0.792	1.35	1.125
0.9	0.792	0.8	0.762
0.9	0.792	0.8	0.762
0.3	0.408	0.75	0.762
0.3	0.408	0.3	0.388
0.3	0.408	0.3	0.384
—	—	0.3	0.384

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

BY EDMOND BRUCE

Lewis Cove, Hance Road, Fair Haven, N.J., U.S.A.

PART 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.

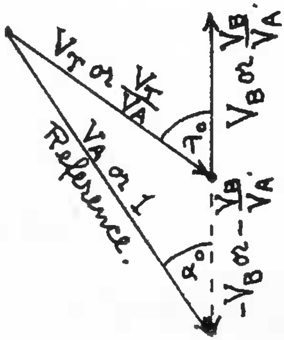
The Apparent Wind

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 realitivity 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 realitivity 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:

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

Trigometric Equation:

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

$$\tan\tau^\circ = \frac{\sin\alpha^\circ}{\cos\alpha^\circ - \frac{V_B}{V_A}}$$

Fig. 1.

V_B is boat's speed through water (including current).
V_A is apparent wind velocity.
V_T is true wind velocity.
α° is apparent angle between boat's course and the apparent source of wind.
τ° is true angle between boat's course and the direction of the true wind's source.

Note : Dividing all vectors by the scaler 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 wind. A brief description of an accepted

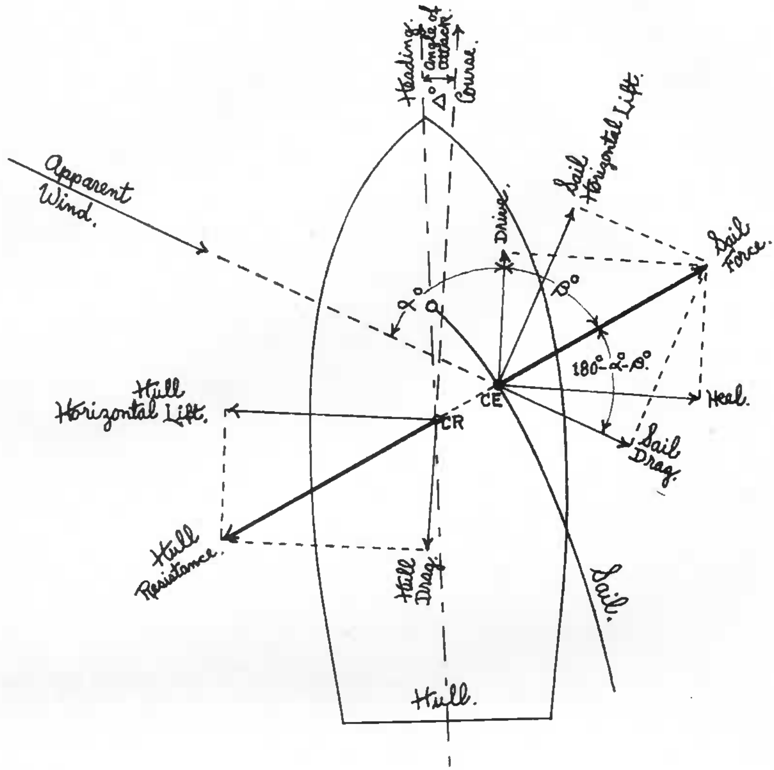


Fig. 2.

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 " Bernouilli's principle " for nonturbulent 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 of 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 control 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 C-clamp proved satisfactory. Use of a short line limits the hull travel and also the restabilization 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

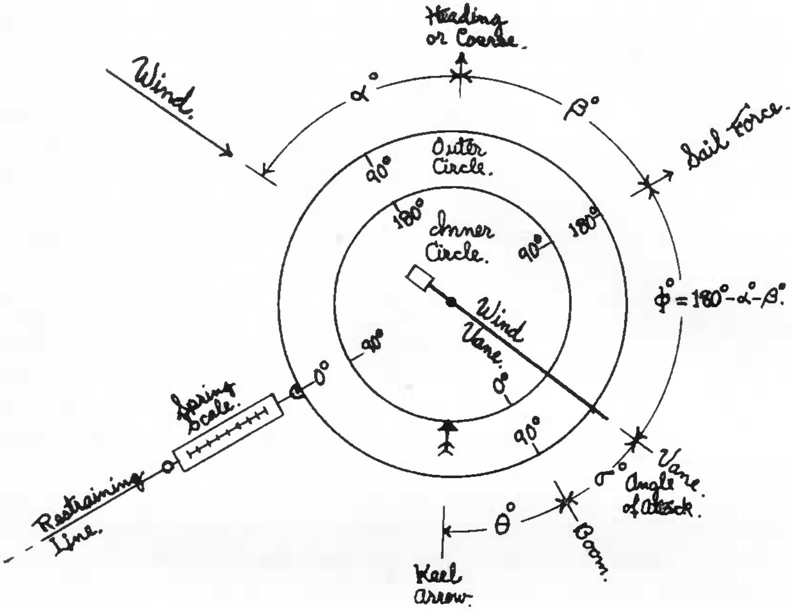

Heading or Course.
Wind.
α°
β°
Sail Force.
Outer Circle.
Inner Circle.
90°
180°
180°
90°
φ° = 180° - α° - β°
Wind Vane.
90°
0°
0°
90°
Spring Scale.
Restraining Line.
θ°
σ°
Vane. Angle of Attack.
Boom.
Keel arrow.

Fig. 3.

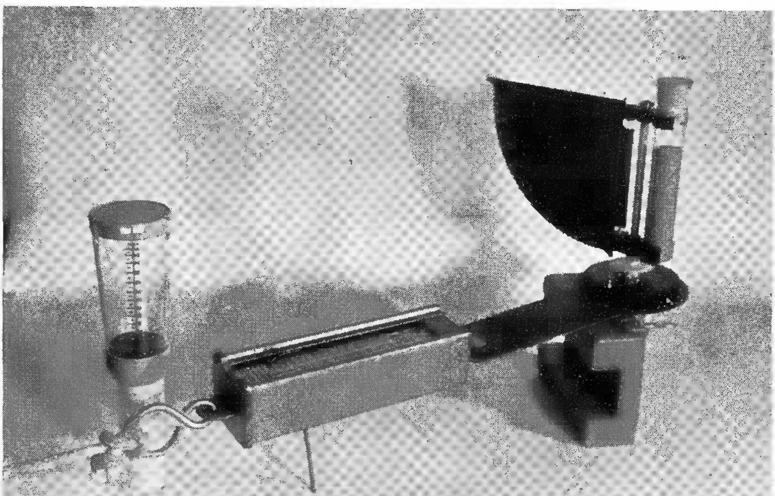


Fig. 4.

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

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 obstructions.

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 stabilized 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.

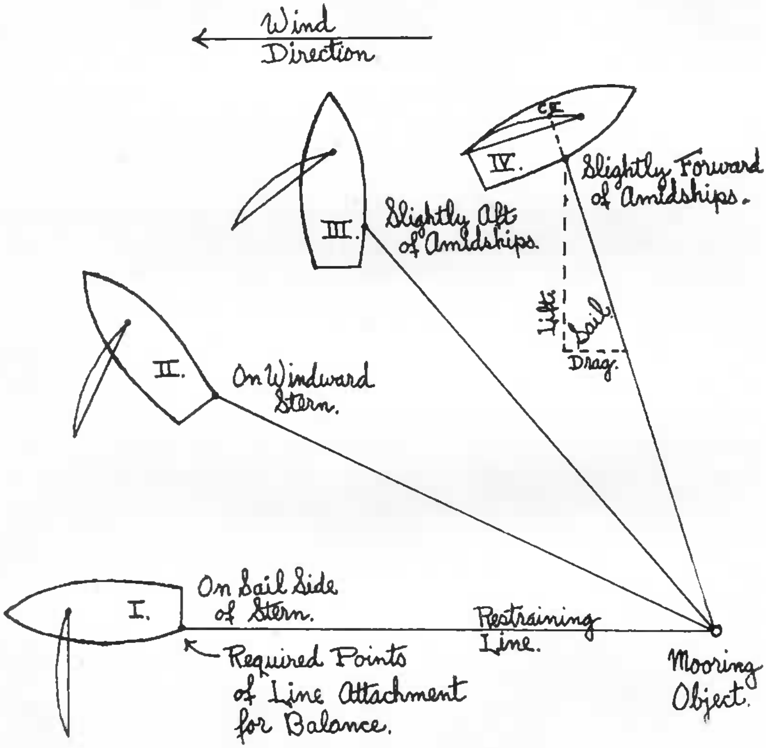


Fig. 5.

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 manouvered 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.

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 square feet is used. This results from a luff of 16 feet and a foot of 8 feet. It's actual area, including roach, is 80 square feet. This sail contains two short battens and is mounted on a rotatable streamlined aluminium mast. Other statistics are : L.O.A.—12 feet. Beam—56 inches. Draft (C.B. down)—4 feet. Total Weight with Mast, Boom, Rigging and Sail—207 pounds. 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 twelve statuate miles per hour. Tables show that the force per square foot of area for this wind may approximate 0.6 pounds. For 80 square feet of actual sail area a 50-pound 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 to be of any value. Building a wave barrier would

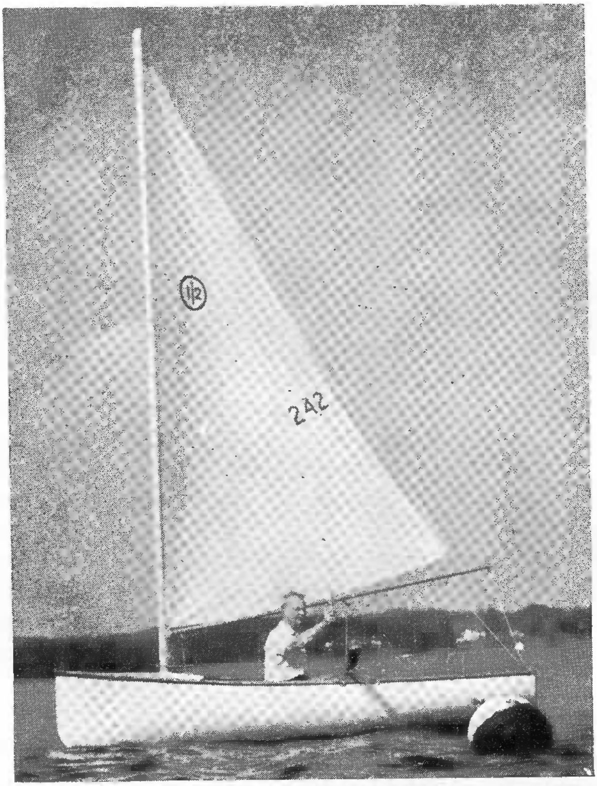


Fig. 6.

improve this situation but I have not done this. I keep at hand a second spring scale with a range up to 200-pounds 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 feet 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 feet compared with the convenient measuring height of 4 feet 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 lfting 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.
Study of Boom Vang.

Test	Measurements						Calculations			
	Boom to Keel	Angle of attack	Force to Wind	Wind M.P.H.	Total Force in Lbs.	C.E. Feet from Mast	Heading to Wind	Force to Boom	Force to Keel	Total F / M.P.H.²
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

$$\text{Ratio } \frac{0.42}{0.33} = 1.27$$

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

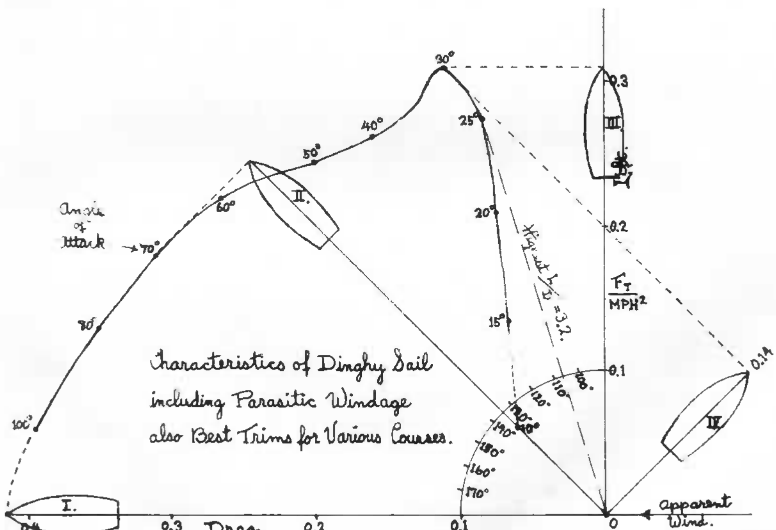


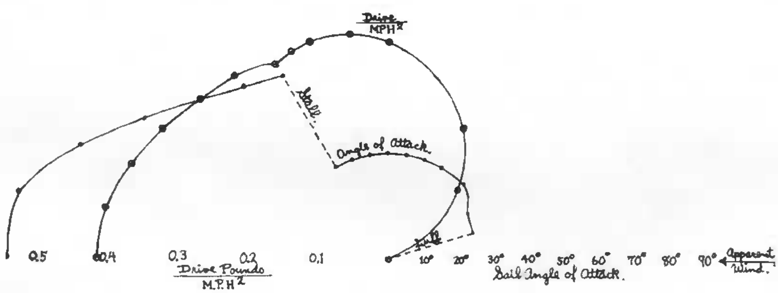
Fig. 7.

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.

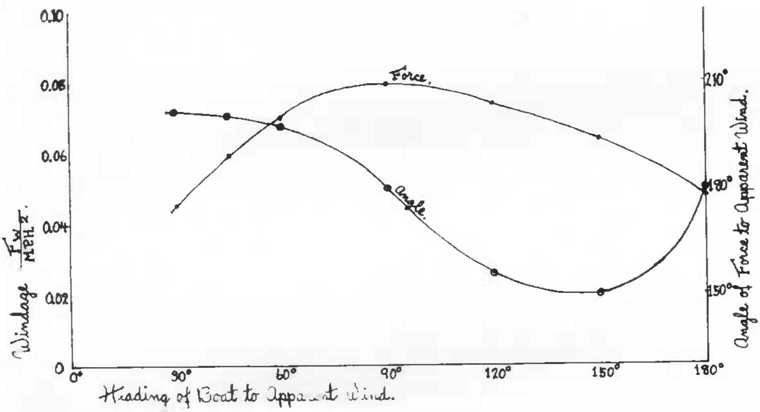


Summary of Boat Ratios of Drive over Wind Velocity Squared and Optimum Angles of Attack for Sail for Various Courses to Apparent Wind.

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 summarizes 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 the writer's article in A.Y.R.S. No. 37 for a discussion of this sail versus hull relationship in achieving high pointing.



Parasitic Windage versus Heading.

Fig. 9.

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 was 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

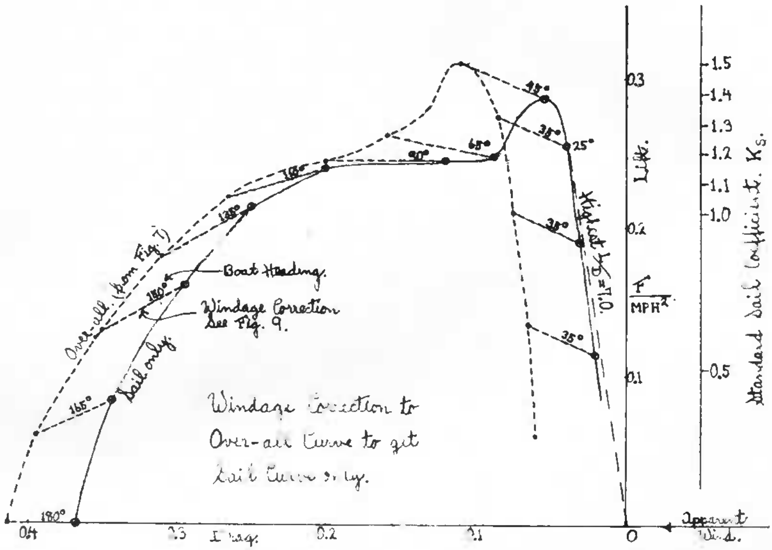


Fig. 10.

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,

$$K_s = \frac{F}{\rho/2 . A_s . v^2} = 4.83 \frac{F}{M.P.H.^2}$$

where F 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, C.E., 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 percent of the foot of the sail and is measured from the mast.

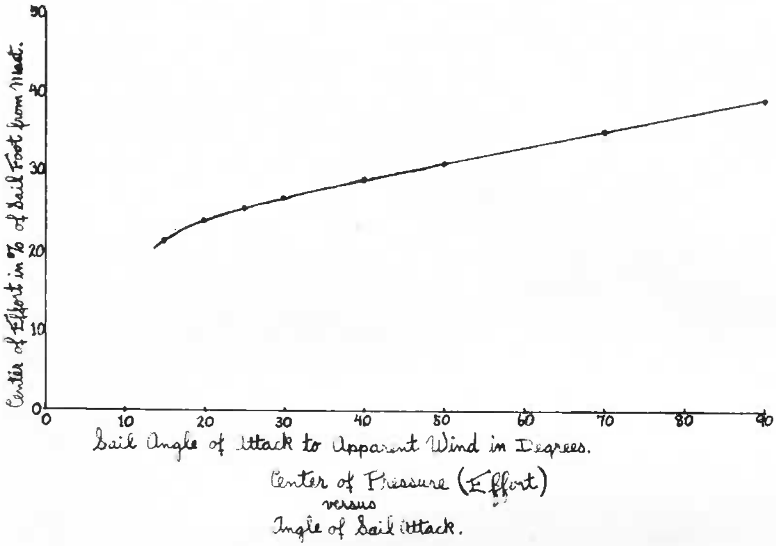


Fig. 11.

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 $\pm$ 15 percent. 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 $\frac{F}{M.P.H.^2}$ 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 A.Y.R.S. If so, publication of their results in this 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 optimized, 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-Foot Dinghy, without sail, which was described in Part I. These were measured with a crew of two when the wind was calm, on various course angles, in respect to the tow line, by the method that was described by the writer for models in A.Y.R.S. No. 30.

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, C.E., of the wind on the sail. For good balance, this C.E. should be aligned, in the horizontal plane projection, with the hull's centre of resistance, C.R., as shown in Fig. 2. Actually, in the hull test, it is the horizontal plane location of C.R. that is experimentally measured.

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

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

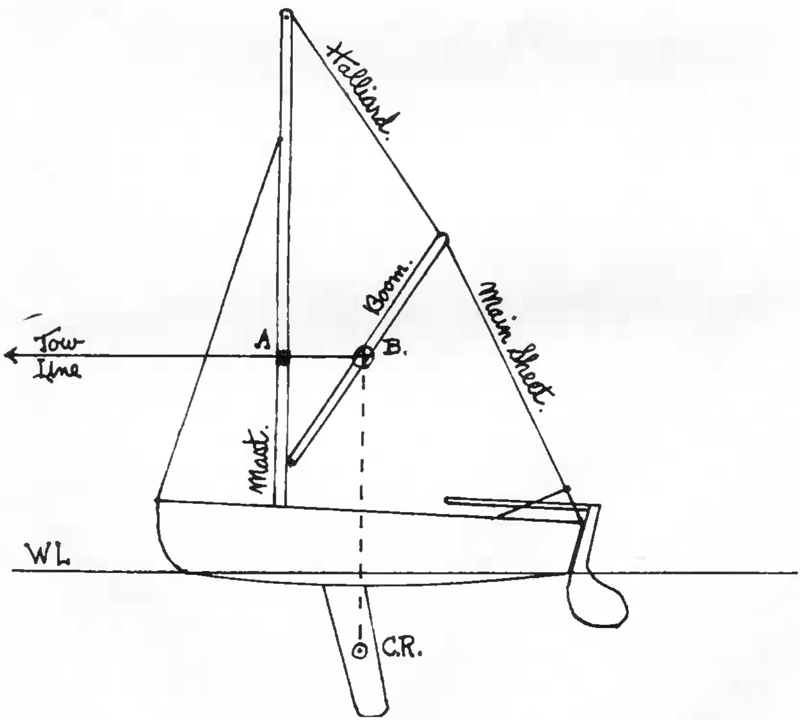


Fig. 12.

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 distance should be measured and recorded.

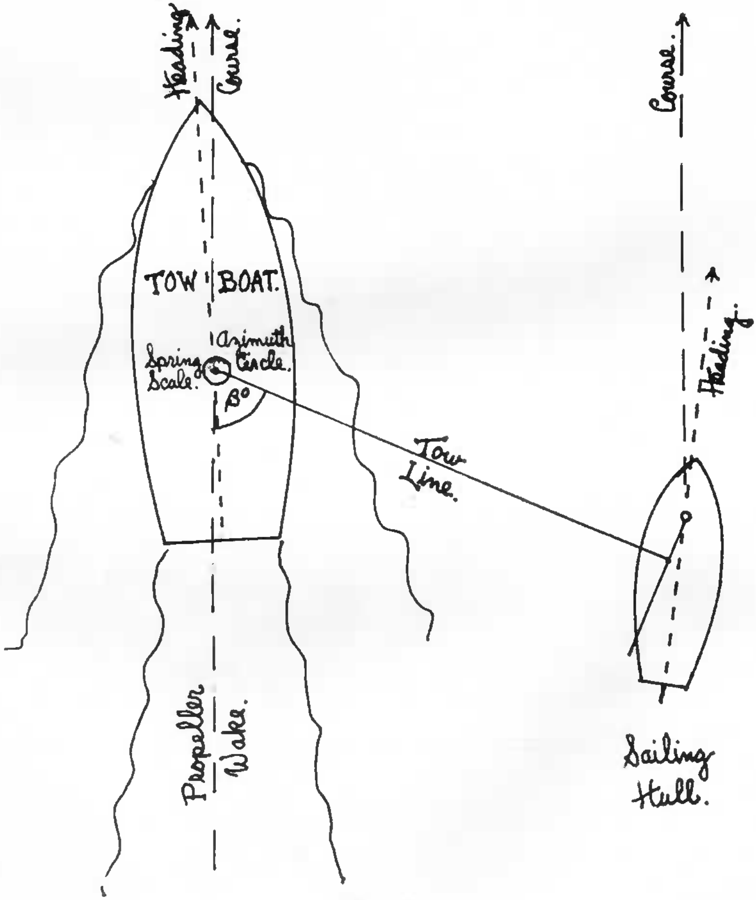


Fig. 13.

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 C.E. in vertical alignment with C.R. Many a dinghy race has been won by this manoeuvre. Incidently, 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 propeller 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 stabilization.

The photograph of Fig. 14 shows the measuring equipment aboard the tow boat. It consists of a spring scale capable of several

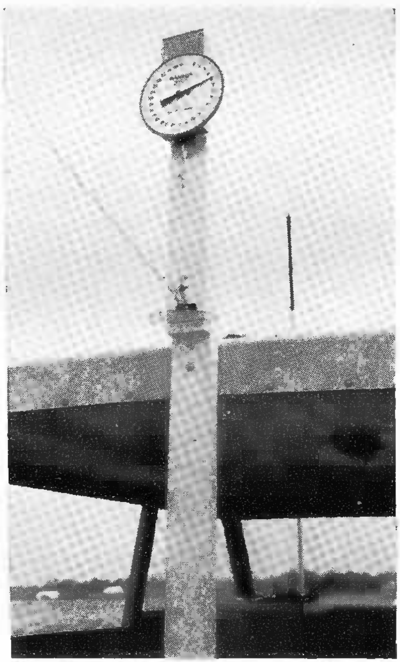


Fig. 14.

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

Hull Measurements

The 29-foot 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 1/8 inch 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 a unusually high aspect ratio,

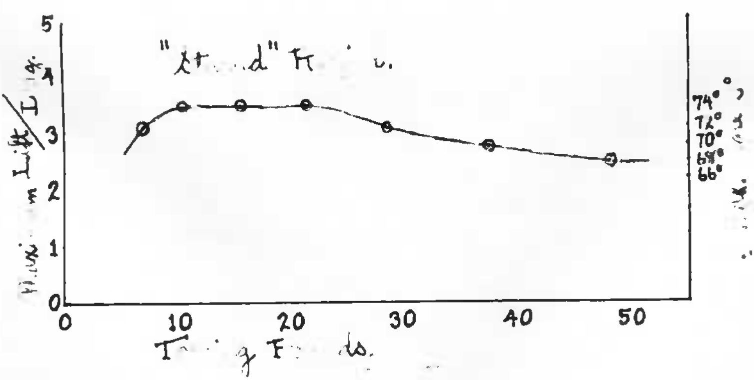


Fig. 15.

span 5 times average cord, one must conclude that more centreboard area would improve the windward performance of this boat, probably because of it's 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, 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.

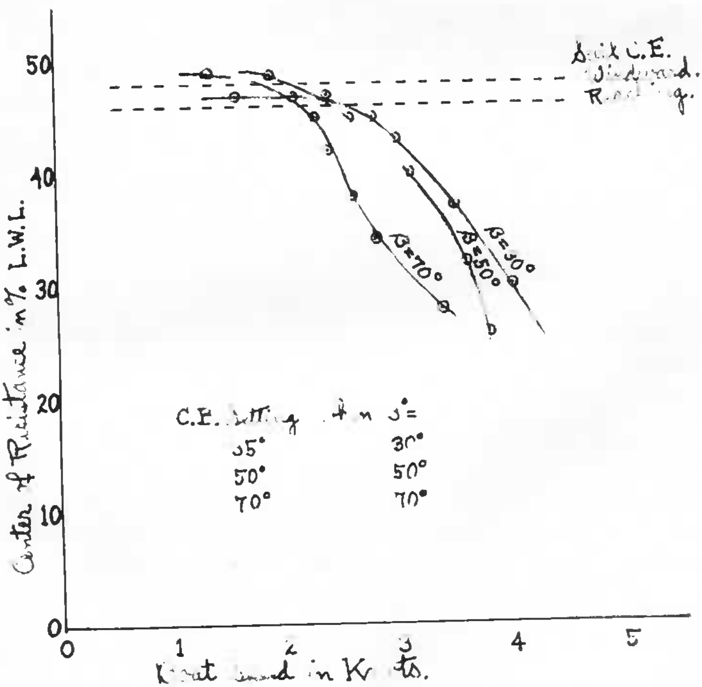


Fig. 16.

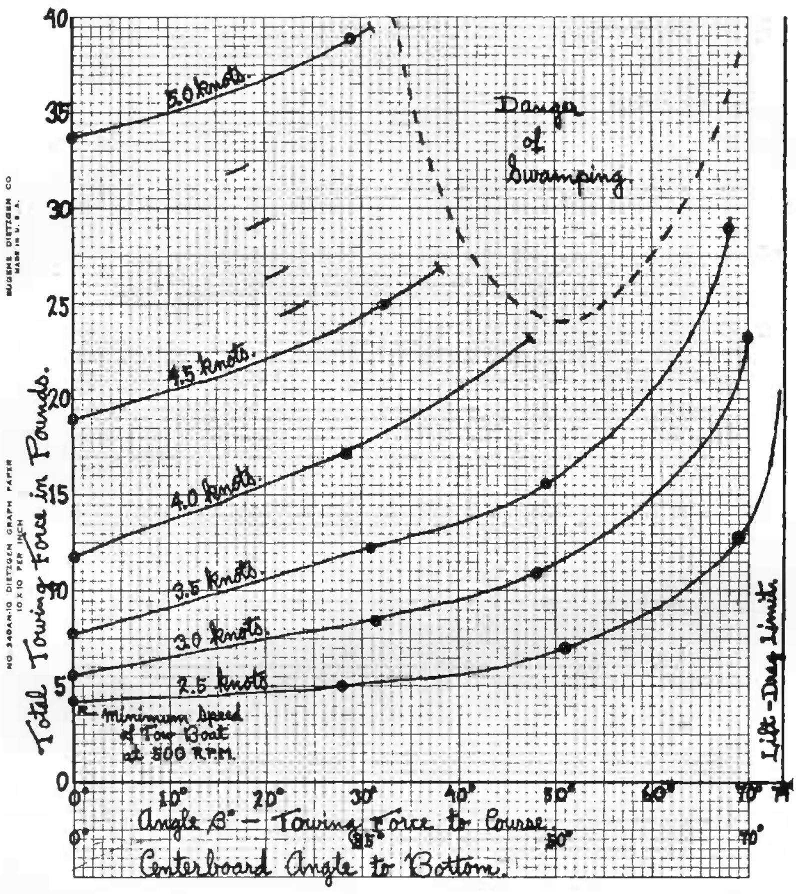


Fig. 17.

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.

Pointing Ability

Fig. 15 indicates, for the dinghy hull alone, that the maximum possible angle β° between towing force and the achieved course is 74 degrees for total sail forces between about 10 and 22 pounds. For the angles shown in Fig. 2, the sail ratio of Lift/Drag equals tan $(180^\circ - \alpha^\circ - \beta^\circ)$ for all points of sailing. (See writer's article in A.Y.R.S. No. 37). Fig. 7 indicates that the maximum overall Lift/Drag of the dinghy sail including windage was 3.2. Thus 3.2 equals tan $(180^\circ - \alpha^\circ - 74^\circ)$. Trigonometric tables give tan $72.6^\circ = 3.2$. Then $180^\circ - \alpha^\circ - 74^\circ = 72.6^\circ$ and $\alpha^\circ = 33.4^\circ$ 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 lee-way 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 C.R. with the dotted curves of C.E. 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 dyssymmetry 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 $\frac{F_T}{MPH^2}$ 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 statuate 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 $\frac{F_T}{MPH^2}$.

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 $\frac{F_T}{MPH^2}$ 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 $111^\circ - 90^\circ = 21^\circ$ as sketched in Fig. 7.

Since we are concerned with a 10 MPH apparent wind, $\frac{F_T}{10^2} = 0.328$ and $F_T = 32.8$ pounds total sail force.

Plotting on Fig. 17 the above force of 32.8 pounds 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.

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

TABLE II.
Summary of Results.

Assume			Obtain from Fig. 7					Obtain from Fig. 17	
Apparent Wind		Course to App. Wind	$\frac{F_T}{MPH^2}$	F_T	Sail Angle of Attack	Force Angle to Apparent Wind	Force Angle to Course	Boat Speed	C.B. 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.

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. 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 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

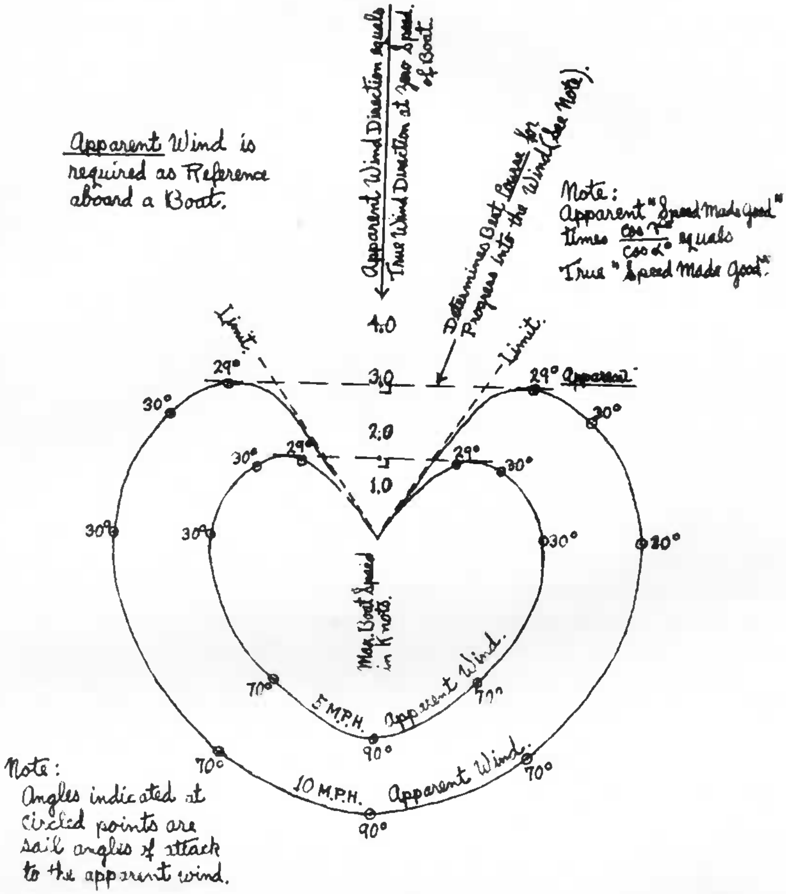


Fig. 18.

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 $\cos \gamma^2 / \cos \alpha^2$ 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 $\frac{\cos \gamma^\circ}{\cos \alpha^\circ}$ 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.

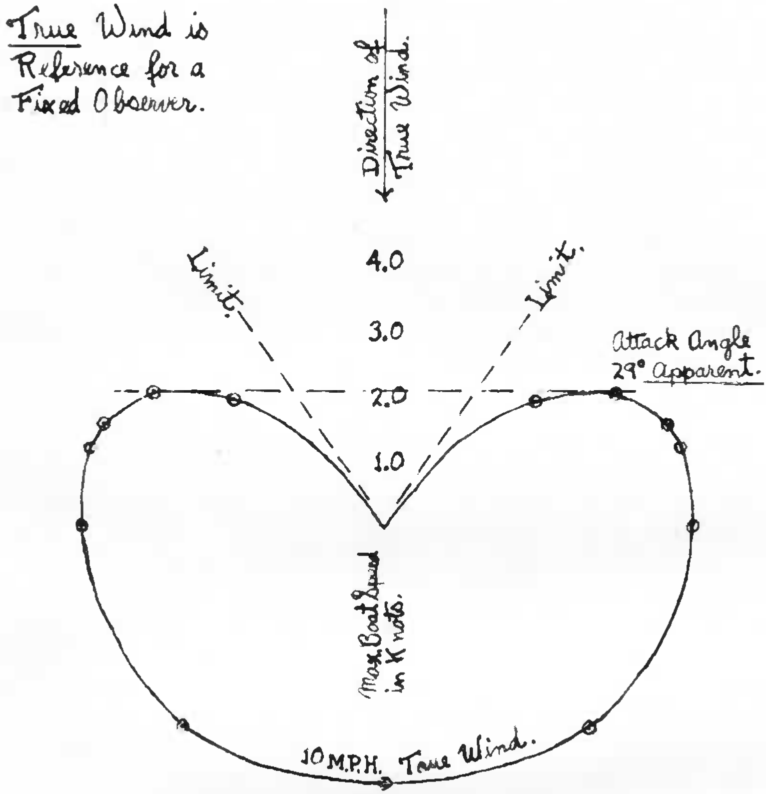


Fig. 19

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. Only the unobstructed windward one would be read. 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 apparent 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.

Dear Sir,

I take this opportunity to praise your writing in Aerodynamics I in A.Y.R.S. No. 37. I have one comment regarding " System 1 " and " System 2 " for the resolution of the sail and hull forces.

If the hull's side-slip is mechanically restrained, in a wind tunnel test, it can be treated as having an infinite lift-drag ratio. If the forward motion is restrained also, the apparent wind and the real wind are the same. So we see that System 2 becomes System 1 and are one and the same. My curve of hull infinite lift-drag ratio, on page 18 of No. 37, was intended to cover cases such as Warner's and Davidson's writings.

EDMOND BRUCE,
Lewis Cove, Hance Road, Fair Haven, New Jersey, U.S.A.

A STANDARD SERIES OF SAILS TO CORRELATE TESTS IN DIFFERENT YACHT WIND TUNNELS

BY R. J. HARRINGTON HUDSON, M.ENG., A.R.I.N.A.
Rosemary Cottage, Glampton, Brixham, S. Devon

In support of a Standard Series defining variations from a Basic Sail Form, I cannot do better than quote the following paragraph from a letter dated 20th September, last, which I received from Cyrus Hamlin, Naval Architect of Manset Maine, U.S.A.

" If the concept of unification and standardization, as expressed in the Standard Series, is carried through from the beginning, it will, I feel, have a tremendous effect on the whole field of rig development. The experimenter operating within this concept, whether working with a small home-built tunnel or one of the large institutional tunnels, would be tied into a world-wide standard system. Not only would his results be useful to all other experimenters, but their results would be useful to him. Lacking such a standard system, each experimenter goes his own lonely, and usually fruitless, way."

This paragraph sums up the value which we think the establishment of a Standard Series will have in the development of rigs and sails in wind tunnels.

Cyrus Hamlin thinks that a Master of the standard rig should be very carefully made and placed at the disposal of " any qualified and interested person " at a small rental fee for use in calibrating his wind tunnel. I am doubtful whether this scheme can be carried out in practice. If, as stated above a world-wide Standard System is envisaged in which wind tunnel experimenters using small or large wind tunnels can operate, difficulties would arise in determining the scale, or scales, of the Master standard to suit the different sizes of wind tunnel and in transporting the models without distortion.

As an alternative I would suggest the printing of the Standard on a non-dimensional system, in the from of tables, explained by diagrams as required. Copies of these could be obtained by experimenters at small cost. The experimenter, if a ' qualified and interested person,' could then construct his own Master on a scale to suit his wind tunnel and would have this Master for reference throughout his tests. With the printed copy of the standard, advice could be issued to assist an experimenter in making the Master and, perhaps a brief note showing the value of relating back to the Master any deviations of sail form or rig which he tests.

To commit to paper a non-dimensional standard sail form and rig should not be difficult, but it seems to be important that it should be framed on some simple principle to assist the experimenter in reproducing the Master accurately to the scale he requires. One method outlined in my letter to Cyrus Hamlin, in reference to a Bm. mainsail, is given below. There may be others equally simple.

(1) Assume that the luff is vertical and the boom horizontal.

(2) The ratio foot of sail to luff to be stated.

(3) The luff is divided into ten equal parts and the angles which the horizontal chords at each of these points make with the boom, or with the centre line of the vessel, are measured and recorded.

(4) Roach of leech is expressed as a percentage increase in length of each chord, thus the true length of a chord is the length

to point of intersection of a straight leech plus roach percentage for that chord.

(5) Each chord is divided into ten equal parts and the flow or camber of the sail along each chord is measured at the equally spaced stations along the chord and is shown in non-dimensional offsets as decimal fractions of lengths of chord.

Whether the Basic Standard comprises the yawl rig, as recommended by Cyrus Hamlin, or the sloop or merely single Bm. mainsail as suggested in my letter, I think the configuration of the sail, or sails, can be recorded in the above manner to be accurately reproduced to any desired scale. A Standard headsail, or a Standard mizzen should present no difficulties and the luff and tack of a headsail and luff and foot of a mizzen could be related to the mainsail by ratios thus fitting in to the whole non-dimensional framework of the Basic Standard rig of sloop or yawl.

Referring to the Master Sail configuration from which the Standard Series would be expanded, Cyrus Hamlin envisages no real problem since this is only a starting point. He thinks it makes little difference whether it is a realistic rig or not and he emphasizes the fact that this freedom allows of certain simplification. I strongly support this view, but would go further and say that simplification is so essential that a completely realistic rig should *not* be used as a Standard. Let the Standard represent in simple terms a reasonable representation of the rig but let simplicity be the ruling factor as the complete information to be conveyed to an experimenter to enable him to construct his own scale model of the Master Rig accurately, is quite considerable.

It is also essential that this information should be presented in a suitable form to enable the experimenter to " make accurate gauge blocks of wood over which sails could be moulded of some material like plexiglass or fibreglass " — I quote from Cyrus Hamlin's letter on page 58 of Yachts and Yachting, 14th July, last. Take, for example, the making of the moulding block for a small scale Standard mainsail. When the experimenter has fixed the scale to suit his wind tunnel, he can set out on paper the luff, foot and straight leech and divide the luff into ten equal parts from which chords are drawn parallel to the foot. Roach percentages are added to each chord to obtain their true lengths and the curved leech may then be drawn. At this stage the curve representing *twist* of leech may be drawn from the true lengths of chords and the horizontal chord angles in relation to the foot of the sail. If the moulding block is to be shaped from a solid block of wood the block may now be trimmed to the outline of the sail and, on the sides of the block, the straight luff and foot and the curve representing twist of leech may be scribed. The chords are divided into ten equal parts and, from the offsets given in the tables, the curve of the sail along each chord is drawn to scale. Templates would be made for each of these curves and the block carved to the templates with their ends registering correctly on luff and leech. The surface of the block would then be trimmed down and smoothed off between these curves and sanded and polished.

Moulding blocks for the smaller scales could be made of wood and, if made from a solid block, the above outline would probably indicate usual practice in this case and may serve as a guide when furnishing the experimenter with the information he requires. Larger scale moulding blocks might be built up or made of plaster or other materials and the procedure in making the blocks would, of course, be varied accordingly.

The final selection of the Master rig and Standard sails from which the Standard Series can be expanded is, I think, a matter which should be agreed amongst those interested in the testing of sails and there are many, amateur and professional. If they could be consulted or, better still, could get together and discuss the matter, a final selection might be forthcoming ; but is this possible ? Again, I quote from Cyrus Hamlin's letter in Yachts and Yachting of 14th July in which he suggests "world wide agreement of the A.Y.R.S." and, if this can be achieved, the " use of Standard Series provides a common frame of reference for all investigators."

F. J. Parsons (Kent Newspapers) Ltd., Printers, Folkestone.