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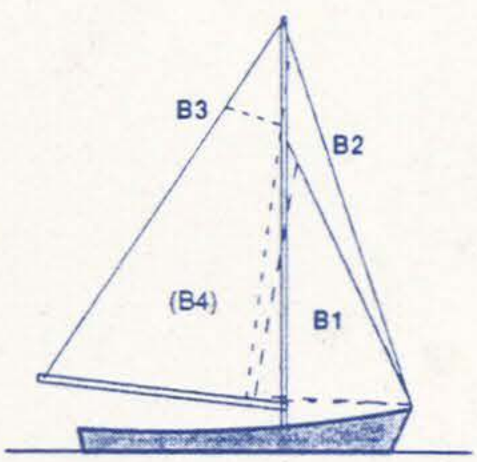
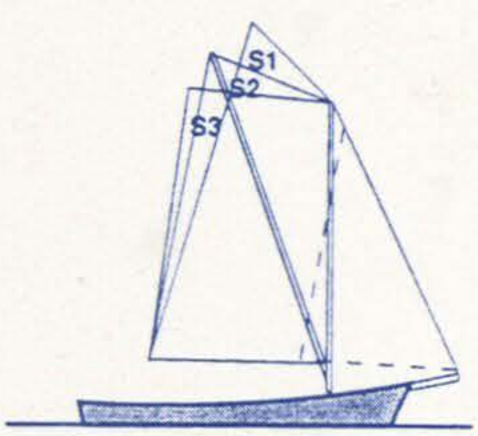
RIG EFFICIENCY



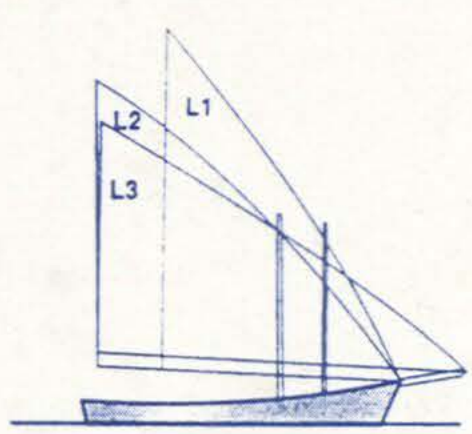
Bermudian B1, 2, 3, 4.


Gunter G1

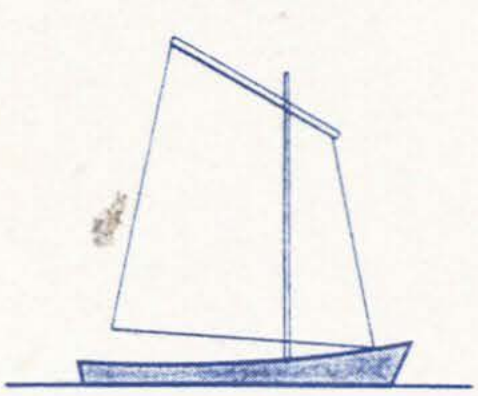
Wind Tunnel tests



Sprit Rig S1, 2, 3.



Lateen L1, 2, 3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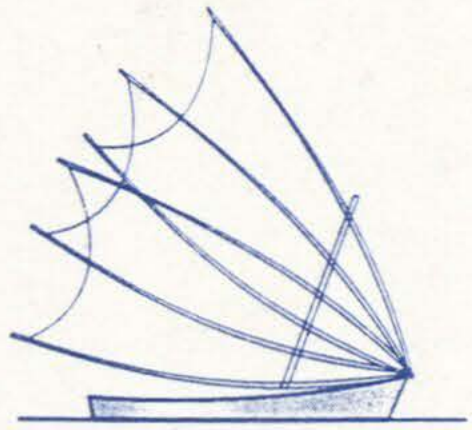
Crab Claw Cc.

reports by
C A Marchaj
and others

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Rig Efficiency

A study of wind tunnel test reports

on various styles of rig

and their comparison with

current racing rigs.

with contributions from

C A Marchaj and others.

Edited by Ian Hannay

Amateur Yacht Research Society

BCM AYRS, LONDON WC1N 3XX

CONTENTS

PREFACE

This report is based upon a series of wind tunnel tests on alternative sail plans for sailing craft and is compiled in the main from the the proceedings of the **Regional Conference on Sail–Motor Propulsion,** held in Manila in 1985. Quoting extensively from the writings and researches of C A (Tony) Marchaj *(pronounced "mark–eye")* and others.

The tests were aimed at finding suitable rigs for third World fishing boats and as auxiliary power for larger trading vessels. In interpreting the results here the emphasis has been changed more towards the cruising yacht and performance sail craft. This has required representing the original data in a different way and produces slightly different conclusions.

It would be impractical to test models of all combination of sails and care has to be exercised when interpreting these test results for alternative arrangements.

One of the problems is that it is only with close racing that important performance factors are proved in the real world. With the current racing rules severely restricting the options allowed, it is not at present generally possible to try out new styles on the race course.

In the end we have to rely on tests like those reported here to give us some idea of what we might have been missing by worshipping the Bermudan rig and the symmetrical spinnaker for most of this century.

My thanks to Tony Kitson, Simon Fishwick and Roger Glencross for their assistance and advice in preparing this publication.

Ian Hannay *Editor* *January 1993*

Notes:
If anyone knows of any *verifiable* performance figures on any type of rig – conventional or unusual – the AYRS would be very pleased to hear about them.

The following convention has been used for the formulae:
Knots *have been used for velocity rather than* **feet/sec.** *or* **metres/sec.**
It is generally more practical for real yachtsmen to use knots and this has been combined with metres or feet. (Apologies if this upsets the purists amongst you).
Formulae **(m)** *are for use with* **knots** *and* **metres**.
Formulae **(f)** *are for use with* **knots** *and* **feet.**
The two sets will not give exactly equal answers, but the results will be well within the level of accuracy available from this type of calculation.

INTRODUCTION

While much is known about performance sailing rigs for racing – mainly the triangular Bermudan – little or no systematic research has been carried out into other sail configurations. It is difficult, if not impossible, when selecting a sail plan for any boat, to determine with certainty whether a proposed rig is more efficient (for a given sail area, heeling moment, cost, etc.) than another, whether it be a new design or a well established one.

In any case, there is considerable bias regarding the merits of different rig types to begin with. Most people believe that the Bermuda rig, which dominates the contemporary sailing scene both for racing and cruising, must be the best rig available. After all, the America's Cup and IOR yachts – epitomes of ultimate progress – use this rig.

To gain recognition, any competing sail configuration should at least match the Bermudan's sail power and, preferably, surpass it on some points of sailing. However, the current rating and racing rules have practically precluded any development of alternative sail configurations. Even when unorthodox sails are not explicitly prohibited, the wording of the measurement system is such that experiments with unusual rigs are effectively discouraged. So it is that people regretfully abandon any hope of developing other types of rig under the current state of the racing rules. Recently there has been a chink in the armour with asymmetrical spinnakers and fully battened sails are beginning to be accepted.

One may rightly ask the question: what is the basis for the assumed superiority of the Bermudan rig; can it be proven that this triangular sail is more efficient than some other style? Wind tunnel tests of the potential power from a number of rigs — Bermudan, Lateen, Sprit, Gunter, Dipping Lug, Crab Claw and multimast rigs — some with modification, will enable the advantages and disadvantages of various sail configurations to be better understood. It will also indicate directions for improvement in traditional rigs and guide the selection of appropriate sail configurations in all sorts of sailing boats. A comparative assessment of the merits and demerits of various rigs can be made and explanations are given as to why certain rigs are superior.

These test results indicate directions for improvement in rigs, while guiding selection of more efficient sail arrangements for designs that are not constrained by the arbitrary limitations of the racing rules.

The whole problem of wind tunnel testing and how tests are conducted is closely allied to what one hopes to gain from the investigation. If one wishes to determine the forces on an actual sail, under normal sailing conditions, then the logical thing to do is to go on a boat and measure those forces in action. A task which, although difficult and time consuming, is not insuperable and can be very pleasant. Testing in a wind tunnel, however, allows a systematic variation of important geometric and physical factors, which can be held under closer control. Thus one may rightly expect dissimilar results when sail area is kept constant but changes are introduced into the sail plan, in the form of sail area distribution, aspect ratio, etc.

Some of these factors are determined by design (sail cut, cloth properties), some depend on crew expertise, and some depend entirely on the wind (gradient, velocity, turbulence). It is evident that rigid control is necessary over any experiment whether conducted full size or on a model. It is difficult, if not impossible, to determine the effect of changing one factor if at the same time one or more other factors alter. The wind tunnel offers great advantages; good control of the tests provides repeatable results which can be presented simply and therefore understood more easily. Information can also be obtained comparatively quickly.

The use of a model which is not the same size as the original must inevitably impose limitations on the results and the art of wind tunnel testing is largely in obtaining representative results with the minimum of effort. Even if exact quantitative data may not always be obtainable due, for example, to scale effect, absence of wind gradient, the unsteadiness of the real wind, etc., important trends can easily be established. Otherwise the designer must rely on guesswork and full scale long term observations of boat behaviour in conditions where everything is real and natural, but nothing can be precisely measured or controlled. For this reason, certain factors contributing to successful designs sometimes remain obscure or misplaced.

The main scaling problem is with Reynolds Number (Re) but, fortunately, thin foils such as sails do not alter their performance significantly even with large changes in Re. On the other hand aerofoil sections with rounded leading edges (wing masts) display changing characteristics, and testing at significantly different Re values may sometimes give misleading results.

The principle of Reynolds Number is:

velocity × distance (chord) = constant.

To keep this unchanged, the speed must be increased by the same amount as the size is reduced. Thus a $^1/_{10}$ scale model requires 10 × velocity with the result (if you care to work it out) that the total load on the model remains the same as at full size. This loading problem is a severe limitation on any model testing.

It is not proposed to enter into a detailed discussion of all the factors which can influence the forces developed by a sail, but only to give an indication of their complexity.

WIND TUNNEL TESTING

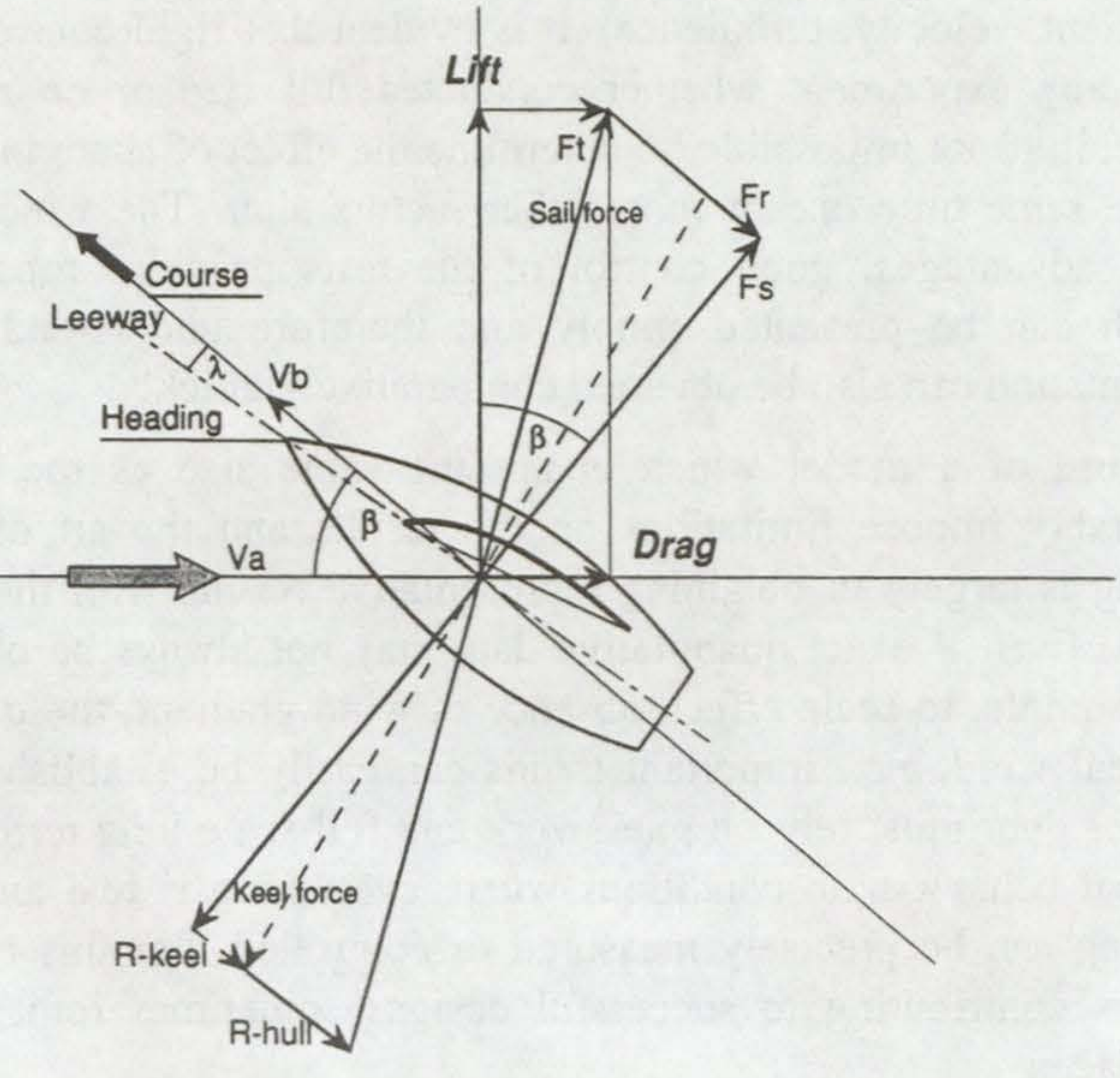


Fig. 1.

The model is mounted in the wind tunnel so that it can be rotated to the required apparent wind angle. The dynamometer measures the lift (L) perpendicular to the air flow, drag (D) in the direction of the flow and heeling moment (M) of the model.

On the basis of theory, the best lift/drag (L/D) ratio is when C_L/C_D is a maximum. The drag is calculated as follows:–

Drag = Profile + Induced vortex

$$C_D = C_d + K \,.\, C_L^2 \div (\pi \,.\, AR) \qquad [1]$$

where; C_D = total drag coefficient

C_d = section (form) drag coefficient

C_L = lift coefficient

AR = height / mean width, or h^2/ area

K = constant depending on lift distribution.

(K = 1.0 for ideal elliptical lift distribution; >1.0 for others).

The higher the aspect ratio, the lower is the induced drag contribution to the overall drag, C_D.

Induced drag is a direct consequence of lift being produced and cannot be avoided; the aim is to minimise the effect. It varies as Span Loading^2. Double the loading on a fixed span (height) and the Induced Drag will increase four fold. AR is a convenient way to display Induced Drag (C_{di}).

A wind tunnel will not provide all the answers but, when properly used, it assists in establishing some of the fundamentals of sailing rigs. A representative undecked hull consisting of that part normally above the water and at a nominal angle of heel ($\theta = 10°$ in these tests) was used. For a performance keel boat 20° – 25° and a decked hull might have been more representative and could possibly have produced different results.

The forces for a given set of sail configurations (camber, twist, planform, aspect ratio, etc.) are known by both theory and experiment to depend upon the sail area (S_A) and the so-called dynamic wind pressure (q) = ½ . ρV_a^2 (where ρ is air density). Thus:

$$L = C_L \,.\, q \,.\, S_A = C_L \,.\, S_A \,.\, V_a^2 / 60.45 \qquad [2.m]$$

$$L = C_L \,.\, q \,.\, S_A = C_L \,.\, S_A \,.\, V_a^2 / 295 \qquad [2.f]$$

$$D = C_D \,.\, q \,.\, S_A = C_D \,.\, S_A \,.\, V_a^2 / 60.45 \qquad [3.m]$$

$$D = C_D \,.\, q \,.\, S_A = C_D \,.\, S_A \,.\, V_a^2 / 295 \qquad [3.f]$$

Symbols C_L and C_D are, respectively **lift coefficient** and **drag coefficient**. They can be determined by dividing the measured values of lift and drag by the dynamic wind pressure and sail area.

$$C_L = L/q \, . \, S_A = L \, . \, 60.45 \, / \, V_a^2 \, . \, S_A \qquad [4.m]$$

$$C_L = L/q \, . \, S_A = L \, . \, 295 \, / \, V_a^2 \, . \, S_A \qquad [4.f]$$

$$C_D = D/q \, . \, S_A = D \, . \, 60.45 \, / \, V_a^2 \, . \, S_A \qquad [5.m]$$

$$C_D = D/q \, . \, S_A = D \, . \, 295 \, / \, V_a^2 \, . \, S_A \qquad [5.f]$$

Thus coefficients C_L and C_D represent forces that would be developed with a unit of wind pressure (q) on a unit of sail area (S_A)

One of the advantages of plotting a diagram of sail coefficients is that we can readily compare results of tests on any arbitrary sail form obtained at different wind speeds, and thus study the reasons why and by how much the performance of one rig varies from that of another. Obviously, it is desirable to have some relatively simple means of making an assessment of the results of such tests by considering sails on their own merits, i.e. without considering the effect of the hull and keel on a boats performance.

CRITERIA OF SAIL POWER

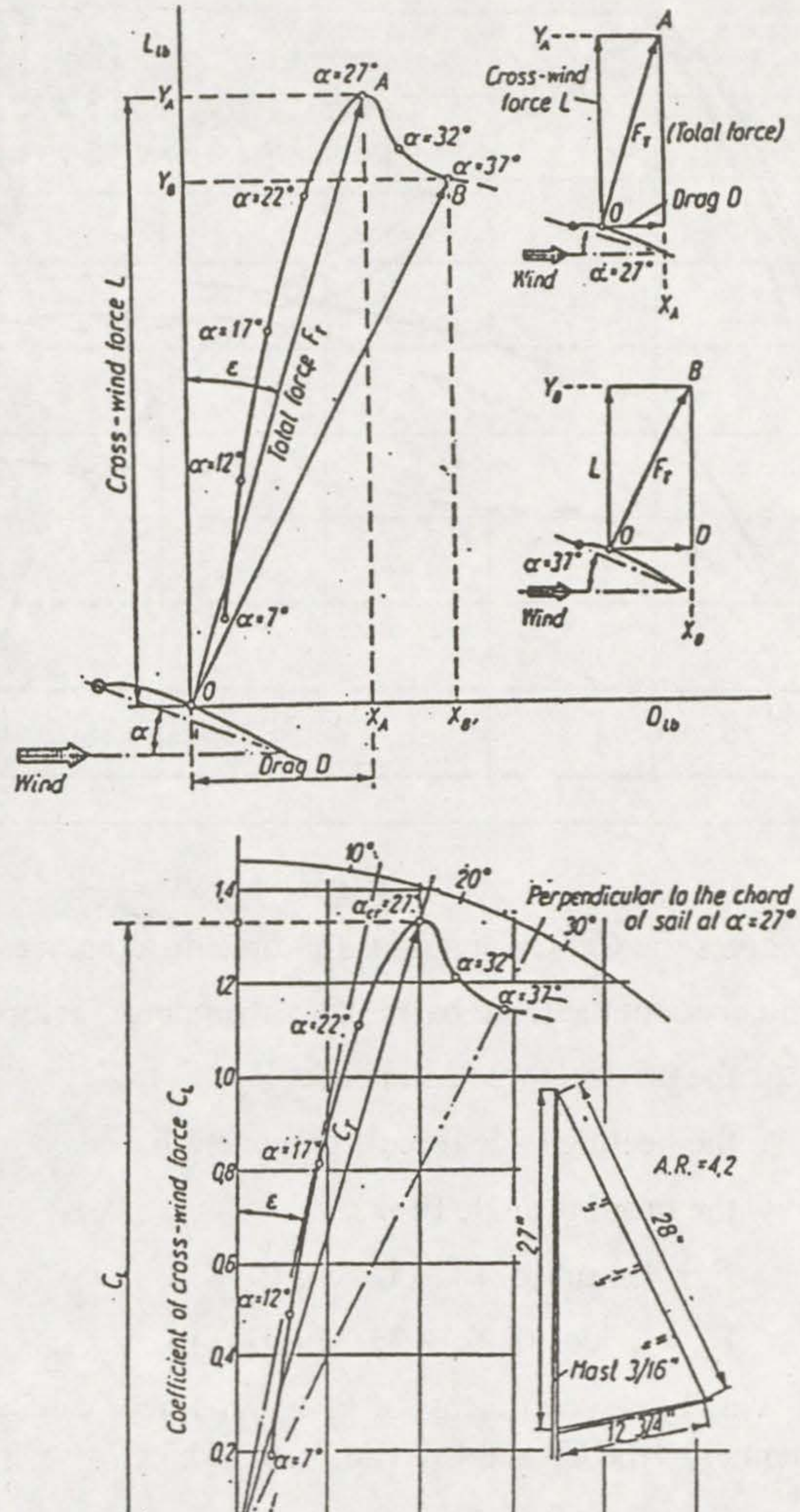
When estimating the merits of a sail as an aerofoil, or as a lift–generating device, we may regard drag (see Eq.l) as the price paid for lift. The drag angle (ε_A) (see figure 2) defines the angle between lift (L) and total aerodynamic force (F_T), this may serve as an index of the aerodynamic efficiency of a sail. This angle specifies the direction of F_T. If drag could be reduced without altering the lift magnitude, the sail would be more efficient, particularly in windward work. Clearly, the total aerodynamic force would then be inclined more towards the bow and the driving force (F_R) would be a larger fraction of the undesirable heeling force (F_H) with which the hull must somehow cope.

The forces F_R (Resistance) & F_S (Side) are respectively in line with and perpendicular to the course through the water, these come from towing tank measurements. F_T (Total) is the total force produced, or $F_T = (F_R^2 \, . \, F_S^2)^{0.5}$.

The forces F_x & F_y come from the measurements in the wind tunnel and are relative to the assumed hull (or rig) centreline.

These two sets of figures differ by the the angle of leeway (λ).

The forces may also be represented by non-dimensional coefficients (C_x, C_y, C_T, C_R, C_S, etc.),but caution, hull resistance is often quoted in lbs/ton.



L_{lb}
$\alpha=27°$ A
$\alpha=32°$
$\alpha=37°$
B
$\alpha=22°$
$\alpha=17°$
$\alpha=12°$
$\alpha=7°$
Total force F_T
Cross-wind force L
ε
O
X_A
$X_{B'}$
D_{lb}
Wind
Drag D
Cross-wind force L
F_T (Total force)
Drag D
Wind
$\alpha=27°$
X_A
Y_A
Y_B
L
F_T
D
$\alpha=37°$
Wind
X_B
10°
20°
30°
Perpendicular to the chord of sail at $\alpha=27°$
$\alpha_{cr}=27°$
$\alpha=32°$
$\alpha=37°$
$\alpha=22°$
$\alpha=17°$
$\alpha=12°$
$\alpha=7°$
C_T
Coefficient of cross-wind force C_L
C_L
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
Coefficient of drag C_D
C_D
A.R. = 4.2
27"
28"
Mast 3/16"
12 3/4"

Fig 2

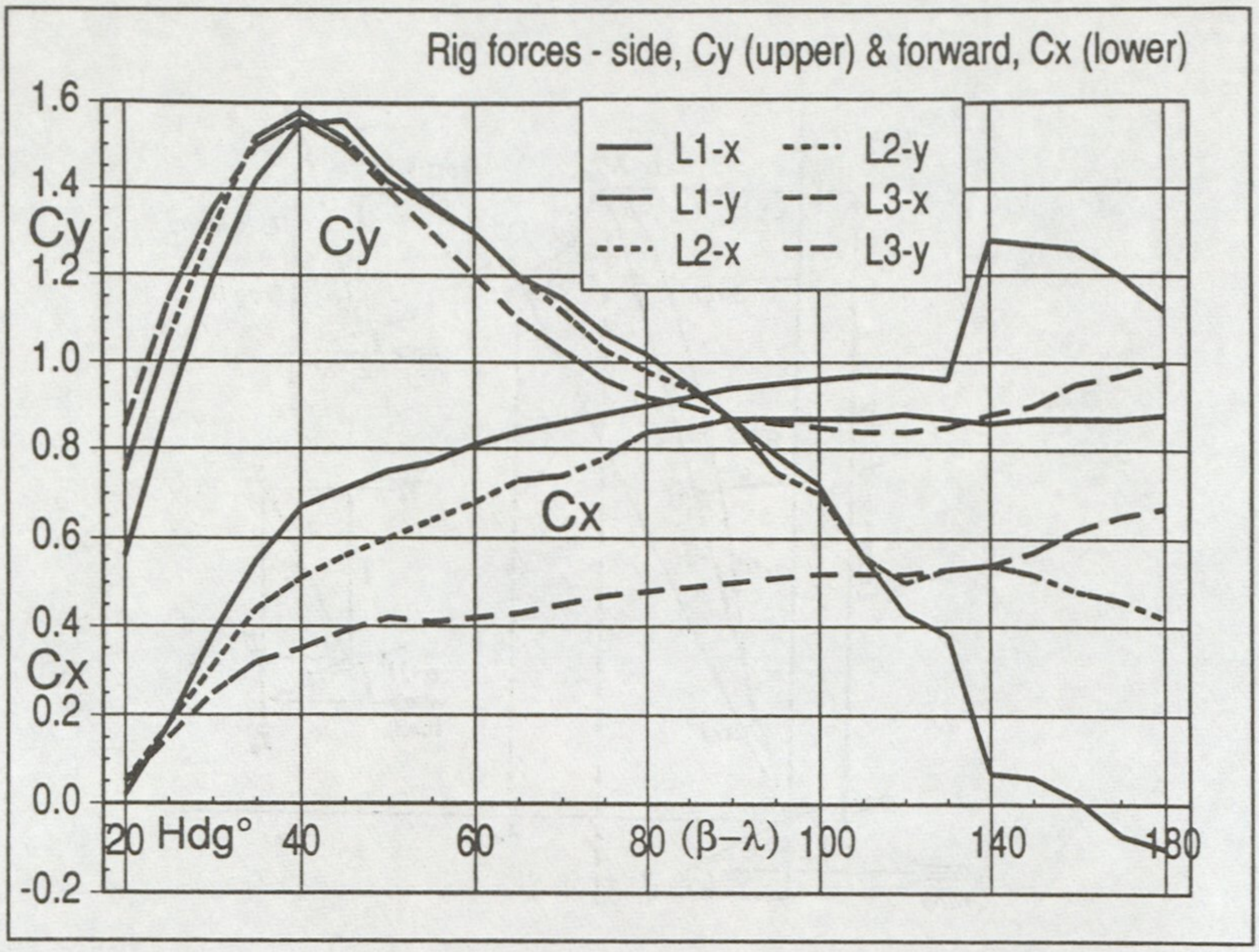


Fig 3.

Figure 3. gives the Cx, Cy diagrams for three different rigs (L1, L2 & L3).

Taking into account the three basic sail performance factors:

the driving force component F_x

the heeling (side force) component F_y

the heading angle (β–λ).

then $$F_x = L \,.\, \sin(\beta-\lambda) - D \,.\, \cos(\beta-\lambda) \qquad [6]$$

$$F_y = L \,.\, \cos(B-\lambda) + D \,.\, \sin(B-\lambda) \qquad [7]$$

C_x and C_y which are coefficients of F_x and F_y forces can be established in a similar manner to the C_L and C_D (Eqs 4 and 5); eg.

$$C_x = F_x \,.\, 60.45 / V_a^2\ S_A \qquad [8.m]$$

$$C_x = F_x \,.\, 295 / V_a^2\ S_A \qquad [8.f]$$

The effective net forward (thrust) component C_R may taken as follows:

$$C_R = f\{C_x - C_y / {}^L/_D \text{ (keel system)}\} \qquad [9]$$

It can be argued that, at a particular heading angle, any alteration of the sail plan which increases the driving force component, **without a corresponding increase in the heeling (side force) component,** will result in a better windward performance. This concept is presented in Figure 4, where it will be seen that the C_R (net thrust) curve of rig L1 is bodily shifted up relative to that of rig L3.

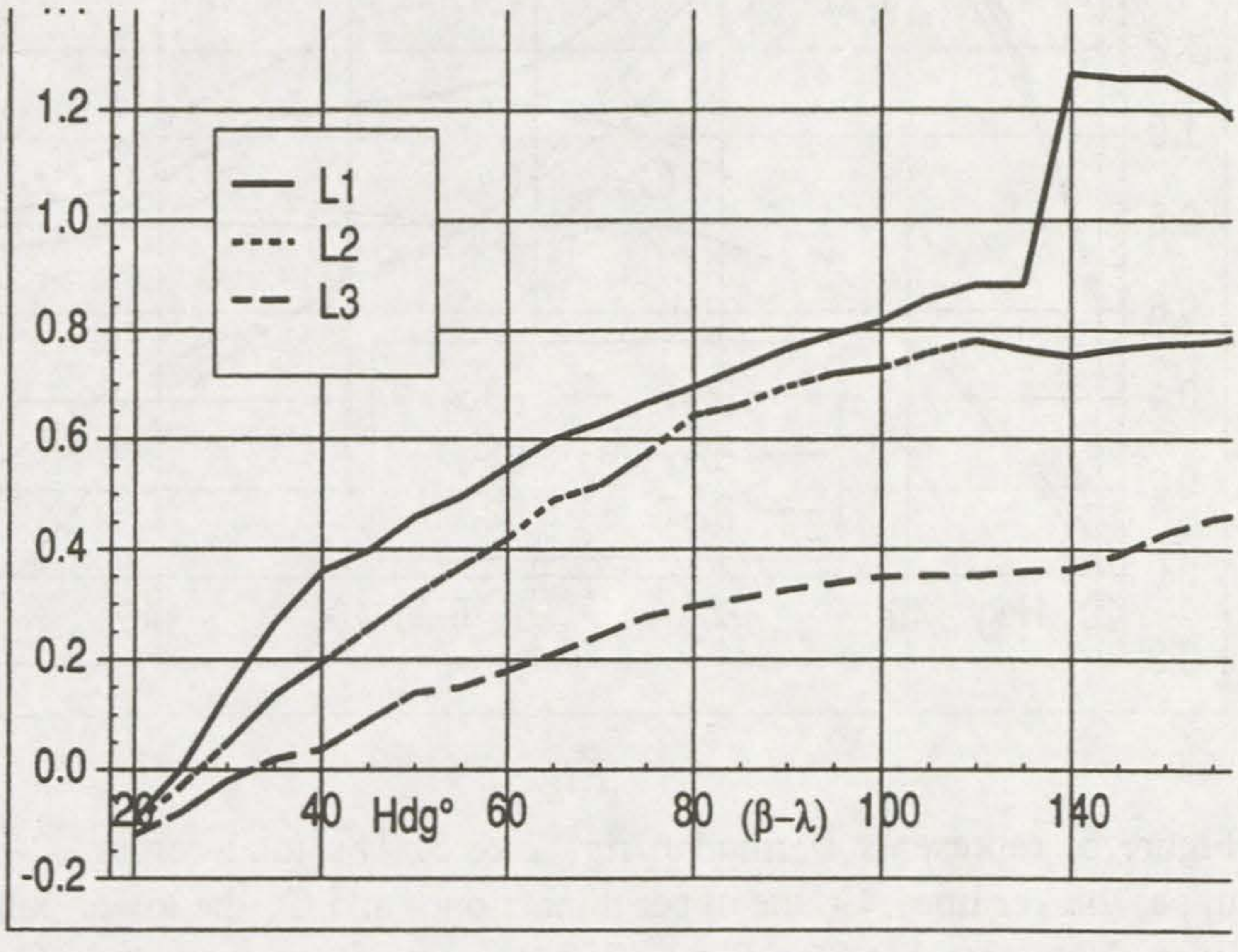


Fig 4.

Close Hauled

In a typical close hauled condition, at a heading angle of 25° to the apparent wind, rigs L1 & L2 develop the same forward coefficient (C_x = 0.18), but Rig L2 produces higher side force (C_Y = 1.05 as opposed to 0.89) . As a result, its driving component is less on a heading of 25°. With the differences in heeling (side) force components rig Ll should be more efficient to windward than rig L3. Evidently, the ratio of driving force to heeling force (C_x/C_y) is higher and therefore more favourable for rig Ll than for rig L2. Thus the hull will be less heavily burdened by balancing undesirable heeling forces, an action which always incurs a hydrodynamic penalty and therefore slows the boat down.

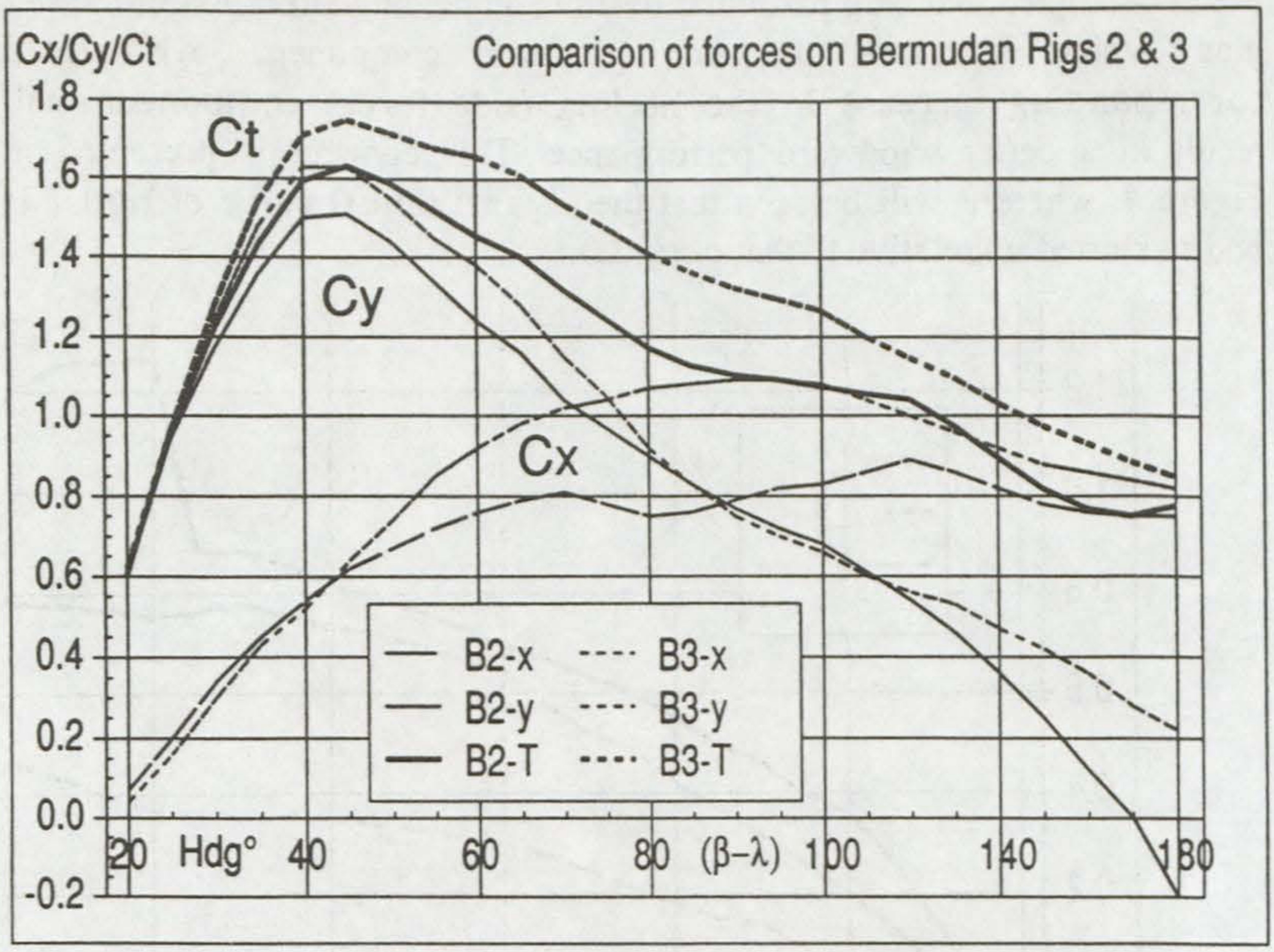


Fig 5.

Figure 5. represents Bermudan rigs 2 & 3. The total forces, C_T are the upper thicker lines, C_Y the upper thinner ones and C_X the lower pair of thin lines. Note that between 20° – 25° the total force produced (C_T) is the same, as is C_Y, but the forward thrust, C_X of rig B3 is less. The result is that the total net thrust produced on these headings will be smaller despite the fact that they both produce the same total force. Above 30° B3 produces a greater C_T and C_Y, but does not produce a higher C_X until 45°. At greater angles than this it appears to be a superior and more powerful rig.

Reaching

When a boat begins to bear away from the close hauled condition, the windward criterion discussed above becomes gradually less stringent. Off the wind with the heading (β–λ) above 50° the sails generate less and less heeling force and hence the ratio of C_x/C_y increases. While beam reaching, the relatively small heeling force component (C_y) is a somewhat irrelevant factor. Instead, the driving component (C_x) dominates – the higher the better. Once the apparent wind is aft of the beam (or more precisely β–λ > 90°), aerodynamic drag (C_D) contributes to the overall thrust of the rig.

Depending on the course sailed (heading), the sail(s) must be trimmed to operate over a particular part of their polar diagram. In reaching conditions, they should be sheeted to give maximum lift (which is generally the same as the driving component).

Running

On downwind courses, sails are usually set at an angle of incidence of about 90° relative to the apparent wind. With the mast supported by normal rigging, this can sometimes be restricted by fouling of the sail and boom on the shrouds. Sails set forward of the mast suffer less chafe and can be more practical (square sails on yards or the less seamanlike spinnaker). In such circumstances, the only criterion for sail efficiency is the maximum drag of the rig, because the driving force is equivalent to aerodynamic drag. Practically, this means that the maximum possible sail area should be exposed to the action of the wind. Since drag is largely independent of the sail planform, all sails no matter what shape should produce the same drag coefficient at an angle of 90°, provided that their exposed area is not reduced by twist or other deformation. This reduces the effective projected sail area and drag coefficients.

For sails that are not fully stalled and still producing useful lift, the best downwind performance is achieved by keeping the true wind at around 130° – 150° and tacking downwind. This applies particularly to all light weight performance boats.

Both rigs in the running attitude produce less driving force than might be expected, due to the jib not being boomed out and other distortions preventing the whole area being exposed uniformly to wind action. If the sail were to be properly set, we would expect $C_R = C_D = 1.2$.

Summary of Sail Criteria

Different rigs may be roughly ranked in order of merit by comparing their abilities to produce the highest driving component without incurring excessive hydrodynamic penalties. The driving coefficient C_R is taken to consists of the forward component C_x, less the additional keel drag caused by the side load C_y. The rig data from the wind tunnel are therefore applied to a series of theoretical keel systems with $^{\text{Lift}}/_{\text{Drag}}$ ratios of 20:1, 10:1, 5:1 & 2.5:1. This represents the range of most practical foil systems.

Sail Criteria for Different Headings	
Heading	**Factors**
Close Hauled	Higher L/D ratio (within the allowable stability). Lower drag for the same lift at the same heading angle. Higher C_R (C_x) component for the same C_T.
Reaching	Highest C_{Lmax} or more sail (set low down).
Running	Higher C_D. Largest possible sail area exposed to the wind.

Overall Potential Driving Power of Rigs Tested

A plot of driving force component (C_R) against heading angle – ranging from close hauled ($\beta - \lambda = 20°$) to running ($\beta - \lambda = 180°$) – may be used as a measure of potential performance of different sails.

The $^L/_D$ ratio is assumed as 20:1 for an efficient keel system down to 2.5:1 for a poor shallow draft one. This is inevitably a simplification of the real world, but it represents the extra drag on the hull and foils due to the side load from the sails and the heel they induce. In other words the additional drag over the no heel, no yaw resistance for the same speed.

The induced drag varies as loading^2/velocity^2

The greatest induced load on the hull and keel is when sailing close hauled, reducing when off the wind due to extra boat speed and reduced side loads produced when the apparent wind is over 50°. It is therefore reasonable to assume better $^L/_D$ ratios from the keel off the wind. When running with higher speed and low side force the ratio for many craft could exceed 100:1 (This calculation takes into account only the induced and additional heeling drag. The surface friction and form drag of the foils are assumed to be part of the hull's fixed resistance).

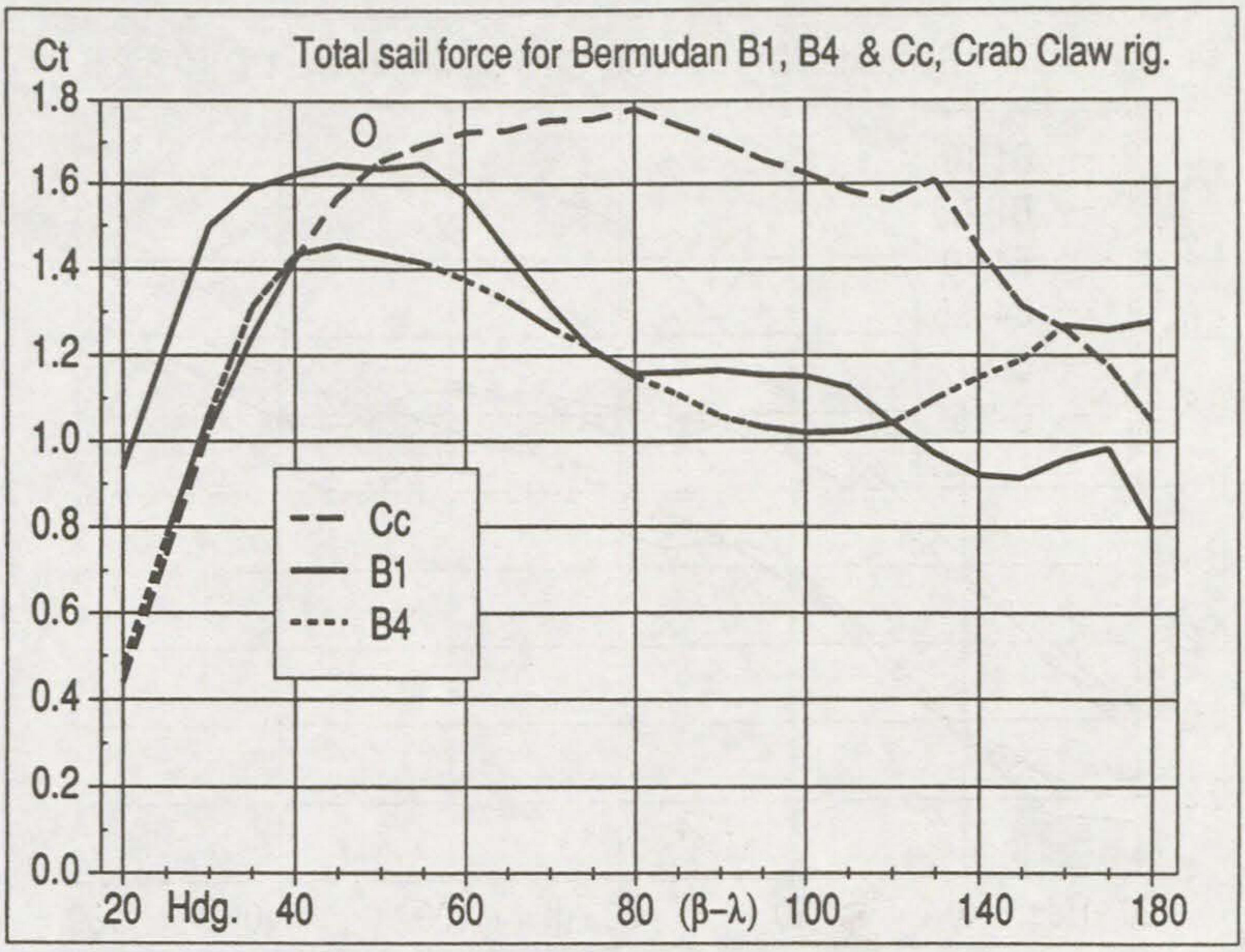


Fig. 6.

In Fig 6 above, rigs B1 (mainsail and small jib) and B4 (mainsail only) are compared with Cc (the Polynesian Crab Claw rig). The point of intersection of one curve by the other, marked O, indicates that at certain (β–λ) angles, one rig is losing its superiority; in this particular case, the Bermudan rig becomes less powerful than the Crab Claw above (β – λ) = 50°.

Note how the mainsail on its own (B4) is very similar to the crab claw close hauled, but much inferior above 40°. Only above 160° is it the more powerful rig, when it has more of its area exposed directly to the wind.

The flow around B4 appears to commence stalling and losing lift around 45° and B1 at 55°. The Crab Claw rig continues to create useful lift up to a heading angle of 130°. This appears to be due to vortex flow developing at the larger angles of attack, the sharp and relatively straight edges of the spars encourage this.

(Note the change in the horizontal (β–λ) scale at 100° in all these graphs.)

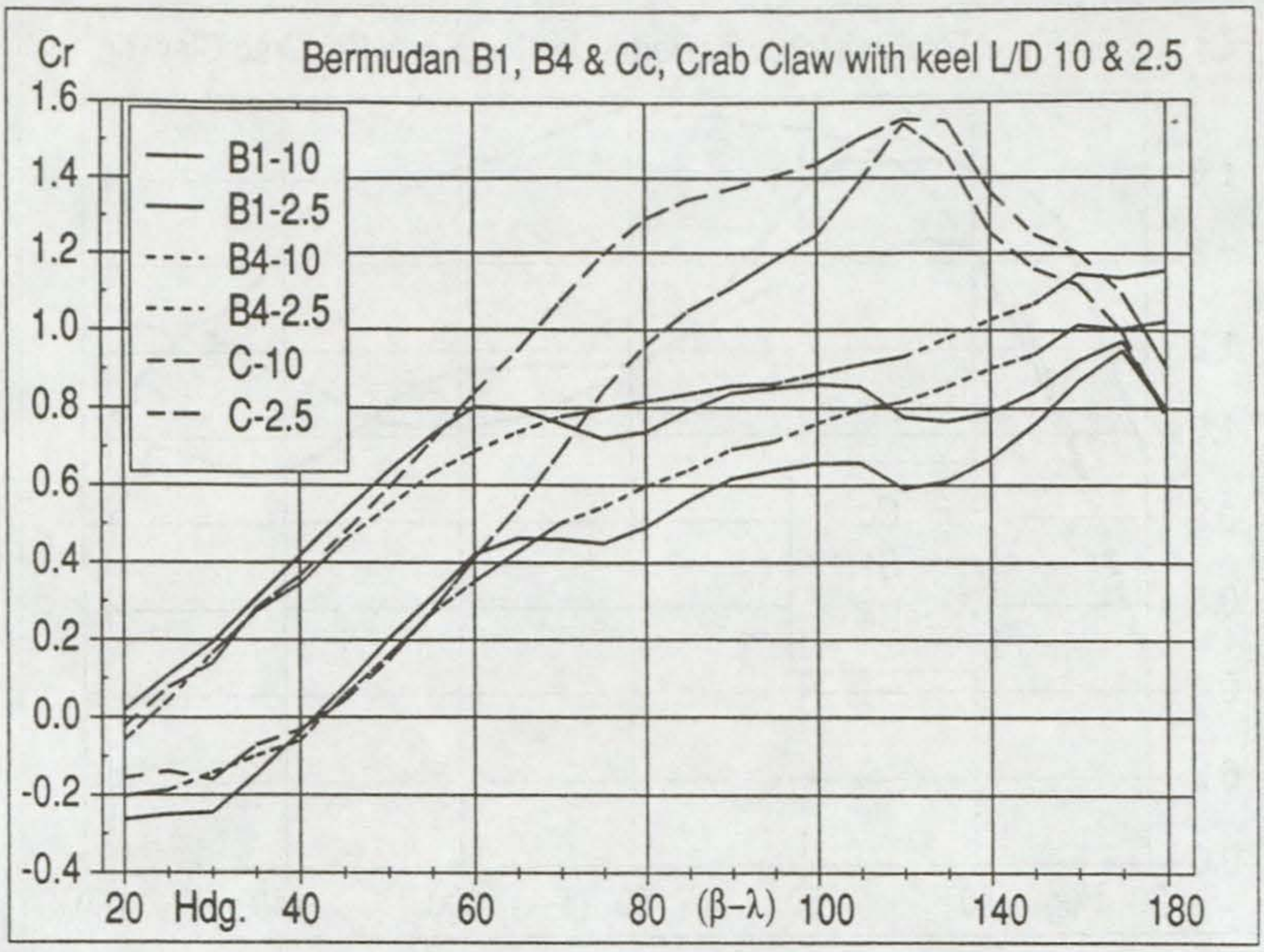


Fig 7

Fig 7 above shows the same three rigs applied in a more realistic manner, The side force is taken into account with keel lift/drag ratios of 10 & 2.5. This represents possibly a good cruiser racer design and a shallow draft design (depth<10% length).

With the efficient keel and a heading of 35° there is a difference in C_R of 10% (.28 - .31), despite the very much greater total force of B1, as shown on Fig 6.

With an L/D of 2.5 the spread is about 10% at 55° and there can be no windward performance with the heading less than 45°.

Above 60° there is a rapid variation in thrust produced, with the Crab Claw showing its greater superiority up to 160°.

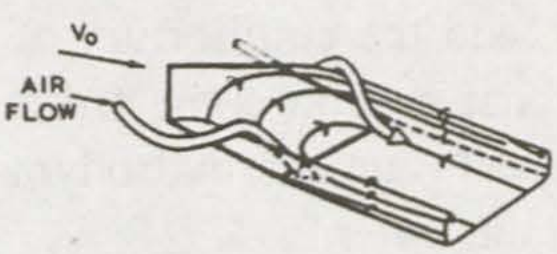
At 120° the Crab Claw produces all its force forward and so there is no reduction in thrust caused by induced drag and the side forces.

As indicated by the wind tunnel tests, no rig is superior over the whole range of heading angles. There are, however, some consistently poor rigs regardless of heading angle, such as the Lateen 3 and certainly there are better rigs than the Bermudan – this includes windward courses where this rig is widely believed to be outstanding. By making predictions of the sailing performance on the basis of the wind tunnel tests, the practical differences between rig have been demonstrated in qualitative and quantitative terms.

The overall rig efficiency is represented by the net thrust of the rigs with the introducing of the Lift/Drag ratios of the keel system into the calculation.

The choice of L/D ratios is somewhat arbitrary as it is part of the total hull resistance. It is based on the total hull drag – zero yaw hull drag (at the same speed).

As the side force reduces and boat speed increases when off the wind the the induced drag reduces and the effective lift/drag ratio improves.



a TAPERED WING WITH TIP VORTEX SHEETS

b SLENDER DELTA WING WITH SPIRAL LEADING-EDGE VORTEX SHEETS

Wings with flow separation from side edges

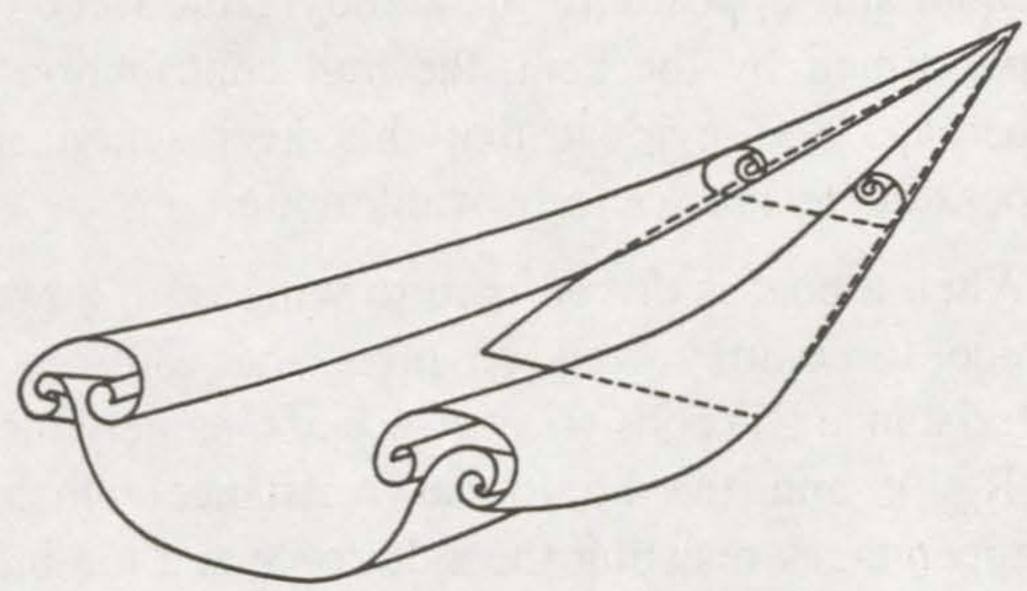


Fig 8

Figure 8 shows the basis of vortex flow. At high angles of attack this gives greater lift forces at the expense of some increase in drag.

SAIL–HULL RELATIONSHIP

One of the objectives of the art of boat designing is to determine with certainty whether a proposed prototype, or modifications to an existing boat (rig and hull), will result in better speed. It is an interesting question which is more important – the sailplan or the hull?

To inquire meaningfully into this question it is necessary to acquire some understanding of the basic principles governing the motion of a sailing boat and the forces involved. Figure 9, which illustrates a boat sailing to windward, will facilitate the discussion.

Good performance close hauled, as measured by speed made good to windward (V_{mg}), is particularly important. The safety of a boat when caught in a gale near to a lee shore can depend upon the ability and efficiency of beating to windward.

Mechanics of Sailing to Windward

The problem can be simplified by looking down from above the boat (Figure 9) and considering separately the horizontal components of the aerodynamic forces, the hydrodynamic forces, and the equilibrium of sail and hull forces. The forces which determine boat motion come from two sources; the apparent wind (V_a) action on the sail; and the hydrodynamic reaction resulting from hull speed (V_b) through the water.

The underwater part of the hull, together with the attached keel (centreboard, leeboard, or fin and rudder) operate as a combined hydrofoil. At some angle of leeway (λ), it must produce a hydrodynamic force (F_H) equal and opposite to the aerodynamic force (F_A). This function is mainly performed by the keel, the hull contribution being relatively small. It is perhaps self–evident that this keel action should produce the smallest possible resistance to forward motion.

When a boat is driven hard to windward, however, the cost of the required side force may well be more than 30% of the total resistance. Thus, resistance (R) consists of two parts, namely the resistance of the hull proper (R_{hull}), and the additional resistance which is due to hull form and appendages resisting the side force and the inevitable heeling force (R_{keel}) – mainly in the form of induced drag.

Thus, the total resistance of the hull expressed in terms of forces can be given in a manner similar to Eq. 1 relevant to sails:

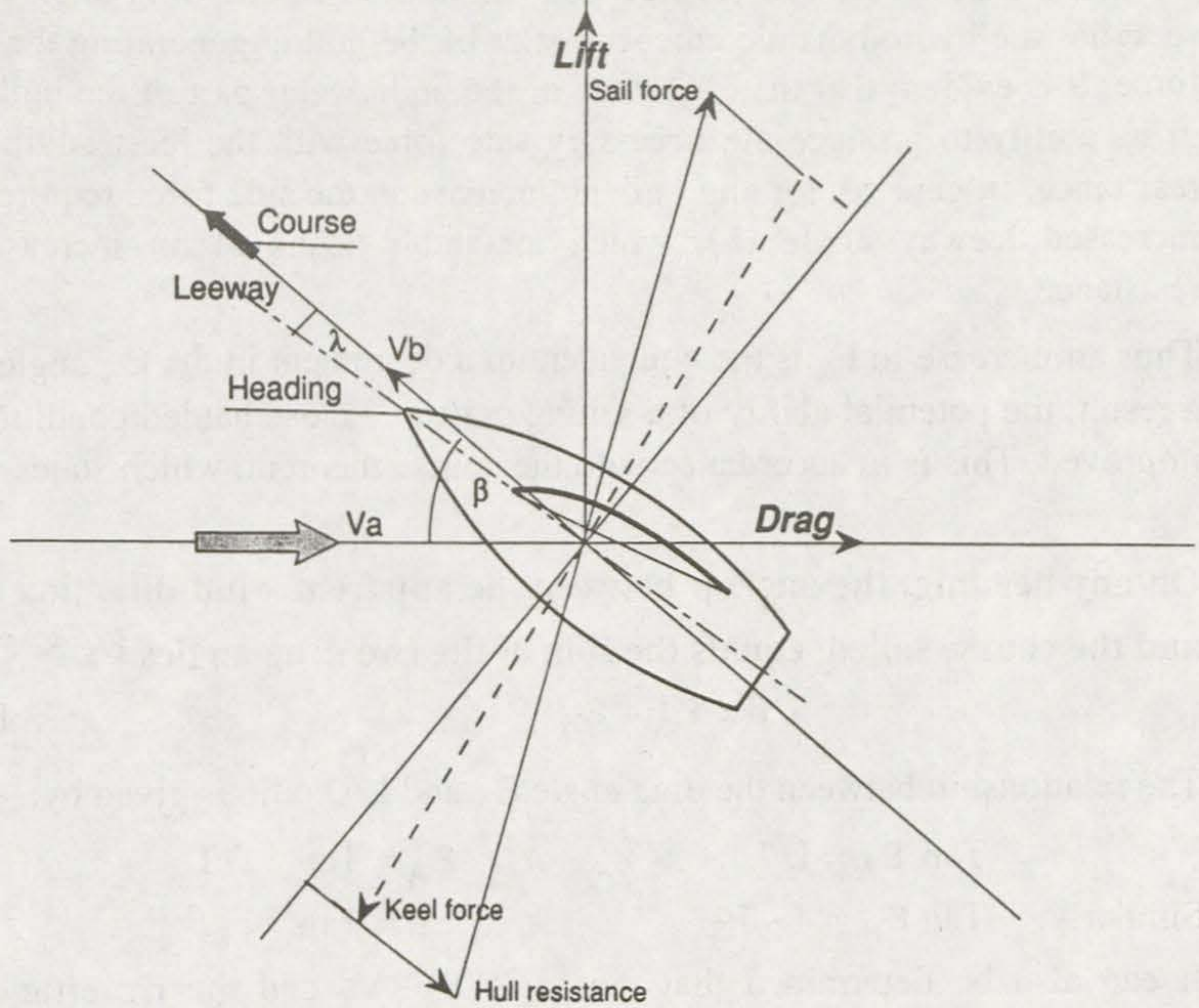


Fig 9

Induced resistance

(vortex drag)

$$R = R_{hull} + K \cdot F_S^2 / (\pi \cdot AR) \quad [10]$$

where R = total resistance

R_{hull} = hull resistance at zero yaw & heel

F_S = hull side force

K = constant,

depending on planform (efficiency) of hull appendages.

The two hydrodynamic force components F_S and F_R can be measured in the towing tank to find the total, or resultant, force F_T, which goes through the Centre of Lateral Resistance of the hull (CLR).

As in the case of the sail (Figure 10), the hydrodynamic drag angle (ε_H) specifies the hydrodynamic characteristics of the hull in generating the side force. It is evident that the efficiency of the underwater part of the hull lies in its ability to produce the necessary side force with the least additional resistance. In general, for any hull, an increase in the side force requires an increased leeway angle (λ), which inevitably leads to an increase in resistance.

Thus an increase in F_R is the equivalent to a decrement in the ε_A angle. As a result, the potential ability of a sailing craft in a close hauled condition is improved. This is in accordance with the course theorem, which states that;

On any heading, the angle β between the apparent wind direction (V_a) and the course sailed, equals the sum of the two drag angles ε_A & ε_H.

$$\beta = \varepsilon_A + \varepsilon_H \qquad [11]$$

The relationship between the drag angle ε_A and L/D ratio is given by;

$$\text{Tan } \varepsilon_A = D/L \qquad \text{or} \qquad \varepsilon_A = \text{Tan}^{-1} D/L$$

Similarly; $$\text{Tan } \varepsilon_H = F_R/F_S \qquad \text{or} \qquad \varepsilon_H = \text{Tan}^{-1} F_R/F_S$$

It can also be determined that the angle ε_A, V_T and the rig efficiency factors ε_A and ε_H are mutually related through the following expression;

$$V_{mg} / V_T = \text{Cot } \lambda / (\text{Cot}(\lambda - \varepsilon_A - \varepsilon_H) - \text{Cot}\lambda) \qquad [12]$$

This formula, which may at first appear complicated, is fairly straightforward in interpretation, provided we are cautious when putting numerical values for the sail and hull drag angles ε_A and ε_H respectively. They are not constant, but depend to a greater or lesser extent on wind speed (V_T) and resulting boat speed (V_b). The formula demonstrates, in yet another way, that both rig and hull efficiency determine the attainable V_{mg} / V_T ratio. This ratio is a good measure of design efficiency.

Thus Eqs. 11 and 12 answer the question asked at the beginning of this section; which is more important, sails or hull? Evidently both are important – after all, any sailing craft is a complex system consisting of two interdependent parts (aerodynamic and hydrodynamic), in which case each part is both cause and effect of the other. Hence, there is no reason to assume or believe that one of the parts is more important than the other. The only difference from, say, the crew's point of view, is that sail efficiency is accessible to intervention through tuning or trimming; while the hydrodynamic properties of the hull, once predetermined by the designer and builder, are not so susceptible to the crew's efforts, except perhaps in the adjustment of the keel (dagger board) and rudder (steering), as well as the maintenance of a smooth and fair hull surface.

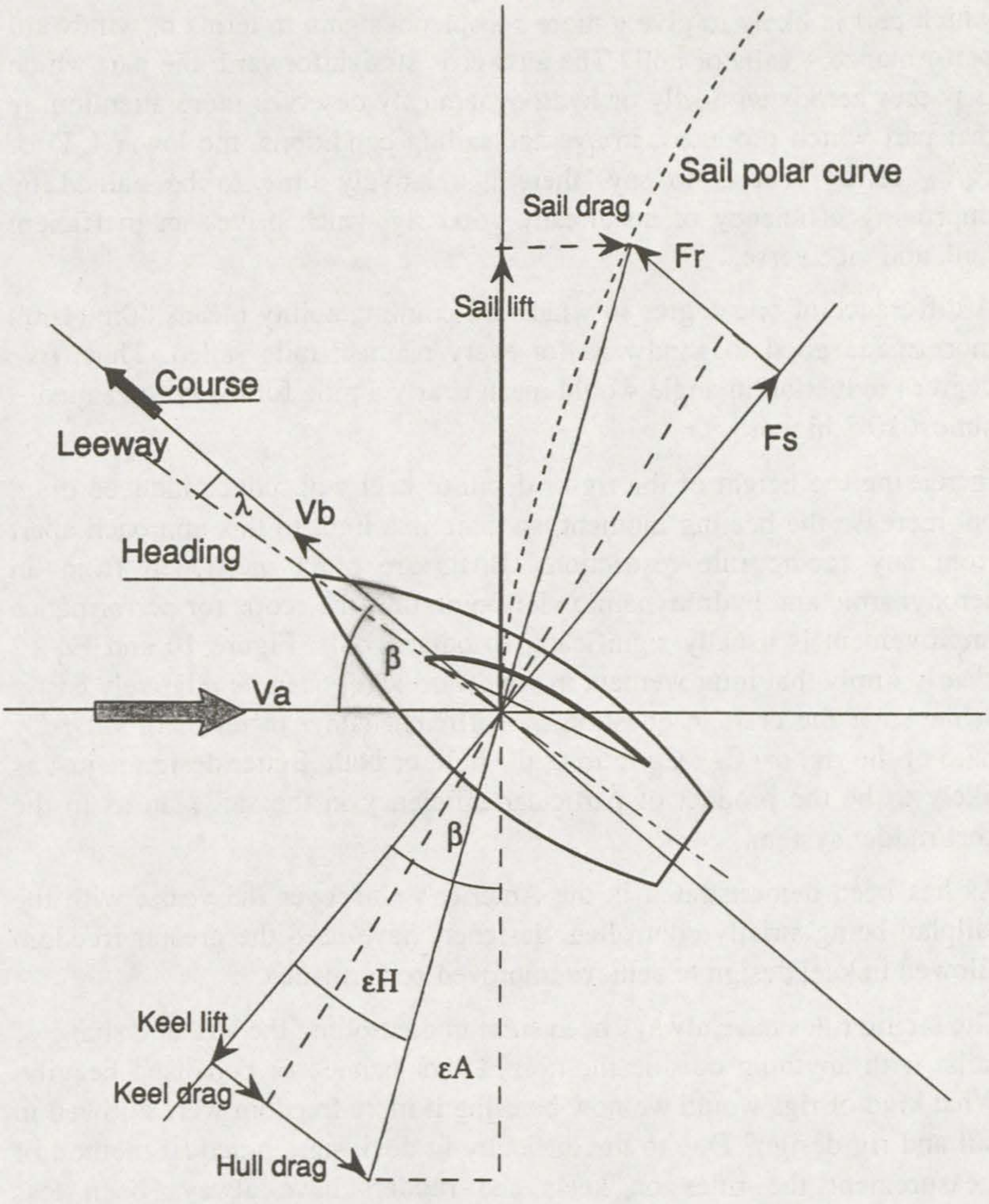


Fig10

Possible Improvements – Sails or Hull?

Another question which can be answered on the basis of Eqs 11 and 12 is if a development or modification of a given boat is under consideration, which part is likely to give a more conspicuous gain in terms of windward performance – sails or hull? The answer is straightforward: the part which is poorer aerodynamically or hydrodynamicaly deserves more attention, *ie* that part which produces, in average sailing conditions, the lower L/D or F_S/F_R ratio. That is to say, there is relatively little to be gained by improving efficiency of an already good rig which drives an inefficient hull, and vice versa.

A difference of one degree in windward pointing ability means 30m (100') more made good to windward for every nautical mile sailed. Thus, five degrees reduction in angle would mean nearly a mile for every ten sailed – almost 10% higher.

Increasing the height of the rig or depth of keel will reduce induced drag, but increase the heeling moment, so there is a limit to this approach apart from any racing rule restrictions. Boats are often inefficient from an aerodynamic and hydrodynamic viewpoint, thus the scope for performance improvement is usually significant; In other words, Figure 10 and Eq 12 clearly imply that improvement in windward ability can be relatively easily achieved if the craft in question is inefficient either in terms of Cx / Cy ratio of the rig, or C_S / C_R ratio of the hull, or both. Better design is just as likely to be the product of particular efficiency in the sail plan as in the keel/rudder system.

As has been demonstrated in the America's Cup over the years, with the sailplan being strictly controlled, designers have used the greater freedom allowed in keel design to achieve improved performance.

The racing rules have always been strict in controlling the size and shape of sails, with anything outside the norm either banned or penalised heavily. What kind of rigs would we now be using if more freedom were allowed in sail and rig design? Due to the difficulty in devising a practical method of measurement the rules on keels and rudders have always been less restrictive.

RIG EFFICIENCY FACTORS

What is the best shape of sailplan for any particular area and what are the shape factors that are most detrimental to sail power?

Planform and Aspect Ratio

Sails can differ one from another in many ways: in planform, aspect ratio (AR), camber, twist, etc. Because of the multiplicity of variables, it is essential to concentrate on the most important ones to make the problem understandable.

To many, the most profitable modification to the sail planform seems to be to increase AR; and the penalty for overdoing just that, as +imposed by most measurement formulae, certainly encourages such a belief. It can also be demonstrated that sails of the same AR and camber distribution, but with different outline shapes, may produce very different aerodynamic characteristics. These differences are due to different flow patterns round the sails, particularly the effects of the hull and mast, as well as around the upper and lower edges.

Every lift–generating device or foil, be it aircraft wing or boas sail (or keel, for that matter), spins the flow near the tips into a kind of small tornado or, in other words, a trailing vortex. Since these vortices are continually generated, as long as lift is produced, a quantity of wind–produced kinetic energy is continually required to generate the. This is subsequently lost to the foil by being left in the wake behind the sail or wing, in the form of a rotating mass of air.

This expended wind energy, felt by the sail as drag, is called either the trailing vortex drag or induced drag. The second term is, in some ways, more descriptive, since it reflects an important consequence of the trailing vortex action – induced deflection of the mass of air behind the trailing edge of the sail in the opposite direction to lift. Due to this deflection of the airstream – which in turn depends on the vortex intensity – the effective incidence angle at each station of the sail height, as distinguished from the geometrical angle of incidence (α) apparent from mere visual observation, is different.

In the twenties the German scientist Max Munk, proved that, for a single wing, minimum induced drag occurs (or minimum energy is lost to the wake) when the airstreams are deflected **with the same induced velocity (ω) all along the trailing edge.** The so–called elliptic wing of the famous Spitfire aircraft has exactly this property and, in this sense it is the best theoretical planform. A large proportion of the upper part of the triangular mainsail shape used, in close hauled conditions, does appear to contribute very little towards the driving force. This test programme showed that up to 15% of the Bermudan mainsail length can be cut from the head, practically without effect on the sail's performance, even with the drag penalty of the now–vacant topmast which is left in place.

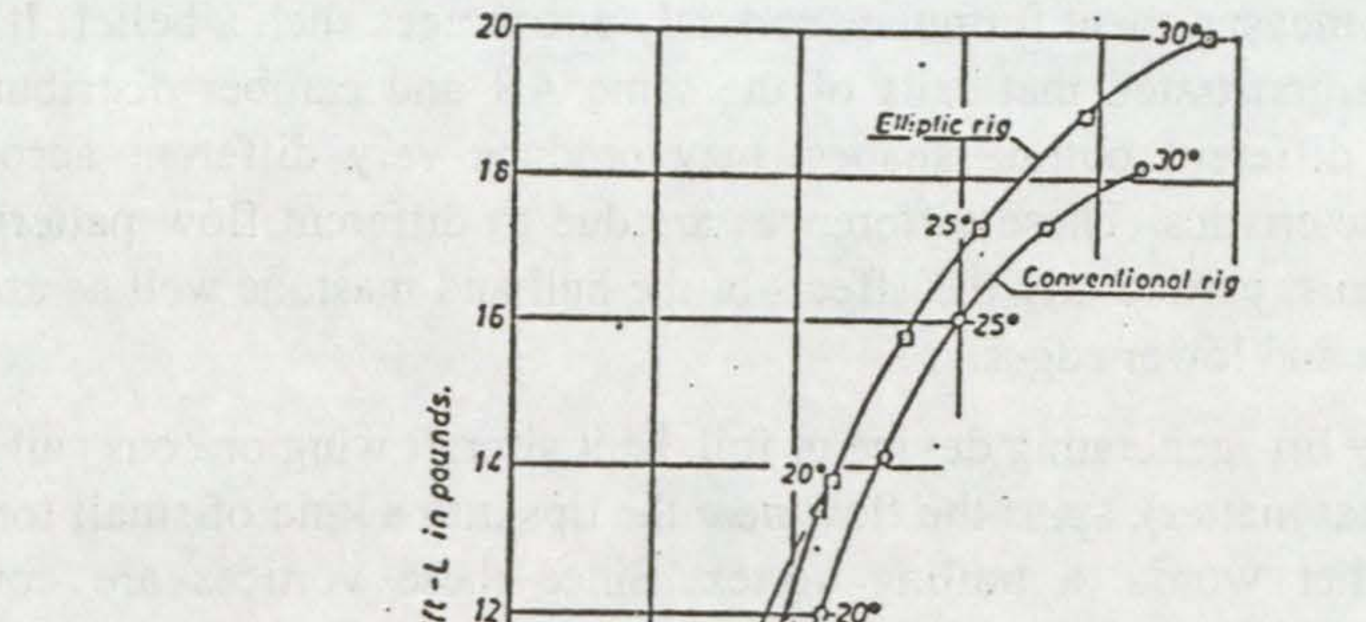


Fig 11

Results of wind tunnel tests on such a modified model rig initiated and carried out earlier by C A Marchaj are shown in Figure 11 (the so–called 'Lionheart' planform) fully confirmed the theoretical premises. It will be seen that the whole polar curve for the elliptical main sail is bodily shifted to the left towards lower drag.

For instance, at the heading angle $(\beta - \lambda) = 20°$, the bent mast rig produced about 30% more driving force (F_R) than a triangular sail with a conventional straight mast; the actual force magnitude depends on the course sailed and range of lift at which the boat operates or, in other words, the true wind speed and direction. Because of the way the sail area on the 12 Metres was controlled at that time this modification had a double advantage in that it allowed the use of extra unmeasured sail as well as having a more efficient shape.

There are several indicators which suggest that this curved leading edge and straight or concave trailing edge might be the best shape as an aerodynamic and structural compromise – after all it is an arrangement frequently seen in nature on the wings of birds and the fins of fish.

It is interesting to note that such an efficient sail, closely approaching this optimum planform, was developed without any scientific theories by the Jangada from the north eastern coast of Brazil. Their present rig is virtually identical to those which were built in the 16th century. The jangadieros or fisherman developed an efficient sail planforms some 400 years before Max Munk proved mathematically that they were correct.

The Polynesians also produced a extremely efficient and practical rig in the *Crab Claw* layout many hundreds of years before the theories behind it were understood. In fact it was only out of curiosity that the rig was included in these tests and it was not expected to be very efficient.

When first run in the wind tunnel the figures from the Crab Claw rig were so unexpected that the tests were halted while the calibration of the balance system was rechecked.

In their striving for 'new' ideas and greater performance from racing rigs it looks as though the yachting world has been largely ignoring the great wealth of information that has been available for hundreds of years from other cultures or even for millions of years from nature.

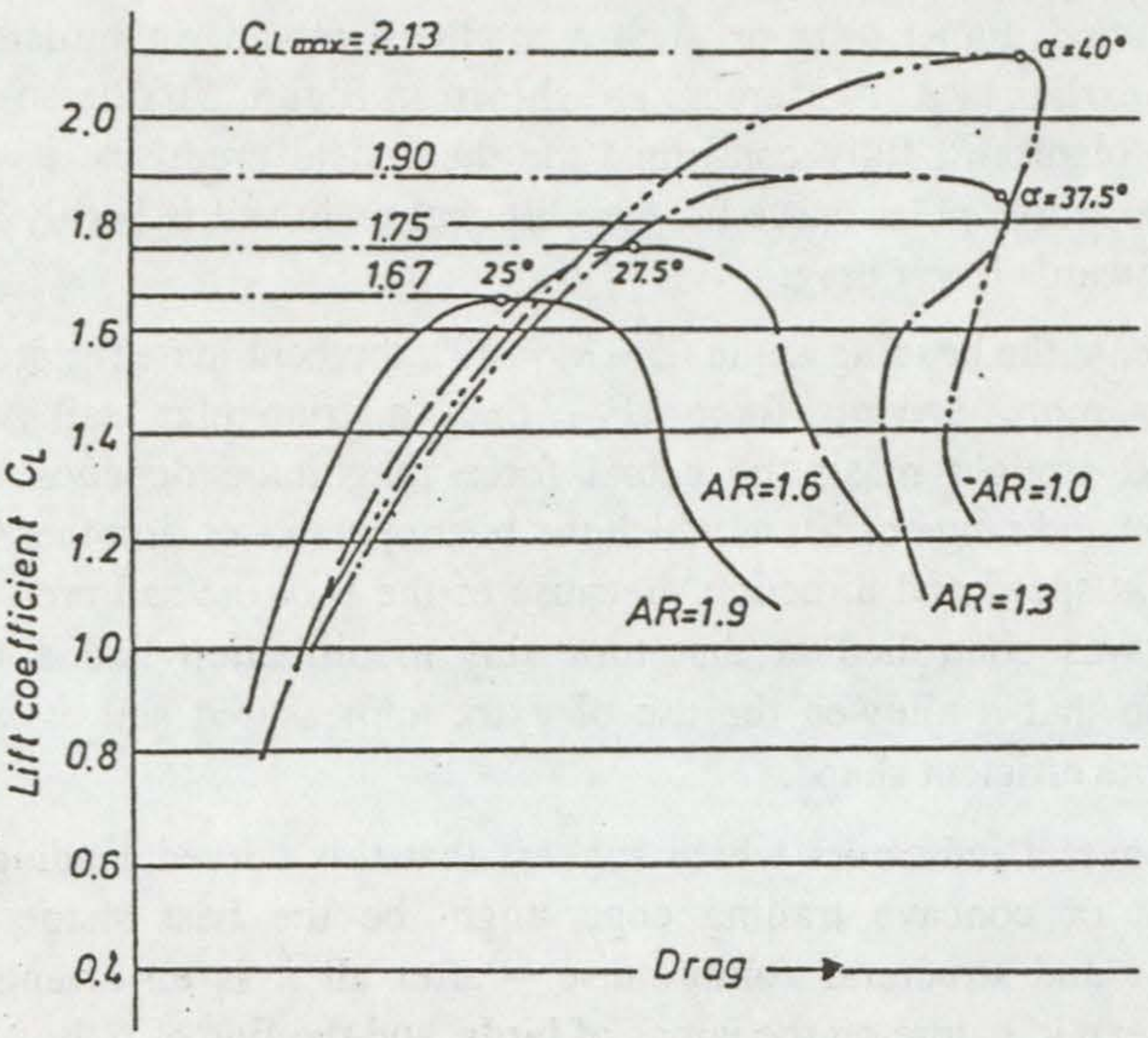


Fig 12

Aspect Ratio effect on Rectangular Sails

Figure 12 presents results of tests on four different rectangular sails of aspect ratios 1.0, 1.3, 1.6, and 1.9, with the same camber of about 12%.

Corresponding to the different aspect ratios, the maximum values of lift varied considerably. As indicated in the plot, C_{Lmax} increased from 1.67 for AR = 1.9, to 2.23 for AR = 1.0, i.e. by about 34%. Such substantial growth of C_L is due to an increasingly dominating flow pattern developing round the upper and lower edges of the sail. It is similar to the delta wings of Concorde, it is also found on the *Crab Claw* and other sails with predominantly horizontal spars.

As mentioned earlier, a foil, be it sail or wing, producing lift, dissipates energy into the airstream at a rate equal to the product of the induced drag (Eq. 1). This energy goes largely into generation of vortices, with the trailing vortex cores spiralling at the tips. As the aspect ratio decreases, this vortex motion is gradually intensified, and the tip vortices are brought closer together. For low aspect ratios (in the order of 1.0) the concentration of vortex energy per unit length of the foil (span) becomes of such intensity that the boundary layer tends to accumulate over the rear part of the foil section, is swept away, and the flow continues without breakdown to high angles of incidence. These tip vortices, so beneficial in one respect, must be paid for in higher drag and lower L/D ratios.

Unlike the high aspect ratio sail, where the flow breaks down at relatively small incidence angles, the low aspect ratio planform is much less sensitive to an increase in angle of incidence because the tip vortex flow does not break down until very high angles are reached. That is why such a high vortex lift can be obtained on low aspect ratio sails, particularly evident in the case of the *Crab Claw* rig.

Concluding, the aerodynamic characteristics of a sail largely depend on which type of mixed flow actually dominates: either the type of flow in which the airstream is basically attached to the sail surface (classic aerofoil theory); or else the spiral, trailing vortex, type of flow. Higher L/D ratio is associated with the former; larger C_{Lmax} with the latter. One cannot have the best of both worlds at the same time; only variable geometry rigs can at present do that particular trick.

Surface boundary layer effect

Figure 13 illustrates the performance of the same sail (of AR 1.0) set in two different positions; one is in a free airstream, in which case the flow is symmetrical in relation to the upper and lower edges, in the second it is mounted close to the wind tunnel floor. The upper part of the sail was affected by the action of the trailing vortex, as in the first case, but the lower part was immersed in the boundary layer of the wind tunnel floor. Such a boundary layer of greater or lesser thickness always exists in proximity to the deck (or hull surface in the case of a rudder or keel).

It will be seen that reduction in maximum lift for the sail with the bottom gap closed is very large, from 2.23 to 1.42, i.e. about 36%, and with a simultaneous and undesirable drop in L/D ratio. This test appears to contradict the commonly held view, expressed in textbooks on aerodynamics and naval architecture, that by closing the gap between one edge of the foil and, say a fuselage or hull, the aspect ratio can roughly be doubled (mirror image theory), with an ensuing advantage of higher L/D ratio. One thing is certain, the detrimental effect of the boundary layer created over the sea or a large body (hull) on the flow round any foil closely attached to it, – cannot be ignored.

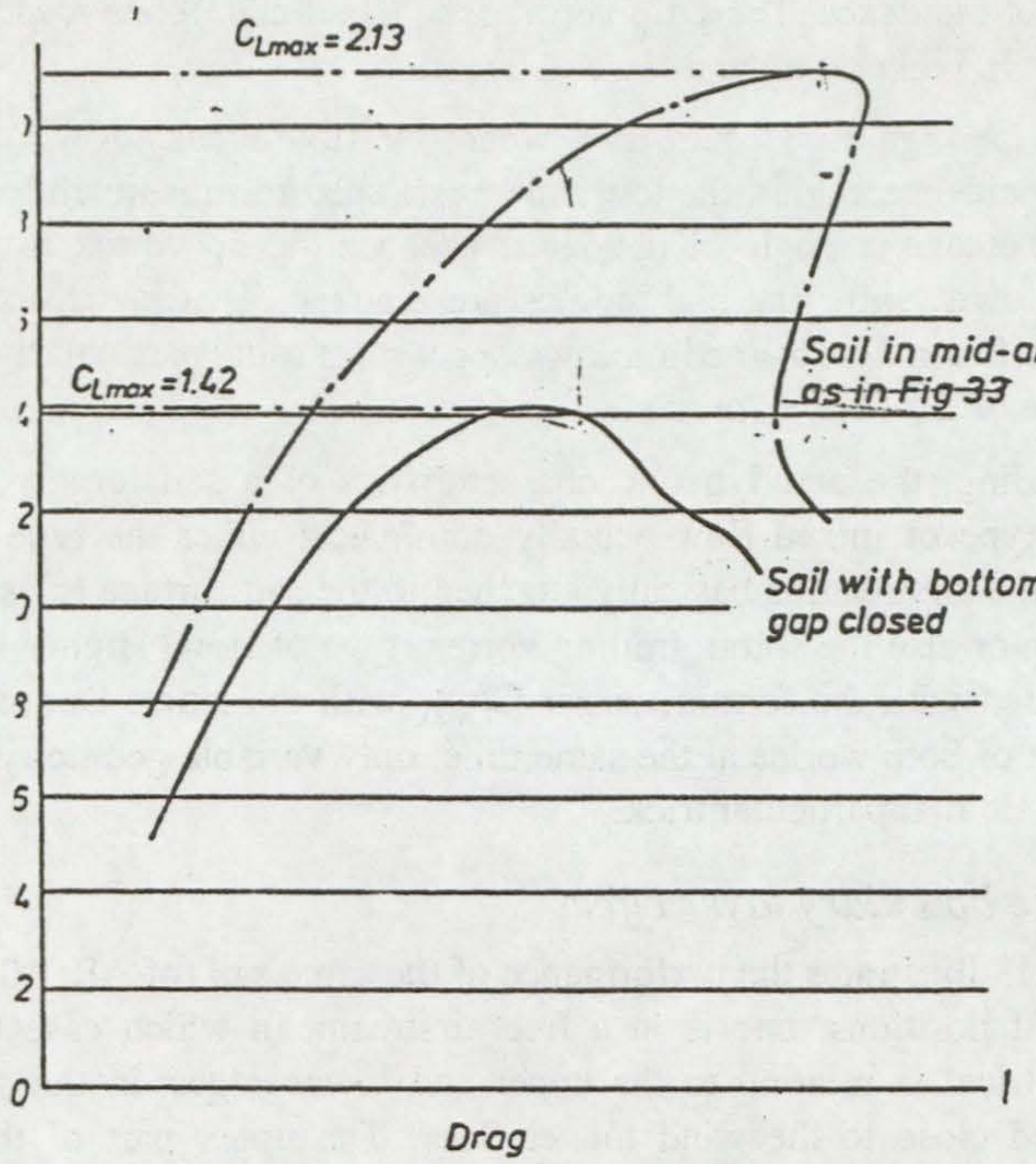


Fig13

Twist

The loss of sail power due to twist, both in terms of maximum lift and L/D ratio (or drag angle ε) can be judged in quantitative terms on an experimental basis. Figure 14 represents a number of polar curves C_L versus C_D for the same rectangular sail of AR = 1.6, but gradually twisted from 0° to 31.5° (measured between the lower and upper edge of the sail). The sail had no mast, but was supported by wires kept under high tension to minimise spanwise variation of its camber.

It will be seen that the sail which is twisted 31.5° developed only 80% of the lift obtained in the no twist condition. The rate at which sail efficiency deteriorates appears to increase gradually as twist increases. That is, from 0° to about 10° of twist the effect of this is negligible, particularly on L/D ratio; thereafter the bad effect becomes more and more pronounced, both on L/D and C_{Lmax}.

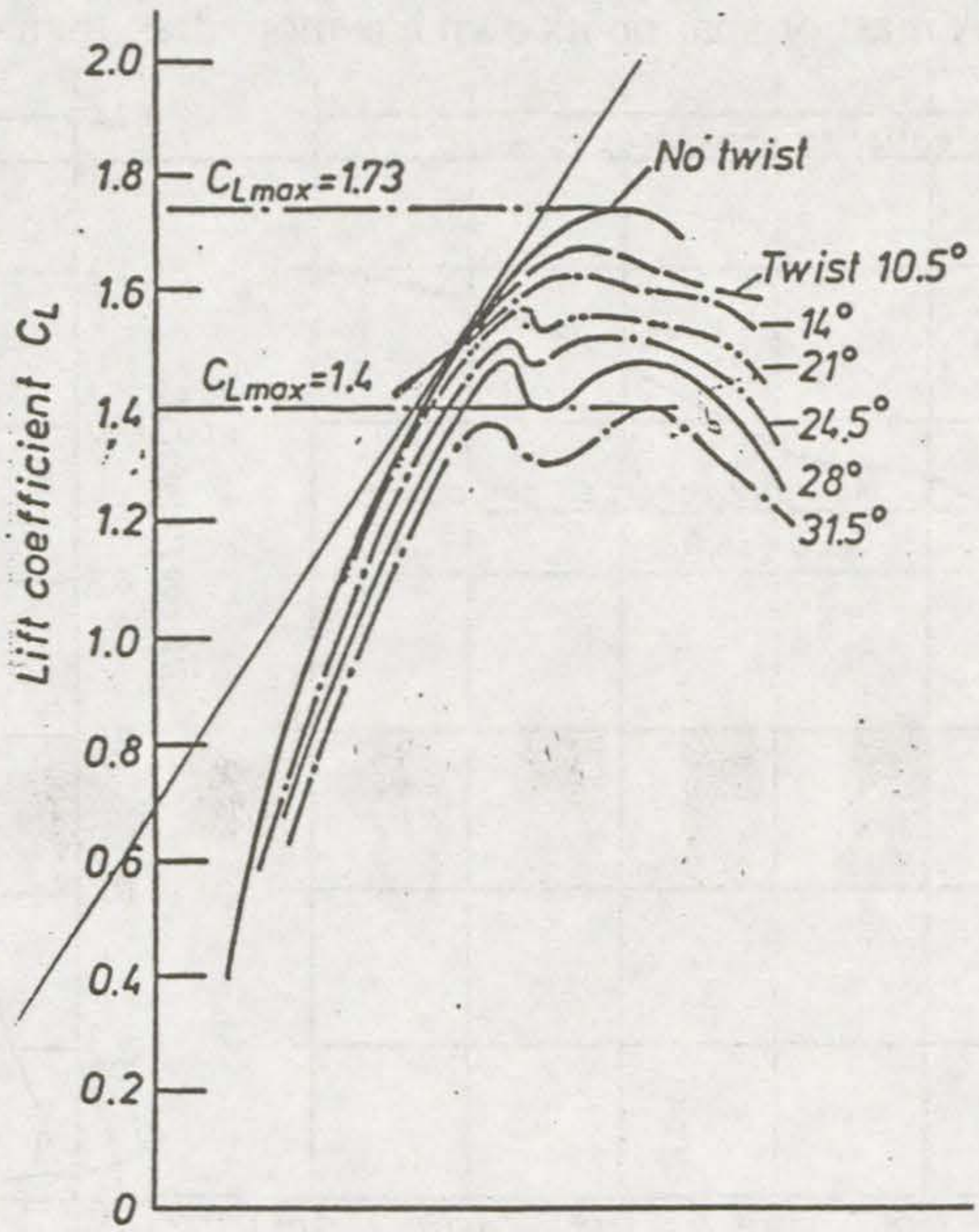


Fig14

Between 0° and 10° of twist the L/D virtually remains constant, but the heeling moment is reduced which will result in a lower angle of heel giving greater sail efficiency and less added hull resistance. The heeling moment reduces with increased twist so that in limiting heel conditions a certain amount of twist is a good thing – any racing sailor will tell you this.

In practice, with a simple sheeting system only (i.e. without a powerful kicking strap or vang), the twist of a mainsail tends to increase rapidly when the boat bears away. In reaching attitudes a sail may twist as much as 70°. Consequently without a jib the sail will experience attached flow along only some of its lee side, and separated flow along the remainder – the extent varying with the course sailed relative to the wind, and sail trim. In such circumstances, the condition for minimum induced drag which requires a uniform downwash velocity (ω) behind the whole trailing edge of the sail cannot be satisfied. Inevitably the losses in terms of induced (vortex) drag must necessarily be larger, but the heeling force is reduced allowing a greater force to be developed within the allowable stability.

The presence of a jib set in front of a mast and sail always improves the flow around them. A mast or spar on its own has more drag than one with a sail attached.

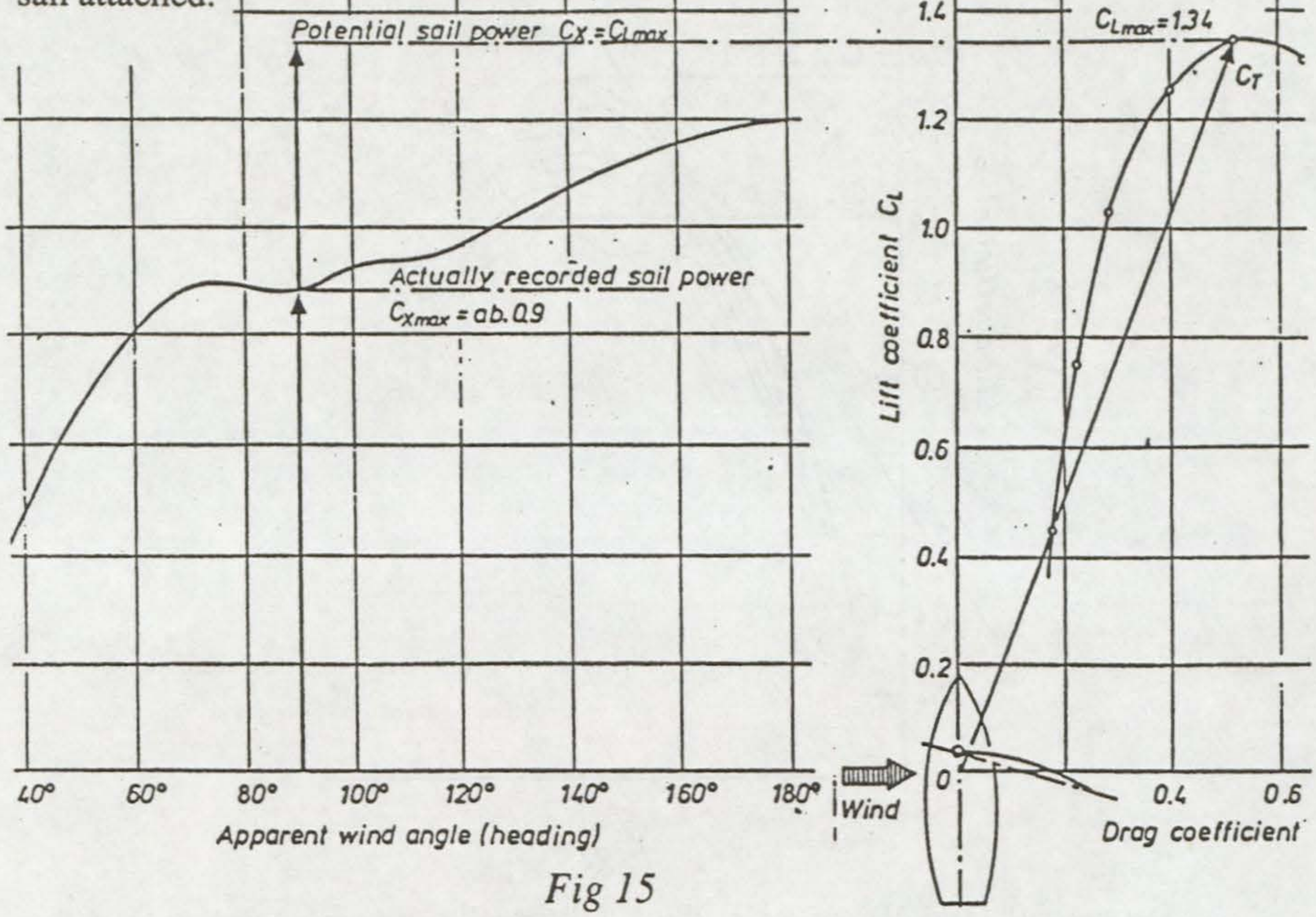


Fig 15

From Figure 15 it will be noticed that Cx is reduced from 1.34 to 0.9 due to the excessive twist in the sail and lack of the hull under the sail. The reduction of drive force is about 30%.

Just as completely closing the lower gap in a turbulent boundary layer greatly reduces the efficiency, so the removal of the hull from under the sails in broad reaching conditions also reduces efficiency.

The integration of hull and rig is a significant factor in sailing performance and at present greatly misunderstood because traditional aerodynamic approaches do not appear to apply directly.

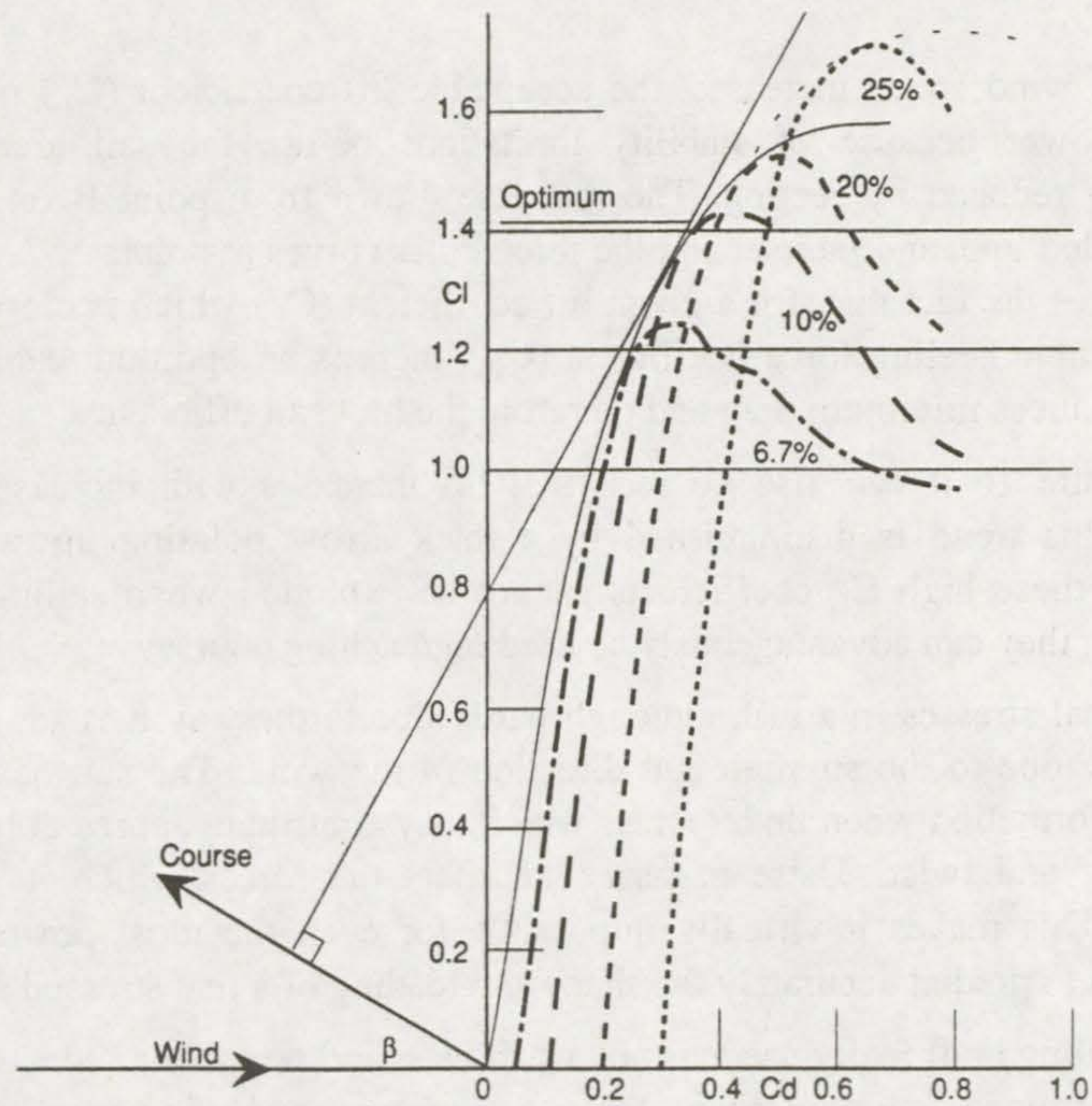
The hull under the rig appears to provide two very useful aerodynamic functions. The rig is lifted out of the surface boundary layer with the hull acting in a similar manner to the boundary layer bleeds on the jet engine intakes of military aircraft. The presence of the hull below the rig also reduces the leakage of the air around the bottom of the rig, increasing the effective aspect ratio.

The message appears to be that the gap between sail and hull should be small, but not eliminated altogether. The optimum gap will be greater the further aft the sail is along the hull and the stronger the local turbulence. The main boom should be drooped so that the clew is low.

Camber and Mast Bend

Camber and mast flexibility effects are considered jointly, and the reason is that in practice mast bend is used as a means of controlling sail camber

Figure 16 may assist in establishing the two fundamental trends associated with camber alteration. The polar curves presented give the variation of C_l versus C_d for four rectangular, untwisted, rigid sail models of increasing camber, from $^1/_{15}$ to $^1/_4$ of the sail chord; their aspect ratio was 4, and the position of maximum camber about one third of the chord from the mast. The essential intention of the test was to demonstrate, as clearly as possible, the trends in variation of C_{Lmax} and L/D ratio, on the assumption that the camber distribution was both vertically and horizontally uniform, and independent of incidence angle or wind strength.



As we shall see, such a clear demonstration is impossible in the case of a soft sail, where camber distribution, twist, and camber ratio, all change whenever the angle of incidence, the course sailed or the wind strength varies, so that the overall picture of trends is somewhat blurred – too many variables are involved at the same time

Figure 16 shows the effect of camber depth on L/D ratio and C_{Lmax}, relevant to rigid rectangular sails without twist. These figures assist in establishing the fundamental trend that C_{Lmax} increases as camber increases, but only to a certain limiting value, which is restricted by separation of the flow from the leeward side of the sail surface.

It will be seen in Figure 16 that, as camber decreases, the L/D ratio increases. and this trend (distinguished by a thick horizontal arrow) is noticeable in the range of C_L coefficients up to about 1.2. Assuming now that the representative close hauled course β relative to V_a is about 30°, we find that there is nothing to be gained in terms of driving force by increasing sail camber beyond $^1/_{10}$. The thin line drawn from point A on the course sailed and tangential to the polar curve, illustrates this conclusion graphically.

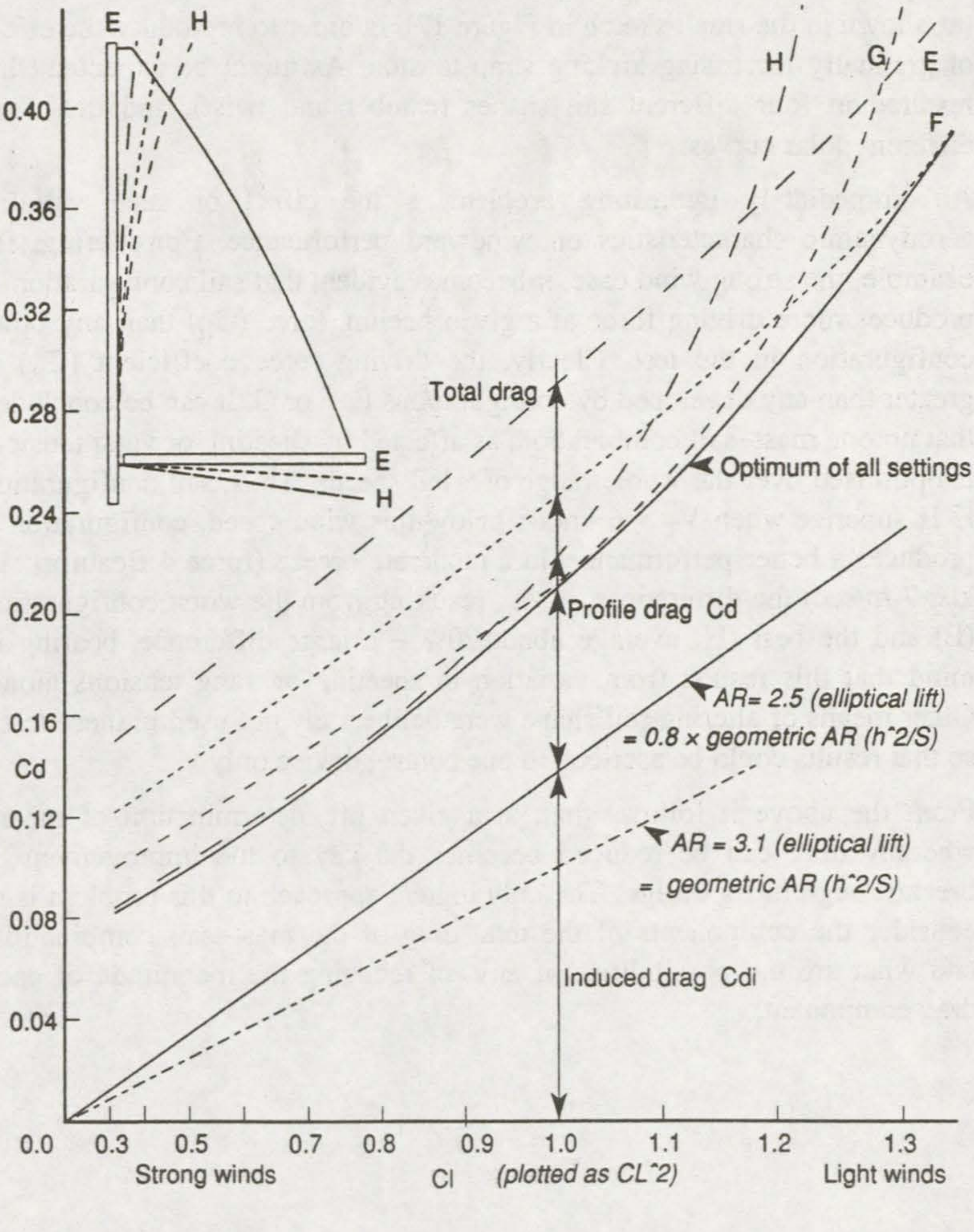
When the wind speed increases, the acceptable lift coefficient (C_L) must become lower because of stability limitations before the sail area is eventually reduced by reefing. The thin line drawn from point B on the course sailed line, and intersecting the three Polar curves at points 1, 2, and 3, illustrates the fact that, for a given lift coefficient (C_L) which is close to the acceptable heeling force coefficient (C_H), there is an optimum camber which produces minimum drag and therefore the best sail efficiency.

From Figure 16 it can also be seen that lift increases with increase of camber; this trend is distinguished by a thick arrow pointing upwards. Although these high C_L coefficients cannot be exploited when sailing to windward, they can advantageously be used on reaching courses.

The internal stresses in a sail, although partly due to the way it is set, are also partly due to the strength and direction of the wind. The sail has an elastic deformation when under stress which may contribute appreciably to its camber and twist. These in turn will affect the forces which it will develop. This makes it virtually impossible for even the most powerful computers to predict accurately the shape and loading of a real stressed sail.

What a sailing craft really needs is not a stiff mast and possibly an ideal sail of predetermined optimum shape for one predetermined wind speed and one course of sailing, but an infinitely adjustable sail to cope effectively with a great variety of wind speeds and sailing conditions. This requires different shapes for near calm and for gale conditions; different for close hauled work, and different still for reaching. To achieve this goal, a certain amount of elasticity in rig and sail fabric is desirable.

Because it is usual in all sizes of boat to have one mainsail for most conditions the flexible but adjustable rig has been recognised as superior to a rigid mast and sail combination, which cannot be altered while sailing.



When a mast bends under the action of the sheet or kicking strap (vang), it has a profound effect on the flow over the whole sail. This is due to changes in the magnitude of camber together with its chordwise and spanwise distribution, and also to variation in sail twist over the mast height. Therefore, the aerodynamic characteristics of the rig must change. Figure 17 illustrates the results of wind tunnel tests, the object of which was to establish the effect of kicking strap tension and associated mast bend on the performance of a given Finn mast–sail combination. The boom was pulled down vertically to four different positions marked E, F, G and H (as shown in the small sketch in Figure 17), in order to reproduce the effect of gradually increasing kicking strap tension. As might be expected, this resulted in four different sail shapes (camber and twist), and thus four different polar curves.

An immediately interesting problem is the effect of such variable aerodynamic characteristics on windward performance. Considering, for example, the strong wind case, it becomes evident that sail configuration H produces more driving force at a given heeling force (C_H) than any other configuration in the test. Clearly, the driving force coefficient (C_R) is greater than any developed by configurations E, F or G. It can be concluded that no one mast–sail combination, as affected by sheeting or vang tension, is optimised over the whole range of wind speeds. Thus, sail configuration H is superior when $V_T > 6$ knots; below this wind speed, configuration F produces a better performance. In a moderate breeze (force 4 Beaufort; 14 kts; 7 m/sec) the differences in V_{mg} resulting from the worst configuration (E) and the best (H) average about 20% – a large difference, bearing in mind that this results from variation in sheeting or vang tensions alone. Other means of altering sail shape were deliberately not used in these tests, so that results could be ascribed to one control device only.

From the above it follows that, at a given lift, determination of means whereby drag can be reduced becomes the key to the improvement or breakthrough in rig design. The only logical approach to this problem is to consider the components of the total drag of the mast–sail combination, and what are the possibilities, if any, of reducing the magnitude of each drag component.

Induced Drag

This is the direct result of lift being produced around a foil of finite length. There is a flow around the tip once lift is being produced and a difference in pressure develops on either surface. This results in a slight time lag in the development of induced drag and its vortices. Induced drag cannot be avoided, but its magnitude may be reduced by reducing the load, increasing the height (span) and careful control of the flow conditions.

Profile Drag

This is caused by the surface friction as well as the shape and thickness of the foil. Like induced drag it cannot be avoided, but it may be minimised by suitable treatment. The surfaces should be smooth and the shapes kind to the flow – an elliptically shaped leading edge gives the minimum acceleration to the flow for a given thickness.

A very smooth surface from the leading edge will encourage laminar flow, but will limit C_{Lmax} to about 1.0. This is sufficient for windward work, but is basically insufficient for efficient reaching or running.

Additional (Vortex) Drag

If a sail set on a bendy mast were of elliptical planform instead of being triangular, its total drag might, in some conditions at least, simply be the sum of its induced drag (C_{Di}) and its profile drag (C_d). In reality, wind tunnel tests indicate a large discrepancy between such a theoretically possible sail efficiency, and that which is practically attainable by this triangular soft sail, as demonstrated by the additional drag curves for our four different configurations E to H. A study of these detached values of additional drag, and the form of their curves, gives a clear picture of the drag penalty paid for the departure of the actual triangular sail from the much more efficient elliptical form, and also the penalty due to incorrect distribution of twist and camber over the sail. The graph indicates from another viewpoint, a large scope for improvement in sail efficiency which has been overlooked by many sailing people and theoreticians alike.

Planform of the sail should not be triangular. Rectangular or trapezoidal shapes more nearly approach the pressure distribution (and hence downwash velocity) of the elliptical lift distribution considered as optimum when not controlled by heeling moment. Camber and twist must be capable of being controlled independently.

DRIVING AND HEELING FORCE COEFFICIENTS

The following series of graphs represent C_x and C_y coefficients plotted against apparent wind angle (heading angle, $\beta-\lambda$) for each of the six basic rigs, together, in some cases, with their modifications .

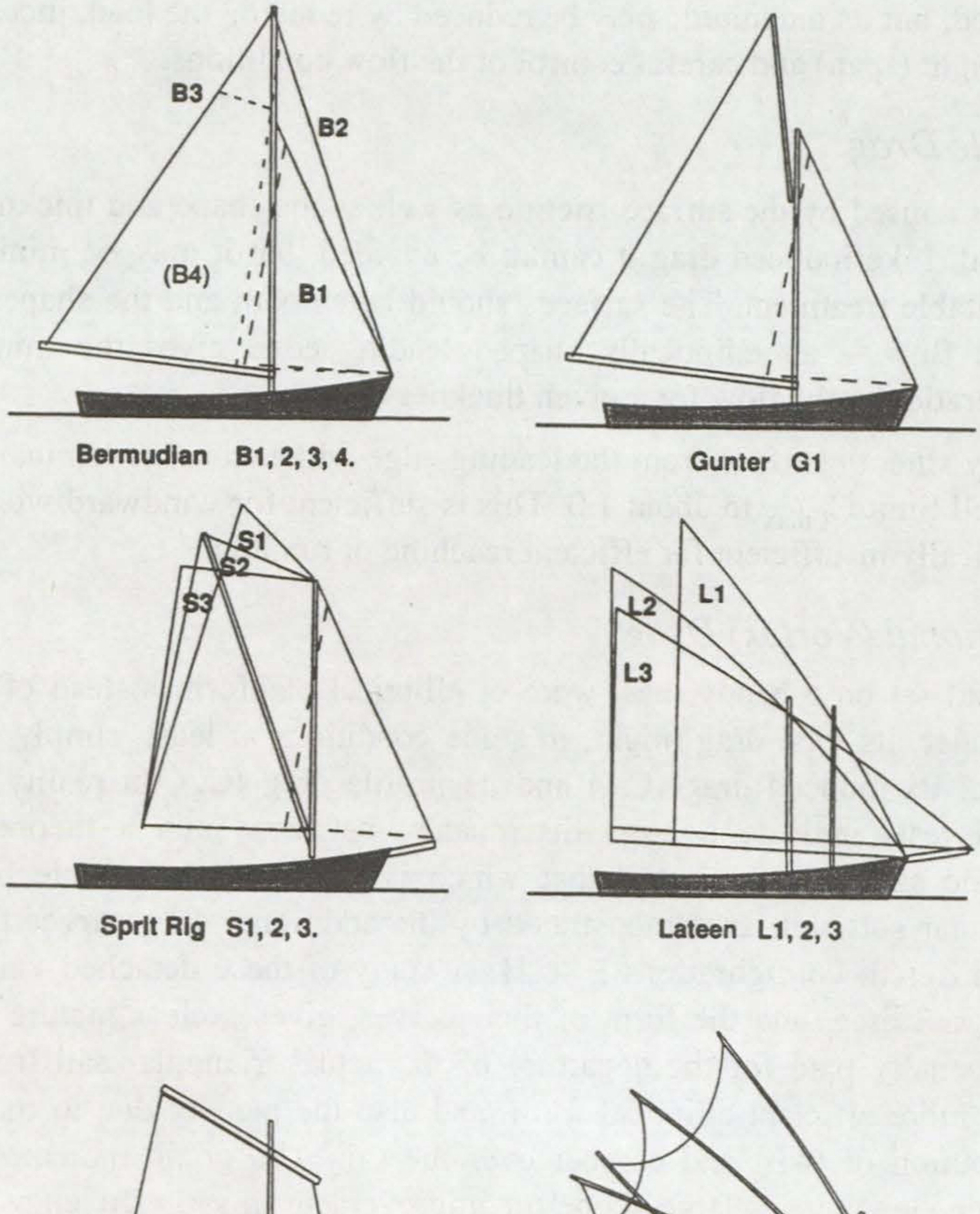


Fig 18

The six basic rigs were tested as illustrated in Figure 18.

Some rigs had one or more modifications .

1.	**Bermudan Rig**	with various jibs and modifications.
2.	**Lateen Rig**	and its modifications.
3.	**Sprit Rig**	and modified top.
4.	**Gunter Rig.**	
5.	**Dipping Lug Rig.**	
6.	**Crab Claw Rig**	set at different angles of rake.

(Neither square rigs nor chinese junk type rigs were included in these tests.)

All tests given were carried out at the same wind speed (18 knots) and set on an open decked hull with the angle of heel set at 10°.

The position of the sail relative to the hull on any particular run was initially adjusted so that the sail assumed a shape which, with the wind blowing, seemed to the practical sailor's eye to be reasonably good for the predetermined range of heading angles ($\beta-\lambda$). This is a limitation of the wind tunnel tests as it is doubtful if the optimum setting for any heading is ever achieved.

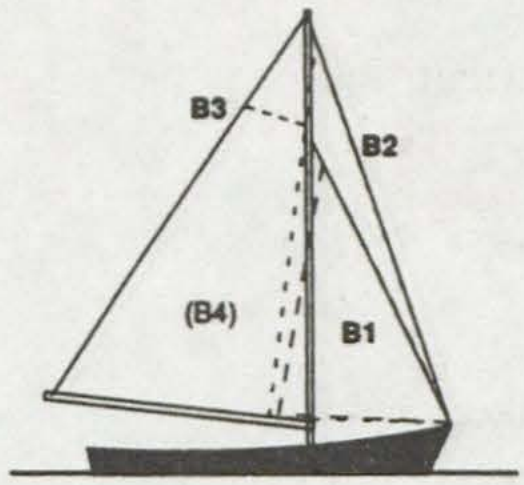
At the completion of this adjustment, the two components of total aerodynamic force (F_T), namely Lift (L) and Drag (D), were recorded and subsequently converted into x and y coefficients for thrust and side forces for each heading angle of $\beta-\lambda$.

The test envelope, ie the diagram that encloses the complete family of data, illustrates the best attainable characteristics of a given rig. All measured points which do not lie along the envelope curve represent those sheeting angles which were not optimally adjusted to the heading angle variation; in other words, they may be taken as indicating the kind of mistake which a crew may make when adjusting sails to the course sailed.

Deliberately, no gadgets such as kicking strap, vang, mainsheet traveller, outhaul, luff downhaul, etc which are commonly used by racing crews to adjust sail setting for best performance, were applied. Although quite effective, these devices are not normally used by less serious sailors, but with a well matched rig and sails these features can be made partially self adjusting.

With the rake of the Crab Claw rig being adjustable underway it is assumed that this is adjusted to the optimum angle for each point of sailing.

Bermudan rigs



Bermudian B1, 2, 3, 4.

B1 Is the standard rig with a small jib

B2 Is fitted with a masthead jib

B3 Has the top of the mainsail cut off and the small jib is used

B4 With the standard mainsail without jib.

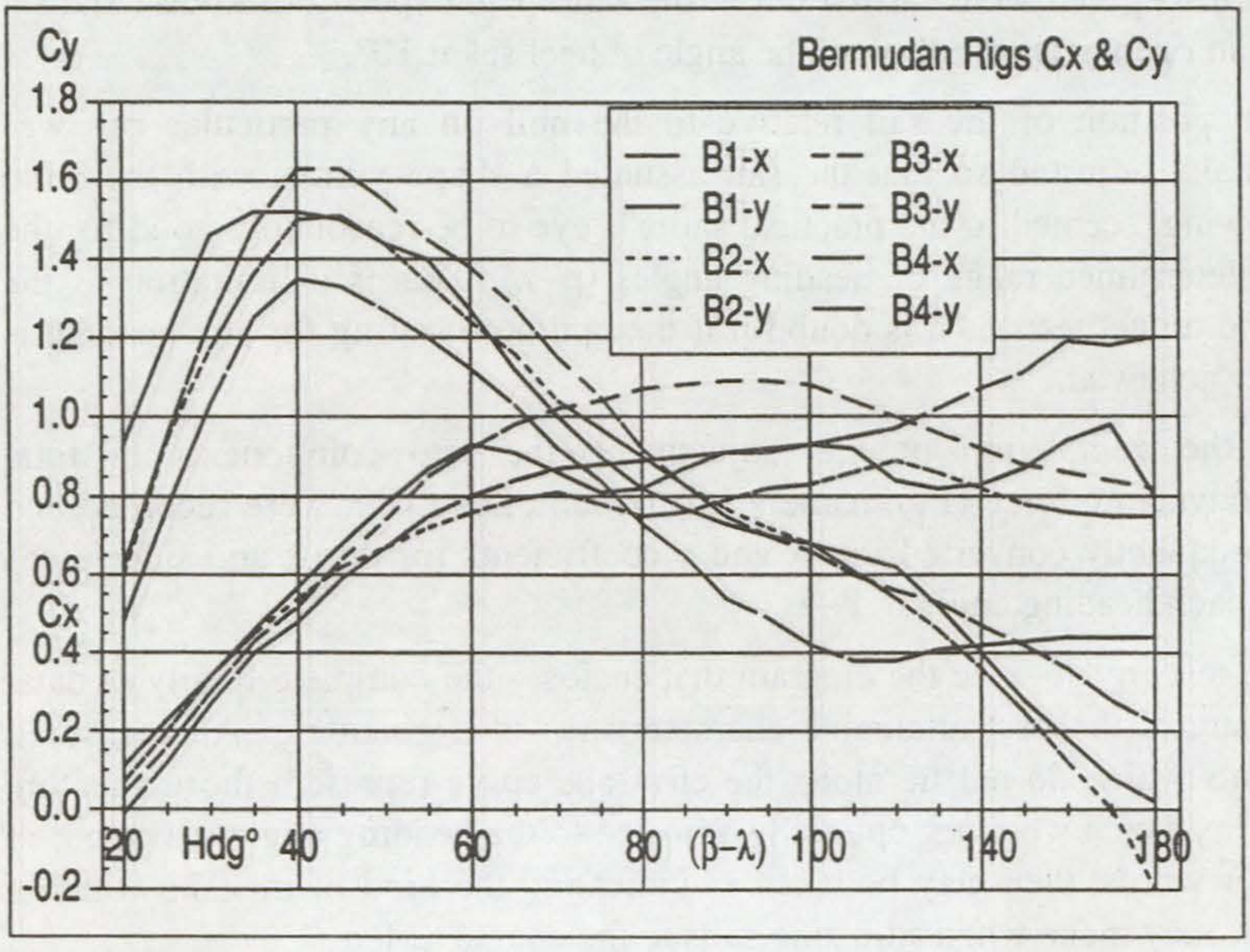


Fig 19

The Cx force is very similar up to 45° but there is a noticeable difference in the larger Cy, heeling, forces

The standard rig with small jib (B1) shows the largest driving force below 60°, but also has a higher side force at wind angles of less than 35°.

Above 60° B3 with its cut head (gaff) has a significantly better driving force at the expense of some additional heeling force.

Do not try to read too much into these figs, note the trends and differences.

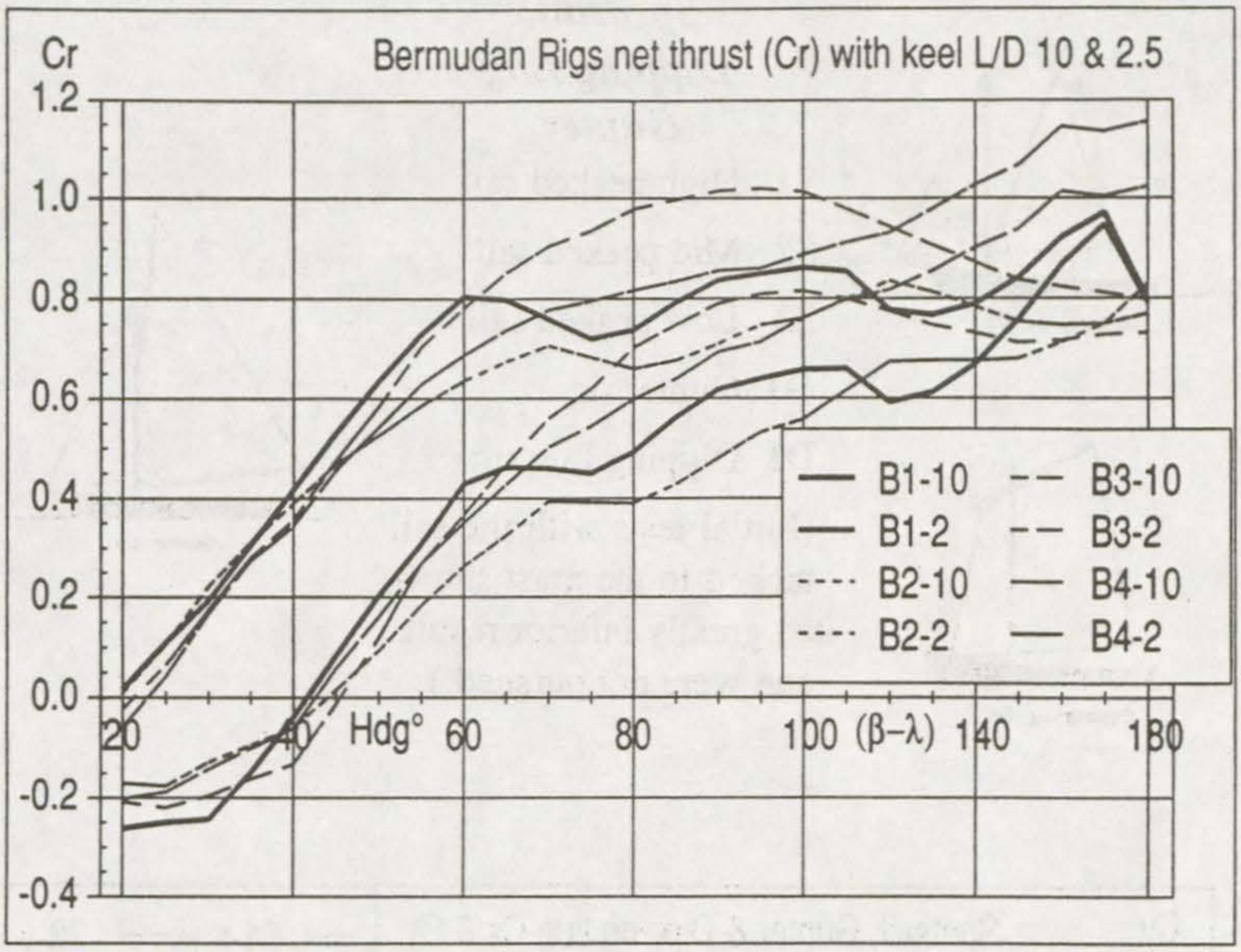


Fig 20

The net driving force of a rig is:

$$C_R = f.\ [C_x - C_y\ /\ {}^L/_D \text{ of keel system}] \qquad \text{[rpt. 9]}$$

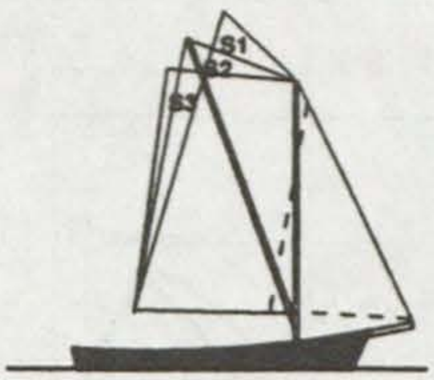
Or simply the greater is ${}^L/_D$(ks) and the lesser is C_y the greater is C_R.

The above graph plots lift drag ratios of 10:1 & 2.5:1. This represents the upper and lower limits of current production boats and approximates to a good cruiser racer and one of the less efficient bilge keelers respectively.

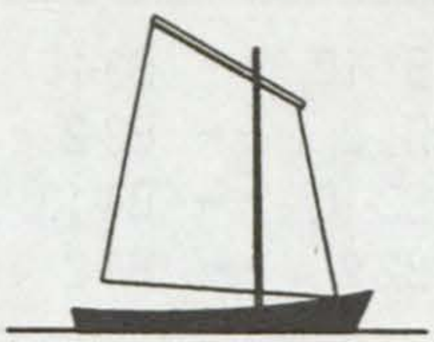
At 35° (β−λ) with an ${}^L/_D$ of 10 there is little significant difference in C_R, but with ${}^L/_D$ of 2.5 the rigs with high side force show themselves to limit performance, particularly to windward.

Between 70° and 120° B3 shows the superiority of the cut top or gaff rig for sailing off the wind.

The plain bermudan mainsail (B4) is superior only in the fully stalled running condition (120°+), when it best at exposing all its area to the wind, otherwise it does not appear to be a particularly efficient sail. This may in part be due to its smaller area (mainsail only) used relative to the fixed size of the hull in these tests.



Sprit Rig S1, 2, 3.


Dipping Lug D1

Spritsail, Dipping Lug Gunter

S1 High peaked sail

S2 Mid peaked sail

S3 Low peaked sail

G1 Gunter rig

D1 Dipping Lug rig.

(Initial tests with the sail tacked to the mast showed greatly inferior results and were not pursued.)


Gunter G1

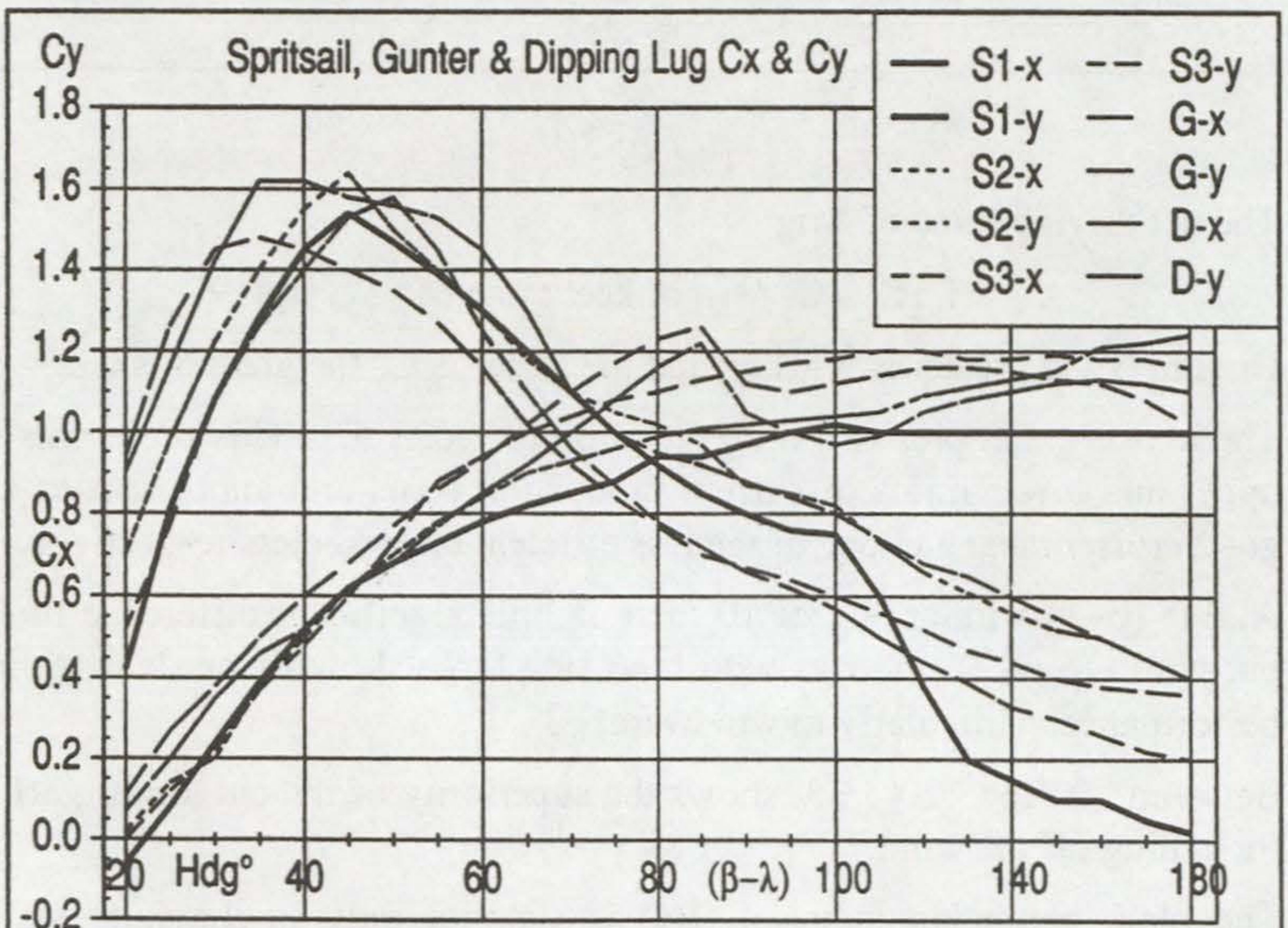


Fig 21

In figure 21 the gunter rig shows the best forward force up to 90° – the drop in the C_x line is where the flow starts to detached and the sail becomes stalled.

The dipping lug has a reasonable performance all round.

The three sprit rigs show very similar figures below 50°, despite the different head angles. S1 showing a higher side force. The relatively low C_x of S1-3 would appear to be due to the jib not being tacked to the stemhead.

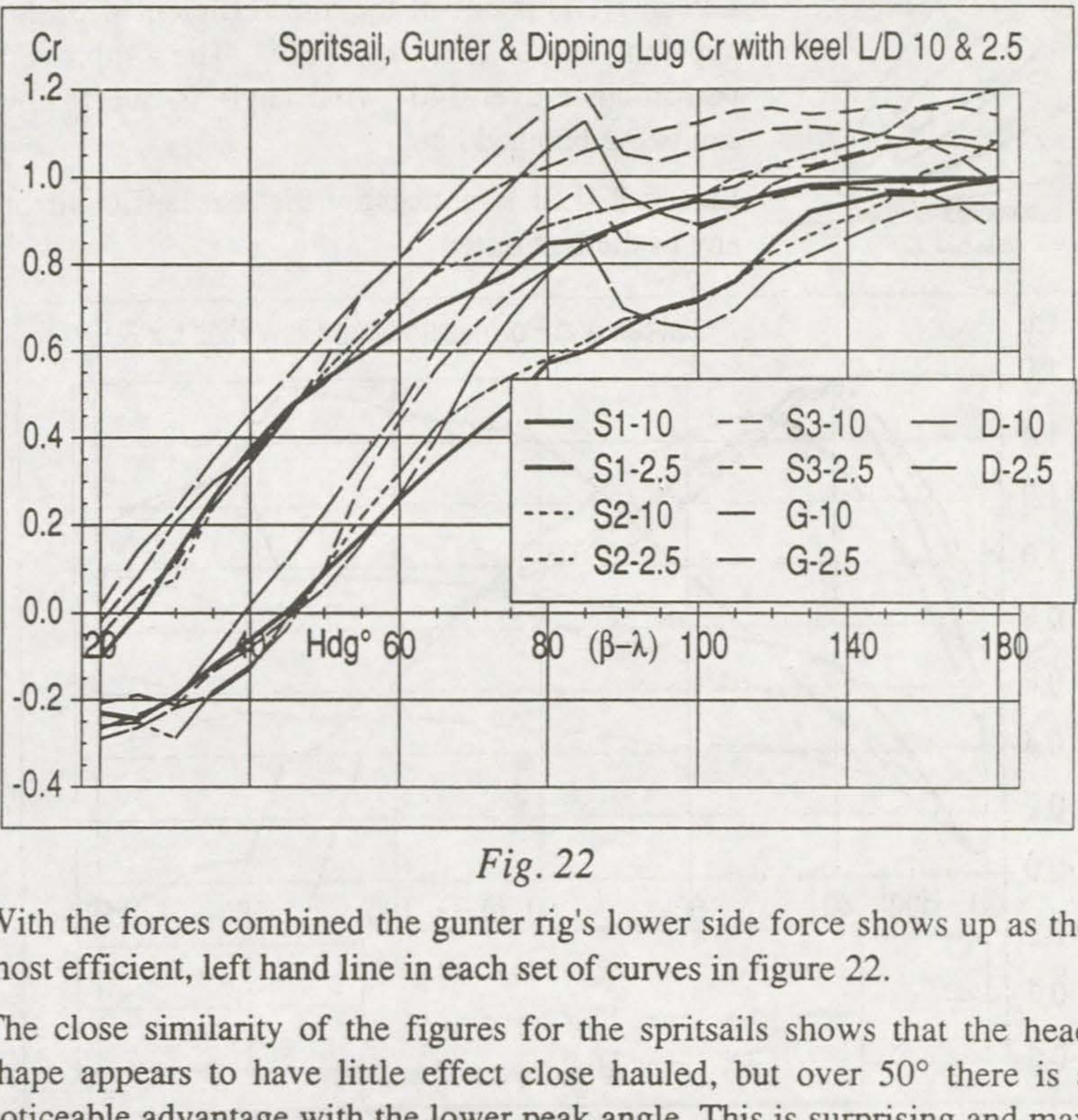
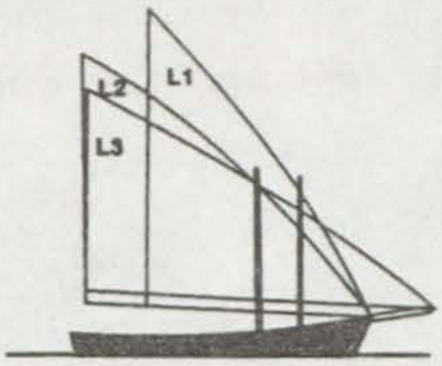


Fig. 22

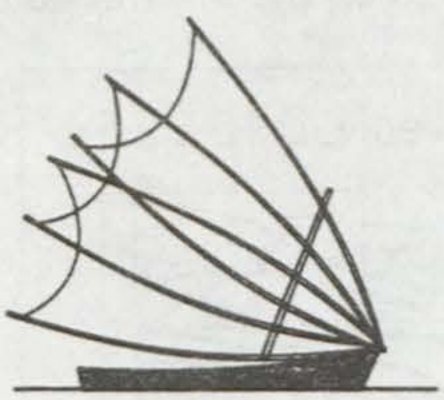
With the forces combined the gunter rig's lower side force shows up as the most efficient, left hand line in each set of curves in figure 22.

The close similarity of the figures for the spritsails shows that the head shape appears to have little effect close hauled, but over 50° there is a noticeable advantage with the lower peak angle. This is surprising and may be due in part to the fullness of the head of the sail tested – vortex formation can be delayed by too much fullness at the head.

All rigs show a marked divergence in performance with headings over 50°. This appears to depend upon the extent of the development of vortex flow around the edges of the sail.



Lateen L1, 2, 3



Crab Claw Cc.

Lateen and Polynesian Crab Claw rigs

These results cover the extremes of the rigs tested. The Polynesian Crab Claw rig has only an average performance closehauled, but outstanding when the apparent wind is between 50° and 150°; significantly greater than any other arrangement tested.

Lateen 1(L1) is one of the most efficient with the apparent wind less than 50°. The improved performance over 140° wind angle is due to the sail being boomed out.

Lateen 3 (L3) is noticeably the least efficient of any of the rigs tested.

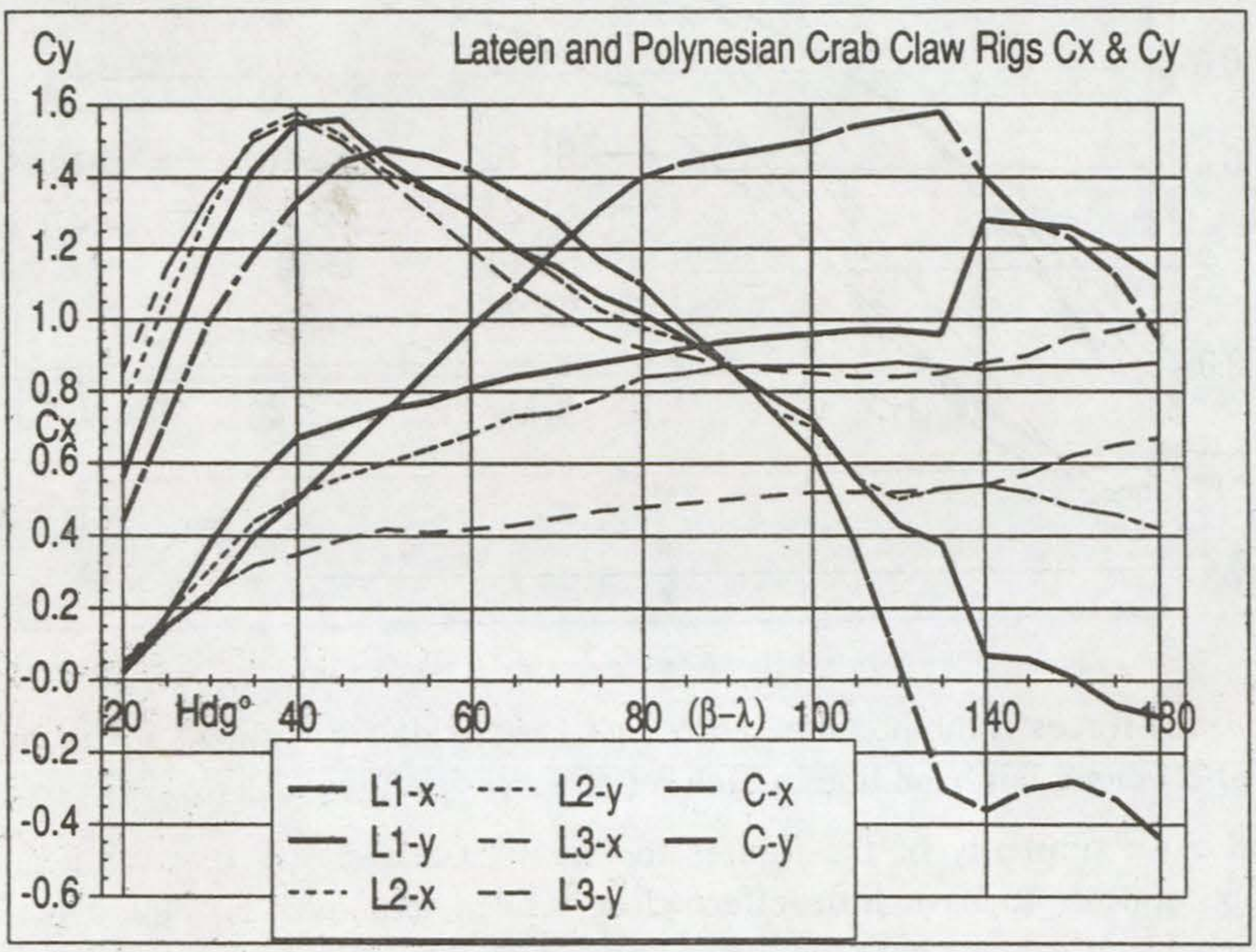


Fig 23

In figure 23 L3 develops a low forward force, but still has the same side force as the other lateen rigs. This would appear to be due to the excessive rake on the yard and not helped by fact that the yard was tacked down to a bowsprit rather than onto the bow.

All rigs with a sail not tacked on the bow showed reduced performance to windward. Going out on a bowsprit appears slightly worse than an inboard rig, but the lack of a deck in these tests obviously had some bearing.

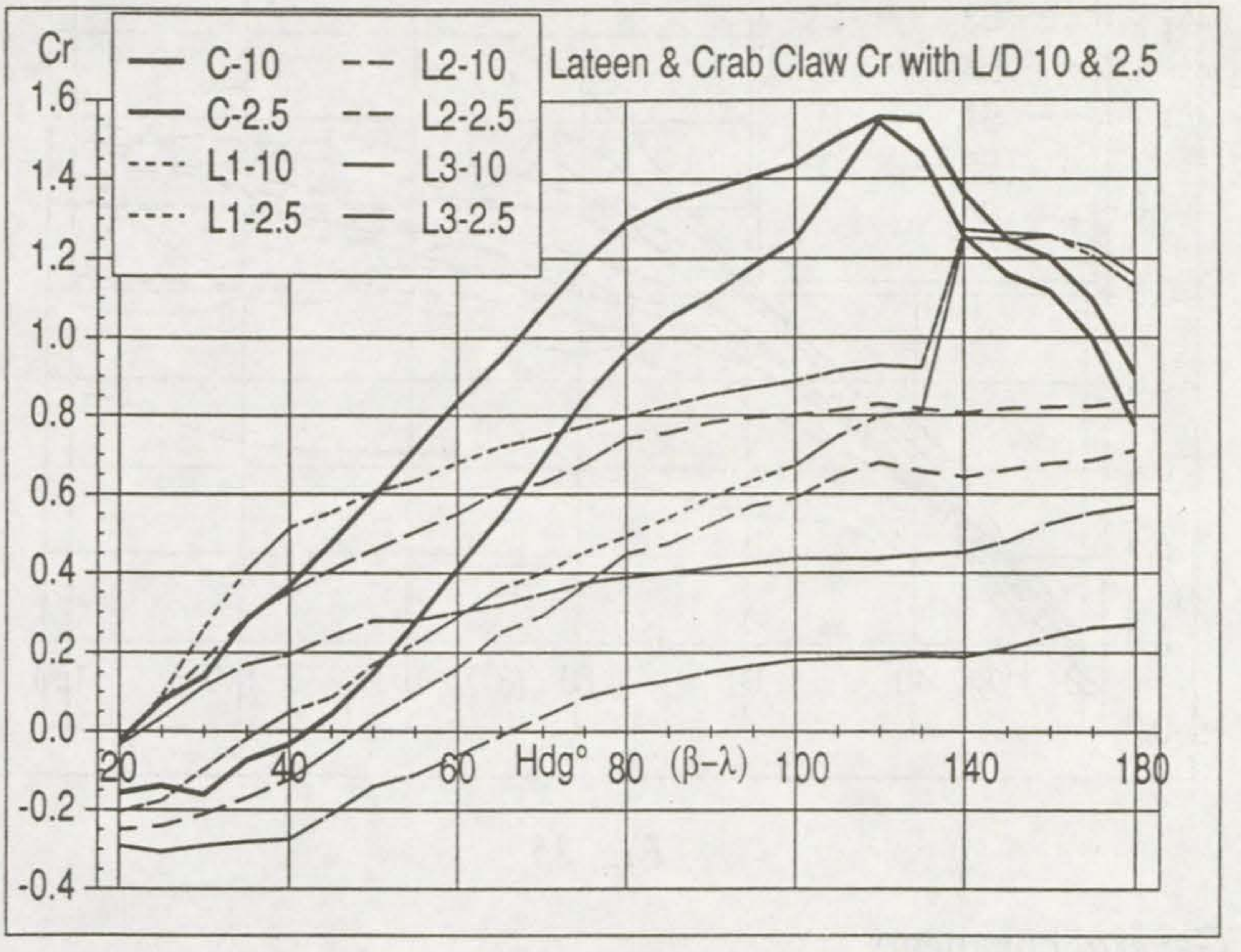


Fig 24

Figure 24 shows that to windward the Lateen proves the more efficient. This may be because the sail and hull interacted favourably aerodynamically. The raked tip also appears to help. Off the wind the lack of a boom appears to limit the vortex power.

L2 appears less efficient due to lower aspect ration and too much rake on the whole rig. The extreme of this is shown by L3.

With the heading greater than 50° the superiority of the Crab Claw rig is shown and the vortex flow remains fully developed up to 130° when the total force is directed straight forward.

When running dead before the wind the fully boomed out L1 is the most effective.

None of the rigs tested resemble the modern spinnaker. It would be interesting to compare their power with that of the Crab Claw rig. The indications from figure 16 are that their total forces, C_T are similar.

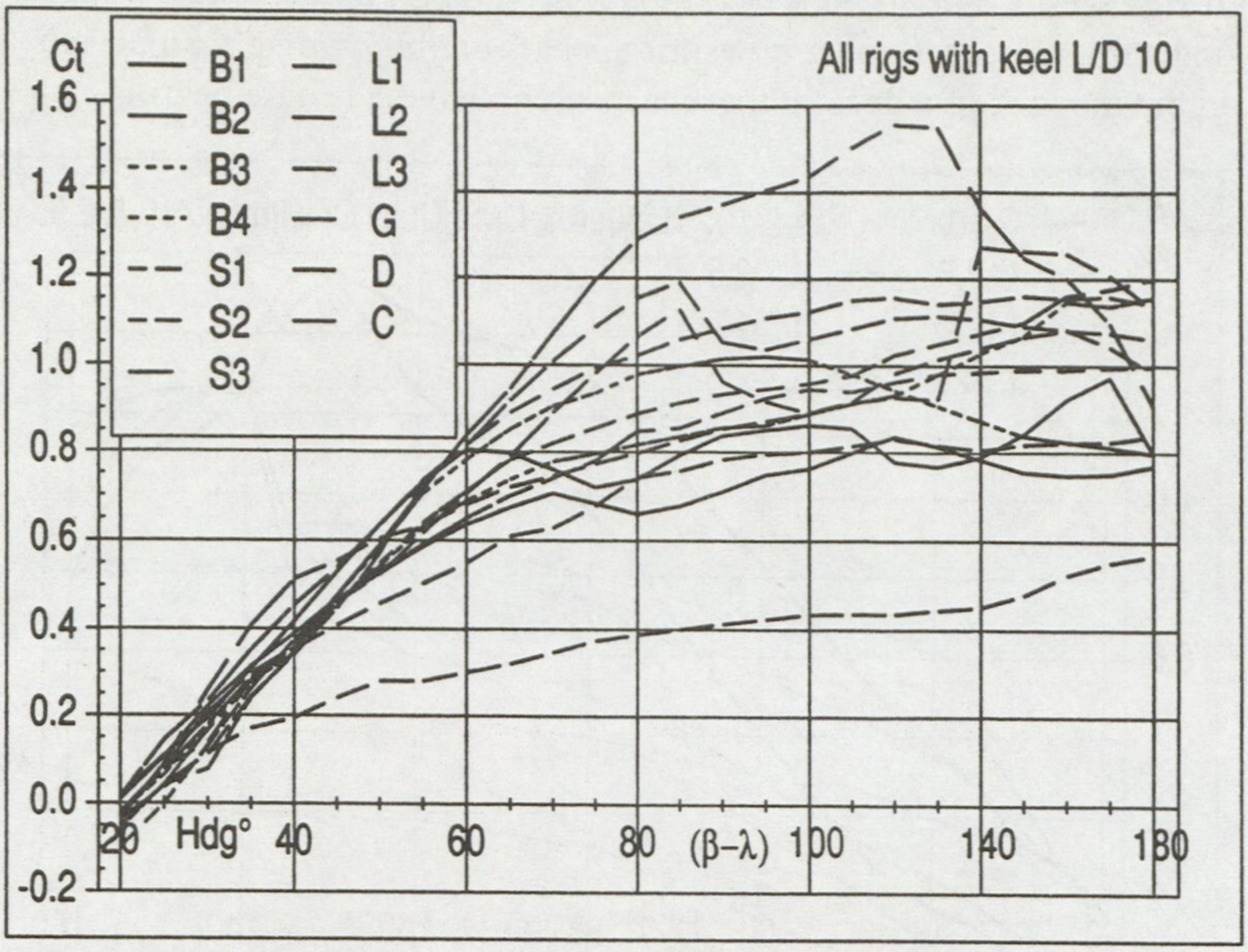


Fig. 25

General comments

Below 30° the results are closely bunched together. Since all the rigs tested had approximately the same height and aspect ratio we can see that planform shape has relatively little impact on windward performance (see figure 25). Fine tuning and the cut of the sails could have more effect than the difference between the good and the bad in these tests.

The Crab Claw rig predominates between apparent wind angles of 60° – 150°.

Lateen 1 is notably more efficient between 30° – 40° and above 150°, yet Lateen 3 is less efficient than any of the other rigs at all angles above 30°, but surprisingly at small heading angles the high angle of rake to the yard does not appear to inhibit the performance as much. Any reduction in windward performance appears to be due to the sail being tacked onto a bowsprit rather than the stemhead.

B1 (bermudan with small jib) surprisingly comes out best with the apparent wind between 45° – 60°.

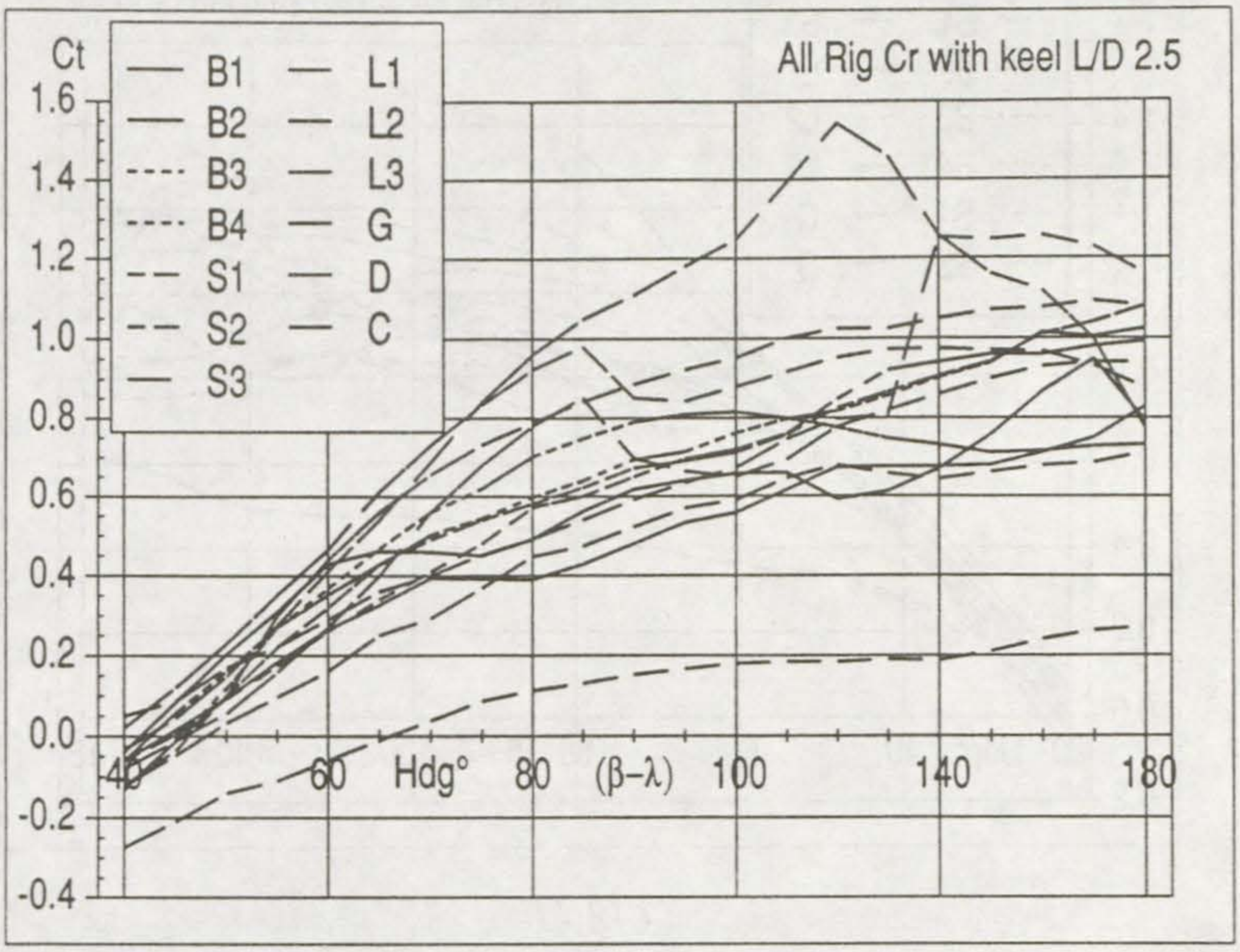


Fig 26

Figure 26 represents an inefficient shallow keel with a draft of probably less than 10% of the length and exaggerates the detrimental effect of a large C_y. Once again note the general trends rather than particular readings.

For wind angles below 70° the gunter rig (G) shows up as the most efficient and above this the Crab Claw (C), although it is not much less than the gunter (G) below this angle.

The boomed out spritsail is the most efficient sail above 140°.

Due to the high side force produced, L3 would fail to achieve any windward performance until the wind angle exceeds 70°. This is the kind of performance expected of a square rigger.

The high thrust of the Crab Claw rig at 120° is due to the fact that it produces minimal side force at this angle, *i.e.* the sail's total force, C_T is directly forward and no energy is being expended on the inefficient keel.

There is inevitably some error produced by the setting of the sails on each rig and it is more likely that the experienced test operators would set a single or conventional rig nearest to its optimum.

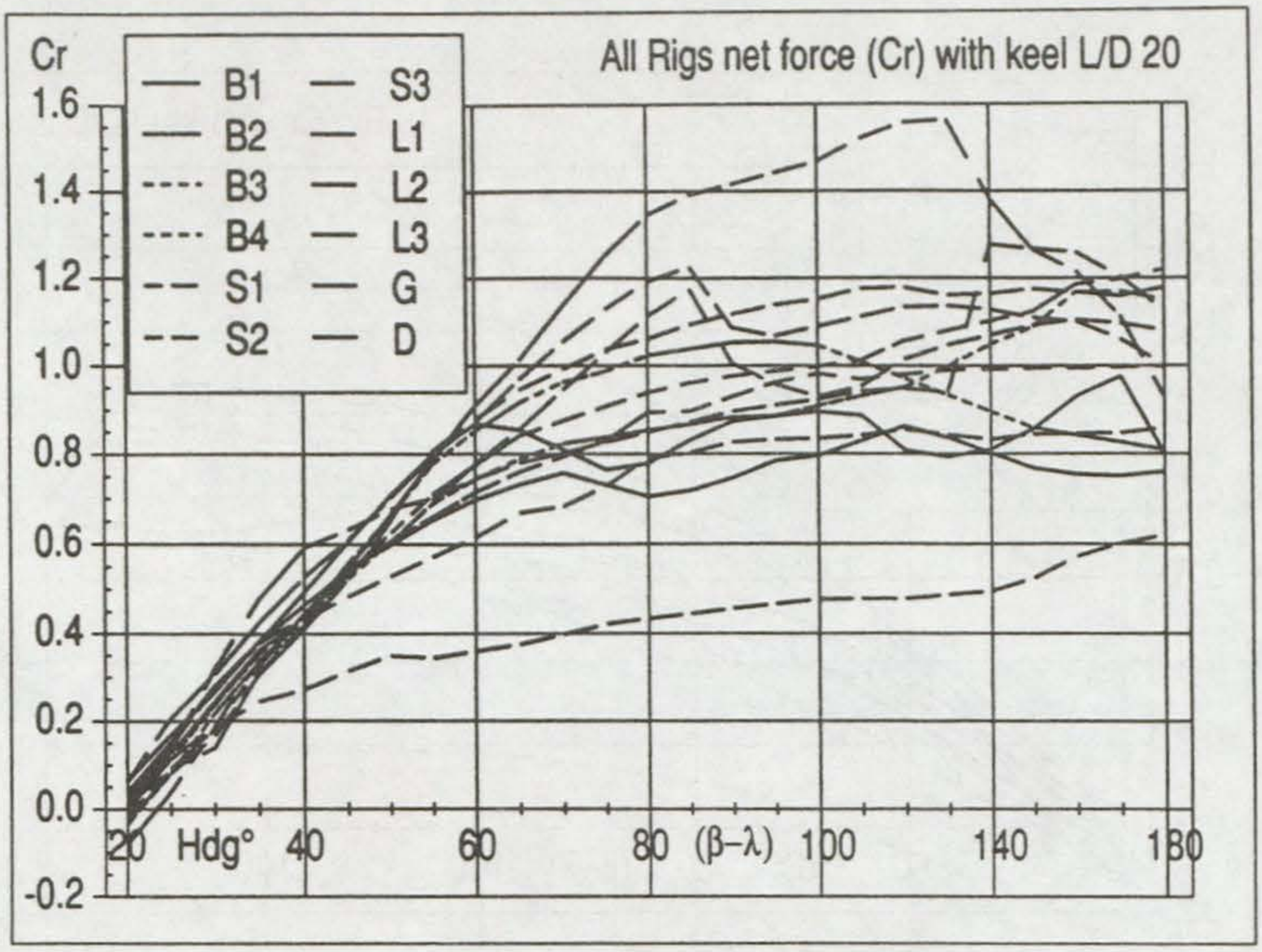


Fig 27

Figure 27 represents about the best possible foil system with the C_y force having minimum effect upon C_R. Once again the large spread above 60° is shown.

The gunter is best below 30°. The lateen rig is noticeably more efficient between 30° – 45°, and the Crab Claw from 50° – 150°,

Summary.

As with most testing, these results pose more questions than they answer, but by combining current racing experience with these tests we can come to some useful indicators.

These tests represent rigs with approximately the same height and aspect ratio, giving the results in coefficients, or force per unit area. The performance of any craft may be improved by increasing the height of the rig and/or the depth of the keel, within any allowable stability.

Windward. The air flow is of the conventional fully attached variety (as on a glider). The aim is for the best C_x/C_y ratio (not directly max. C_L/C_D).

The outline shape and the number of sails appears to be only part of the story. There are indications that a sharply raked tip appears to produce better results. A significant factor is the drag caused by the rig, hull and structure, as is the interaction between the hull and rig. Little is known about this latter point at present. The main point for windward performance appears to be more in the overall efficiency of the design with the outline shape for the sails only one of the factors.

The question of single or multi sails depends upon whether the mutual interaction between the them is beneficial or not.

It is difficult to set a triangular headsail efficiently in front of a wingmast as the sail twists the apparent wind onto the mast and therefore the wing mast ought also to be twisted to optimise the flow around it.

The maximum side force for all rigs is produced at around 40° – 50°.

The rigs that did not have a sail tacked to the bow proved to be significantly less efficient to windward. (A twin headsail cutter and similar rigs were not tested, being too complicated for small craft.)

The performance is improved by the presence of the hull under the rig, The rig L1 appears to match the test hull best, with the sail shape approximating to the hull. This rig produced the best overall windward performance.

Reaching. There is a notable difference between the performance of the various different rig outlines when the apparent wind is above 60°. The outline shape appears to have far more effect on reaching performance than it does close hauled. This requires near maximum lift (C_L) from the sails and although this can be obtained from multi-flap aerofoil systems, these test have shown that a C_L of over 2 is achievable with sails of aspect ratio 1. No similar test were carried out on multi sail rigs.

The best reaching performances are from the rigs that rely upon vortex lift and appear to differ significantly from the current style of racing sails which do not have edges optimised for the encouragement of vortex forces.

The lack of the hull directly under the sails significantly reduces the maximum forces achievable when reaching and running.

The performance of the Crab Claw rig was significantly reduced by the removal of the boom, making it little different from the Lateen rigs tested.

Running. The sails are fully stalled and the maximum area should be presented to the wind. If the craft is not travelling at its maximum speed it always pay to tack downwind to achieve maximum -VMG, that is sailing as deep as possible without losing the flow across the sails.

The effects of Camber, Leech Tension and Sail Outline

To investigate the influence of twist, camber and outline, S. Greenhalgh and H C Curtiss Jr. tested a series of rigid sails made from thin sheet metal, fitted to a 36" (914mm) mast in the Princeton University 4' x 5' wind tunnel. With the sails made from flat metal sheet all the shapes tested were by necessity only conical developments. This limited the subtlety of the sections and could therefore be compared with the simple sails used in the set of C A Marchaj tests reported on previously.

While the two-dimensional or sectional characteristics of membrane lifting surfaces has been the subject of many investigations, there is little experimental data on the aerodynamics and dynamic characteristics of single lifting membrane surfaces in general and no experimental data or theory for membrane lifting surfaces formed from a sheet of inextensible flexible material.

Since the sail is made from flat sheet material the curve of the sail must be a part of an imaginary conical surface, and this leads to the conclusion that only two controls are required to define the shape. The camber distribution at the boom and the position of virtual apex of the imaginary cone, which controls the leach tension. This latter was done by adjusting the rake of the mast by small amounts.

The basic formula for the local chord (width) of the shapes tested is:

$$c = (1 - y^a)^b$$

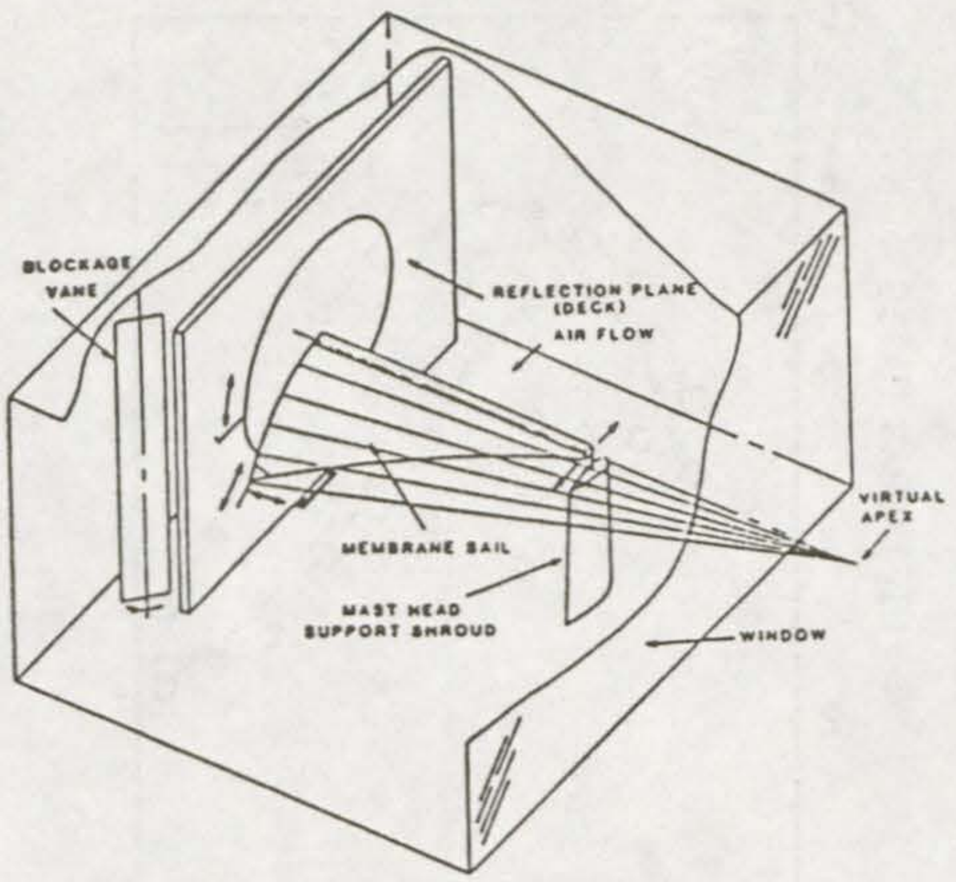
For a triangular shape a=1, b=1, parabolic a=1, b=.5 & elliptical a=2, b=.5

Mast section 1.4" (3,5 cm) x .57" (1.43cm)

Reynolds number used was 7.10^5, based on a foot length of 13.4" (43 cm).

The elliptical shape showed signs of distortion at the upper trailing edge at high lift conditions. This is exactly the same problem experienced when trying to control a large amount of roach on a fully battened sail.

An interesting point that comes out of these tests is that there is little or no penalty for small amounts of twist and that the triangular sail is not as bad as some try to claim. Since sails with twist and triangular form have a lower centre of effort than that of an elliptical or parabolic shapes, any small reduction in efficiency is generally more than compensated by the reduced heeling moment – a taller rig with less induced drag may be used for the same heeling moment.



EXPERIMENTAL SET-UP

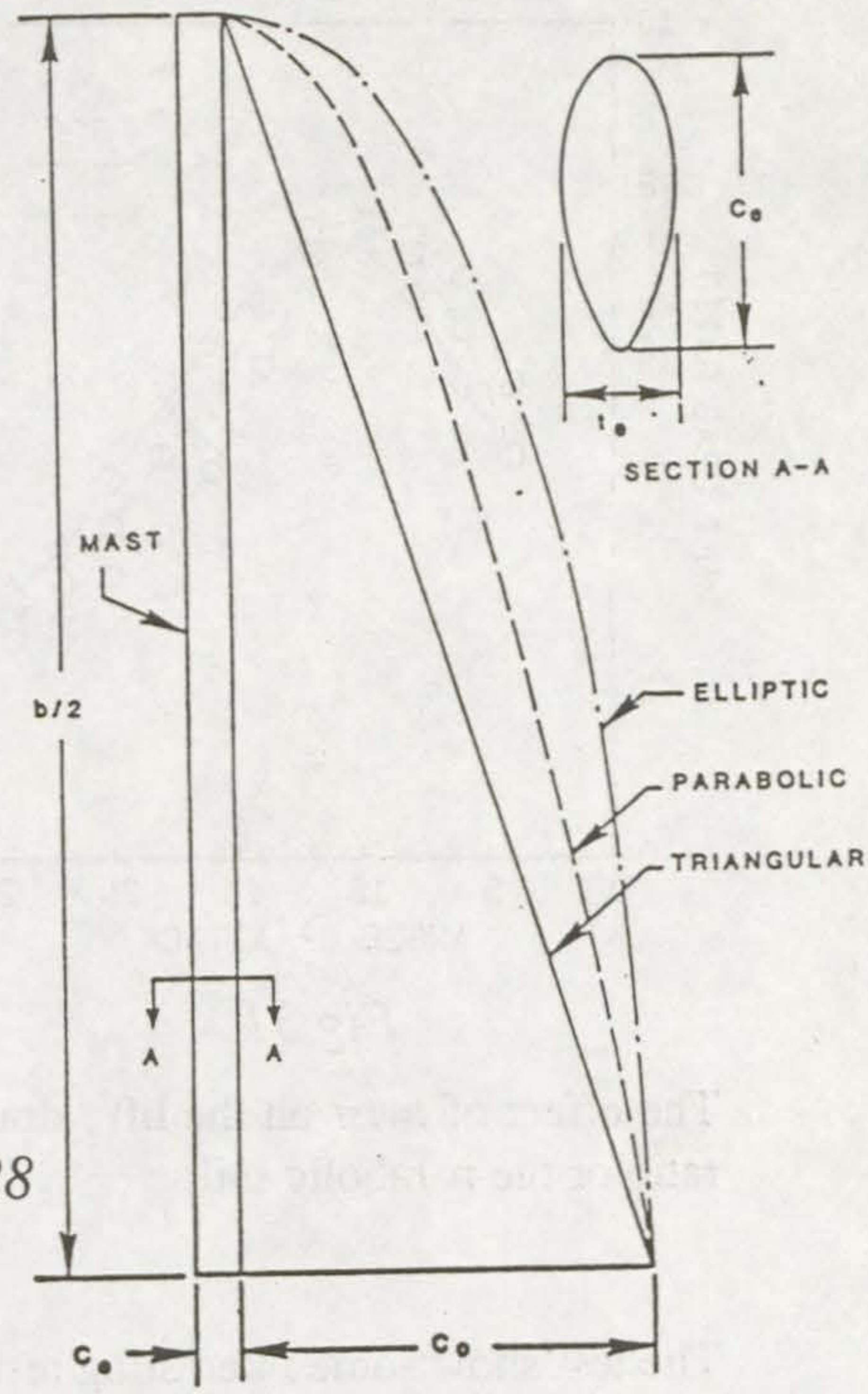


Fig 28

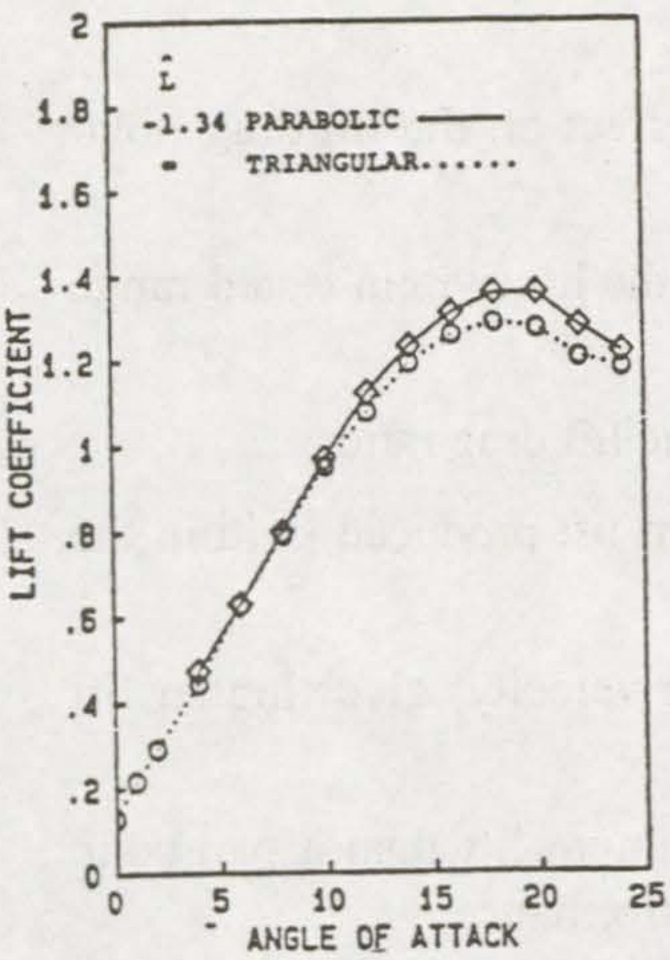


Fig 29

Lift comparison of the parabolic and triangular sails.

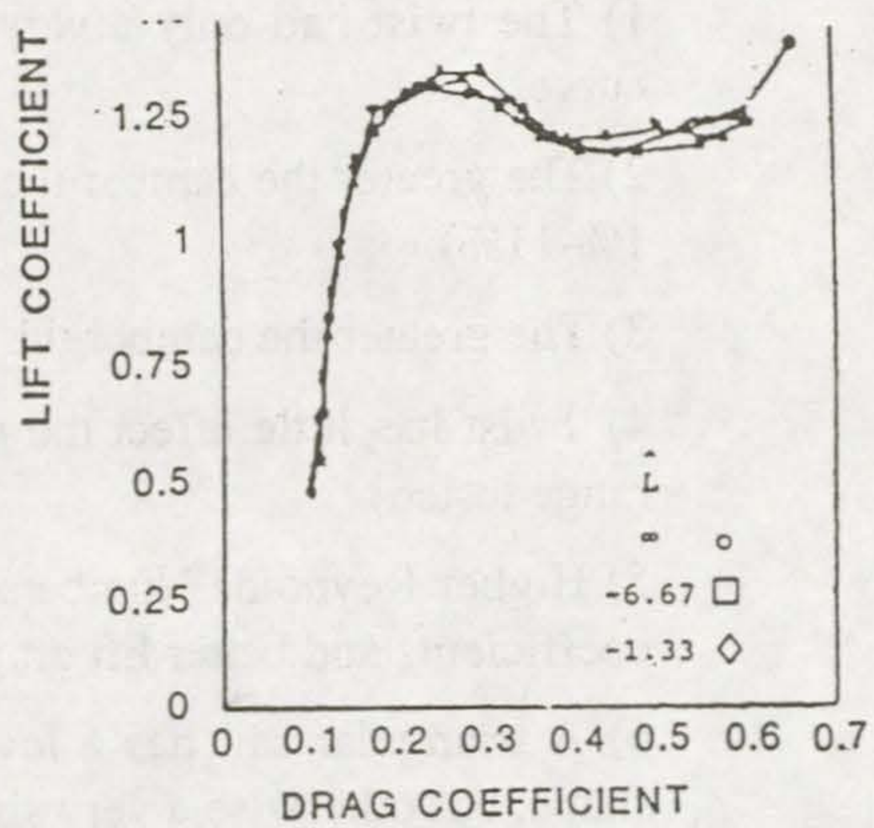


Fig 30

Polar curve for the parabolic sail with varying amounts of twist.

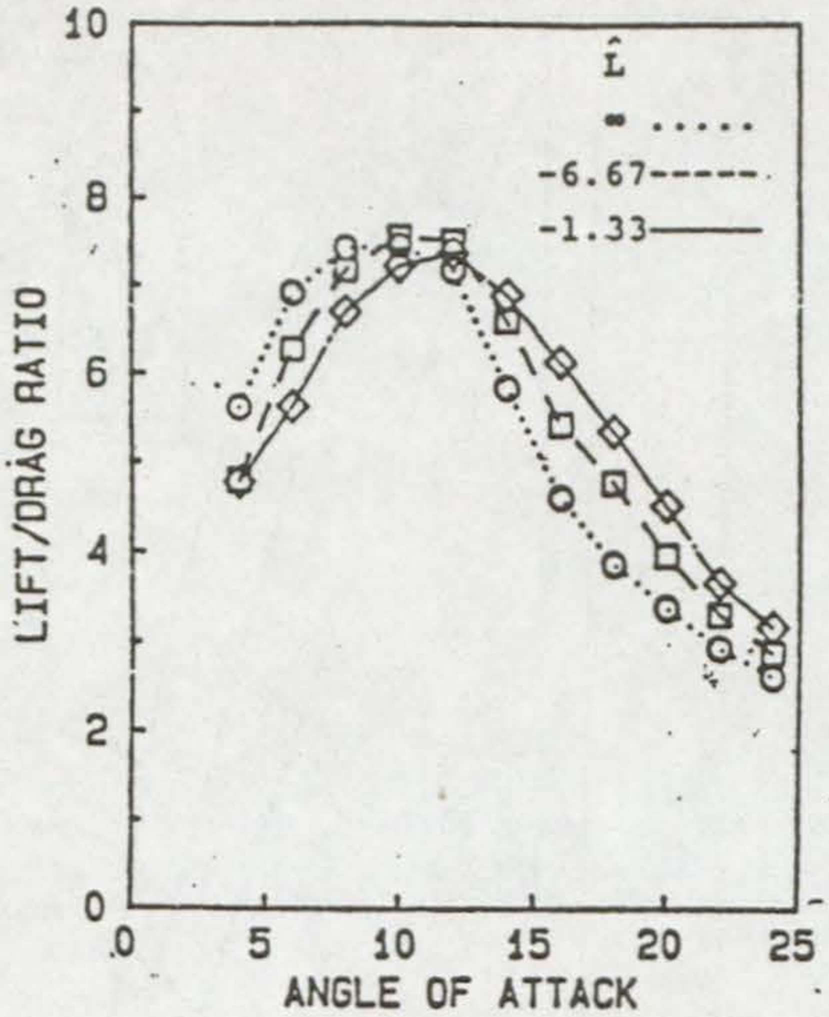


Fig 31

The effect of *twist* on the lift / drag ratio of the parabolic sail.

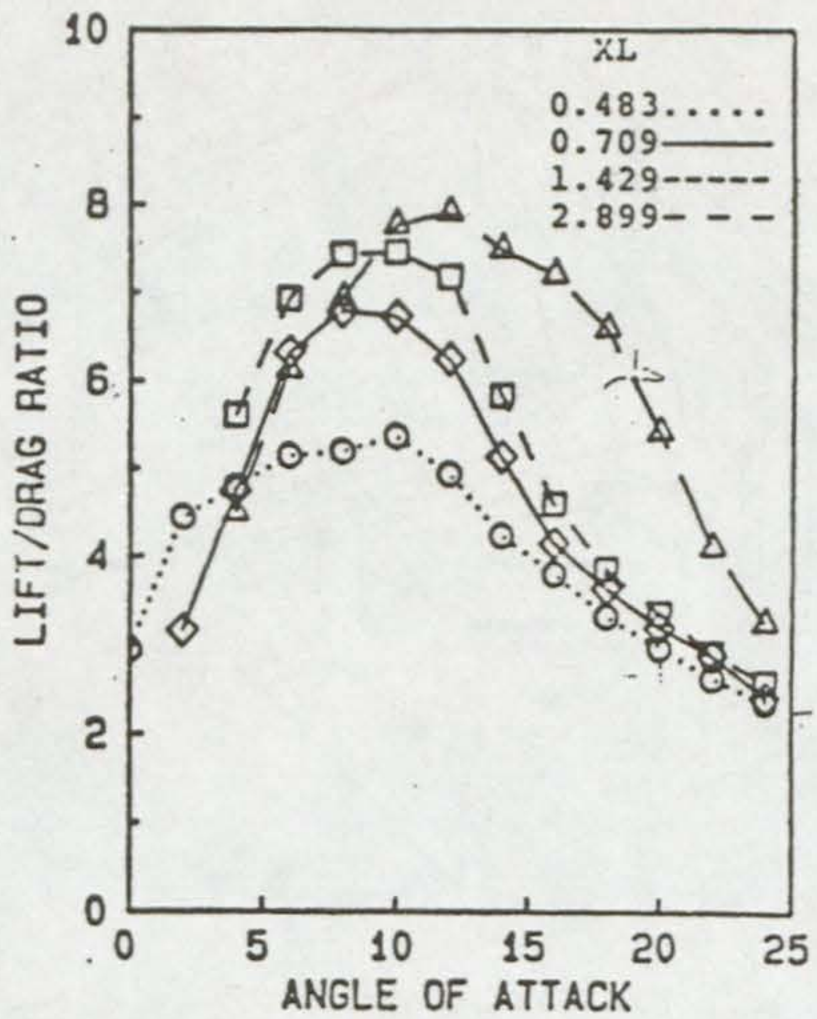


Fig 32

The effect of *camber* on the lift / drag ratio of the parabolic sail.

The test show some interesting results:

1) The twist had only a very small effect on the lift/drag polar curve

2) The greater the camber the greater the lift (within tested range 1%-11%).

3) The greater the camber the better the lift drag ratio.

4) Twist has little effect the maximum lift produced (within the range tested).

5) Higher Reynolds Numbers (greater velocity) gives higher lift coefficients and better lift drag ratios.

6) A triangular sail has a lower maximum lift than a parabolic shape, but otherwise a very similar performance.

RIGS FOR LARGER CRAFT

Hamburg INDOSAIL wind tunnel tests, by Peter Schenzle.

The selection of an appropriate rig for the INDOSAIL trading vessel project was supported by an extensive wind tunnel test programme. The sail models were made from sheet metal, with a 15cm (6") chord. Rigid models were used to achieve a Reynold number of 4.10^5

The sail types investigated were: almost rectangular gaffs, triangular Bermudan mainsails and staysails with variations. The main variation was the shaping of the leading edge at the mast, from the rotatable mast as an integral roller reefing (*mast roller*) via the simpler roller reefing behind the mast (*roller sail*) to the freely tensioned roller between an 'A' framed mast. For comparison special devices were also investigated such as different rigid symmetrical aerofoil wings and a Princeton sailwing.

Complete rig models were tested to investigate the interference effect on various multimast schooner rigs. In the first series of tests with one to four masted models with idealised mast roller (gaff) sails, the effect of the number of masts was studied. The influence of the details of sail and mast type were investigated in a second series of three masted models with roller sail rigs as Bermudan, staysail schooner and gaff sailed schooner with central and 'A' frame masts.

By increasing the number of masts from two to four the best close hauled apparent wind angle increases by only about 2° per additional mast, probably due to the lower effective aspect ratio of the total rig. With the apparent wind between 70° and 90° the tendency is reversed with the maximum driving force increasing more than the increase in sail area when increasing the number of masts.

In broad reaching conditions, the driving force coefficients are practically independent of the number of masts. The greater blanketing effect with more masts when running downwind is not important when there is enough open water to make it practical to tack downwind (but persuading the crews to do this is another matter).

The surprisingly favourable performance properties of multimast rigs are possibly due to the total sail area being subdivided into a system of leading edge slats (foresails & jibs), main wing (mainsail), and one or more slotted trailing edge flaps (the following sails), in much the same way as a modern aircraft wing behave during landing. Here also the angle of each element is carefully adjusted to the local flow conditions in order to delay the flow separation of the whole system and achieve a higher overall lift coefficient.

Note the poor performance of the single masted (racing?) sloop rig in nearly all conditions, particularly in reaching (β = 50° to 130°). This once again shows why the spinnaker had to be adopted along with the introduction of the Bermudan rig to maintain off-wind performance. Only dead down wind is the single masted rig the most powerful!

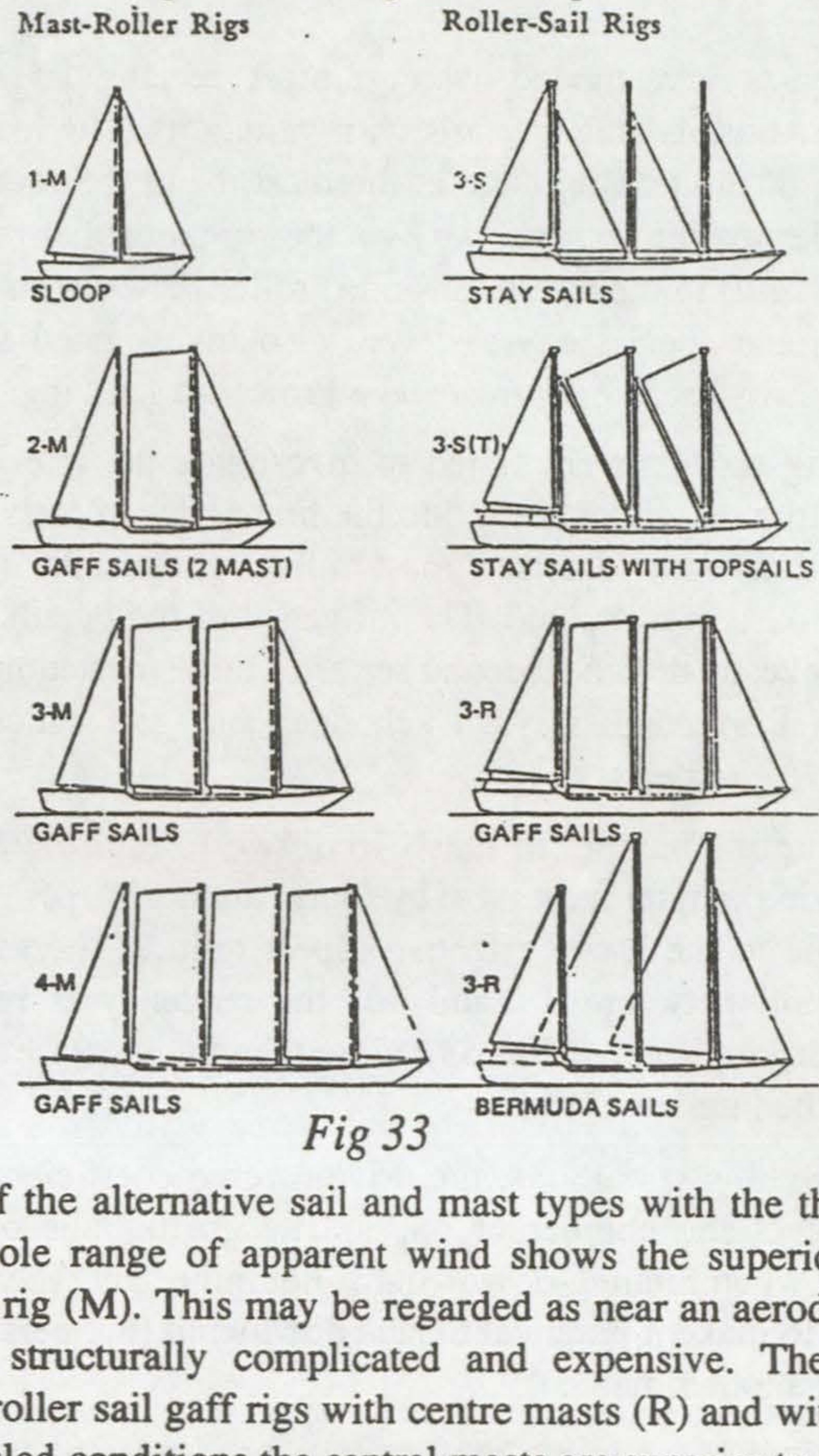


Fig 33

A comparison of the alternative sail and mast types with the three masted rig over the whole range of apparent wind shows the superiority of the clean roller gaff rig (M). This may be regarded as near an aerodynamically ideal case, but structurally complicated and expensive. The next best variants are the roller sail gaff rigs with centre masts (R) and with 'A' frame (A). In close hauled conditions the central masts are superior to the 'A' ones due to lower drag, while in reaching condition the removal of the interference of the mast on the leading edge gives better results.

Presumably both rigs might be improved by using profiled mast sections, but the slight superiority of the central mast in close hauled conditions would still be expected. The staysail (S) and Bermudan rigs (B) follow, but neither could be recommended for efficiency on the basis of this series of tests.

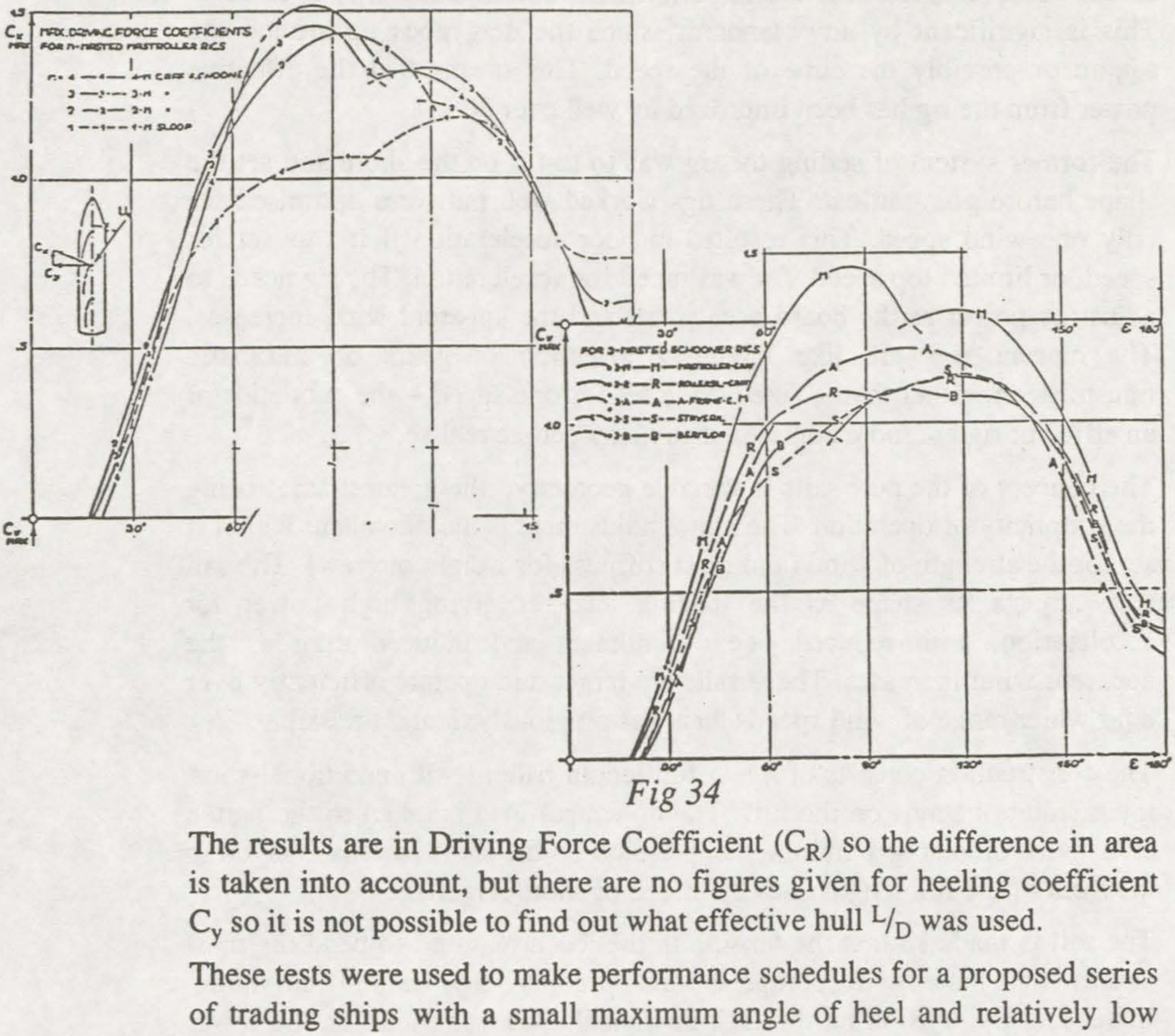


Fig 34

The results are in Driving Force Coefficient (C_R) so the difference in area is taken into account, but there are no figures given for heeling coefficient C_y so it is not possible to find out what effective hull $^L/_D$ was used.

These tests were used to make performance schedules for a proposed series of trading ships with a small maximum angle of heel and relatively low stability. These results show the same general differences between all the tested rig configurations.

The superiority of the multi mast rigs is partly due to the low righting moment available at the limiting angle of heel of 10°. The conventional yacht has much greater stability for its weight than a sailing cargo vessel and can therefore carry a taller rig. The low multi mast rigs are appropriate for limited stability cruisers and motorsailers.

Developments in Sailboard Rigs

There have been subtle changes in the performance of sailboard rigs in recent years. Whereas these details may have been overlooked by the casual observer it has resulted in performance improvements of over 20%. This is significant by any standards, since the drag goes up around the square or possibly the cube of the speed. This means that the effective power from the rig has been improved by well over 50%.

The former system of setting the rig was to test it on the shore and set the shape before going afloat. These rigs worked well but were optimised for only one wind speed. This resulted in poor acceleration if it was set for speed, or limited top speed if it was tuned for acceleration. The rig needs to adjust its power as the board accelerates and the apparent wind increases. The current rigs are like having a selection of gears or automatic transmission, rather than a fixed drive set for one speed – the subtleties of an efficient rig are more complex than many people realise.

The concept of the new sails is variable geometry, the greatest asset being the simplicity of operation. The major adjustment is the downhaul which is set for the strength of wind (and mast stiffness for weight of crew). The sail then adjusts its shape as the loading changes giving high power for acceleration, with reduced heeling moment and induced drag as the apparent wind increases. These sails are larger and operate efficiently over a far wider range of wind speeds than was previously thought possible.

The construction consists of 4 – 5 full length battens with additional short intermediate battens on the luff. The downhaul load is taken to the batten ends by tension straps and the compression on the short battens is taken to the front of the full length ones by means of short diagonals.

The sail is made so that the tension in the leech required to bend the mast causes the battens to compress and produce the desired curvature. Increasing the tension on the tack downhaul causes the load on the lower battens to increase and to reduce that of the top ones. This induces a twist which off loads the head, reducing both heeling moment and induced drag. The flexibility of the whole system is adjusted such that a near constant heeling moment can be achieved. Interestingly the clew outhaul to the boom now has little or no preset tension. All the shape control is with the very powerful downhaul.

The leading edge of the rigs has also been improved with better fairing on the lee side with the help of rotating batten supports. The short intermediate leading edge battens are to improve the shape and rigidity of the forward sections. This prevents vibration in the leading edge fabric which has been shown to reduce performance.

For light winds, moderate downhaul is applied until the luff panels become just taut. This sets the sail with a draft that continues right up to the head and results in a rig with a feeling of power in it. This setting will get you planing as early as possible and gives excellent acceleration – the maximum force is produced by the rig.

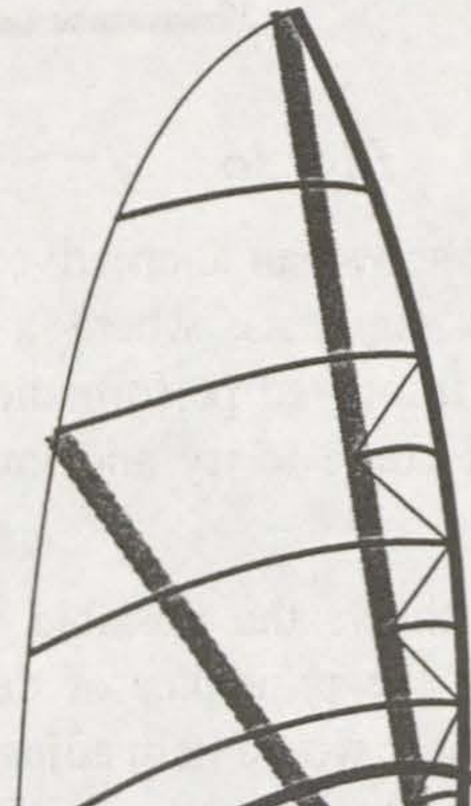


Fig. 35

For medium winds where you expect to be fully powered up *(stability limited)* the downhaul is loaded up until the head of the sail flattens and the leech begins to open *(fall away)*. With this setting the sail will de-power at the head whilst generating maximum drive. The result will be high top speeds and the sail will feel light and effortless to use as it adjusts automatically to the gusts and lulls.

When the wind really blows just crank on the downhaul (over 100kg) and the leech falls away further at the head to shed excess power and minimise drag. The sail retains its shape by the wishbone boom and all the power remains low down enabling a larger sail area to be used in strong conditions. These are in effect semi-automatic compensating rigs.

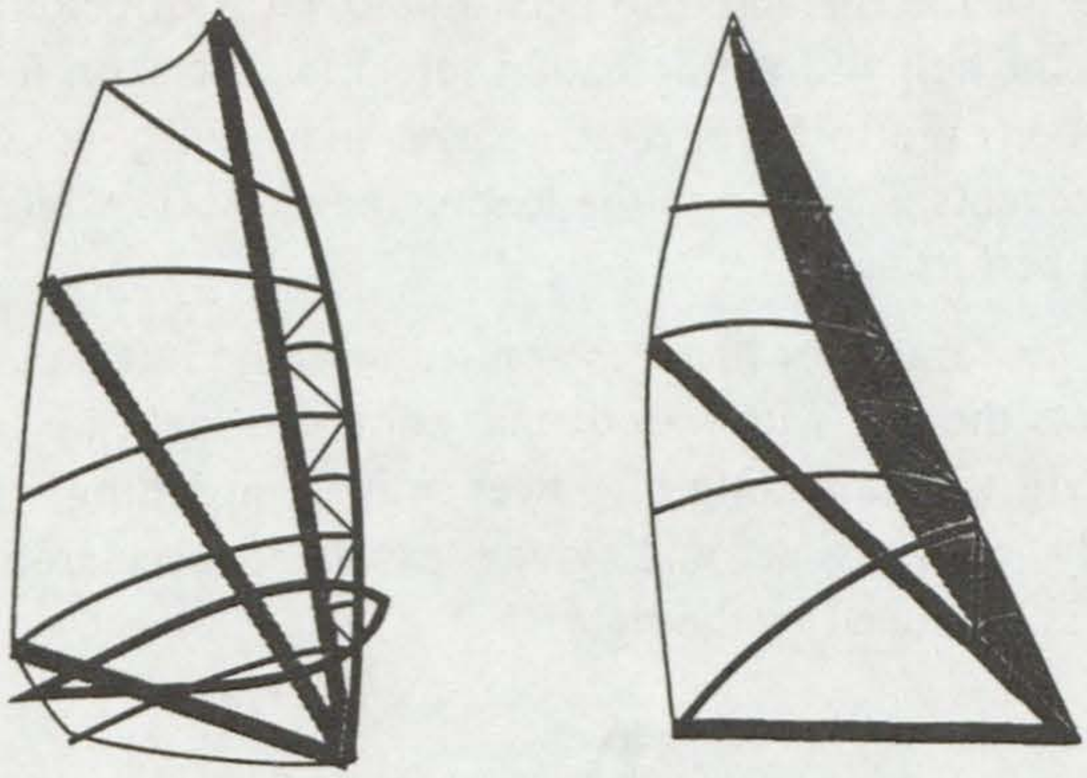


Fig. 36

The drawing above on the left shows an alternative top batten arrangement suggested by the Crab Claw rig tests, where a hollow leech and the separating of the tip vortices improved performance. The current style of head where there is a convex curve to try and imitate an elliptical tip is possibly a mistake.

The sail on the right above shows the possible construction of a fully battened self-tacking jib using the principles of the current sailboard rig. The angle and tension in the sheet would help adjust the camber in the sail. The problem is in lowering and stowing such a sail.

The sailboard has a very limited righting moment and therefore the rig has been developed so as not to overpower the sailor. Using this type of rig on a more stable craft would require everything to be very much stiffer and the initial tensions would then become very much greater, requiring a fundamental change in rigging practices – this may come. It should be remembered that in essence a rigid rig is more efficient and it is only to prevent overpowering that flexibility becomes an advantage.

The sailboard and the crab claw rigs both operate variable geometry in that the rake of the rig is altered when sailing. Being able to adjust the power from the rig as the apparent wind strength and direction varies gives a significant advantage over the more rigid types of rig and wing sail. Noting that more power needs to be developed from the rig while accelerating than for maintaining high speed. With modifications it should be possible for the performance lessons learnt with sailboard rigs to spill over into the rigs and sail plans of larger craft.

SUMMARY OF CONCLUSIONS

The following conclusions may be stated.

–Modern rigs have relatively poor performances off the wind.

–The Bermudan sailplan is by no means the optimum shape for an all–round efficient rig and spinnakers are not necessarily the best shape for developing maximum power.

–There is relatively little difference in the performance closehauled with different profiles and an efficient keel.

–The Crab Claw rig was outstanding off the wind and appears to have an acceptable performance to windward. This rig may be de-powered (reefed) by bringing the spars closer together, reducing vortex development and the exposed area.

–Multi mast rigs can be more efficient than a single masted one, particularly with limited stability and when reaching.

–The faired mast–sail combination has noticeably less drag and a gap between the mast and mainsail reduces performance.

–The position and style of the rig relative to the hull appears to have an important effect on efficiency and power produced.

–Booms and spars can have a very beneficial effect on sails. It is particularly important that the head and foot of sails do not vibrate, as this reduces the stability of the tip vortices.

–In the quest for greater boat speed, both sails and hull are interdependent, and neither is more important than the other. It is most rewarding to try to improve the aspect which is least efficient. All craft and crew have scope for performance improvement.

–The triangular planform sail is not the most efficient. These tests have shown that it is possible to dispense with a significant portion of the head of a Bermudan mainsail and increases the off wind performance. A rectangular or trapeze-oidal shape could be more efficient.

–Low AR sails maintain attached flow to high angles of incidence, giving higher lift, at the expense of also having high drag (but with low heeling moment). This is particularly evident in the Crab Claw sail.

–Near to every surface which is immersed in a moving fluid such as air or water,there exists a boundary layer of fluid retarded from free flow by friction. This influences the pattern of flow over the surface and adjacent areas. A foil operating in a free stream of air (or water) may generate beneficial vortices from both ends If a properly designed end plate is added to the foil, the effective AR may be increased, improving L/D. If, however, a mainsail is made in the form of a so–called '*deck scraper*', its AR is not doubled by the end plate effect of the deck as previously thought, because the lower part of the sail operates within the boundary layer of the deck (not to mention the additional turbulence caused by the deck structures). This may cause premature separation of the flow over the remaining part of the sail through degeneration due to the development of cross flow towards the sail head. In other words, two–dimensional or ideal flow is not possible over that part of a foil which is attached to any surface where a pronounced boundary layer exists. This holds good for a mainsail near to the deck, or a spade rudder in close proximity to the hull. The jib attached to the bow is forward and above the start of the hull's boundary layer and so it has proved practical to have a deck scraper stemhead headsail.

–A sail which is twisted more than 10 degrees begins to lose efficiency, but also has less heeling moment. Where excessive twist (up to 70 degrees) exists, 50% more power can be regained by reducing the twist, and also using a jib to improve the flow around the mast.

–When close hauled there is little or no driving force coefficient to be gained through increasing sail camber much beyond 10%. The sails should operate at optimum C_x/C_y for the heading and keel efficiency.

–Any boat has a maximum allowable heeling force. When the total wind force causes this to be reached for a given sail, reduction in camber will reduce drag. Twist will reduce heeling force. Thus, rig and sails need to be flexible so that camber and twist may be controlled to allow for the variations in apparent wind.

–Practical methods of reducing sail area are required.

–Besides the effects of scale there is the absence of wind gradient and the absence of an undulating sea in a wind tunnel, wind tunnel predictions may not always be the same as full size practical results.

–Spars at the top and bottom of the sail appear to be beneficial, particularly when away from close hauled, as they can produce beneficial tip vortices. The positioning and style of the halyards and sheets should not interfere with this end flow, otherwise the powerful vortices could be punctured.

–The Crab Claw rig has an interesting variable geometry aspect to it. It was found to be at its most efficient to windward when in a raised position, for reaching lower and more horizontal. The former appears to be best because of the increased aspect ratio and attached flow and the latter because of vortex lift is available from the rigid low aspect ratio foil.

–Modern racing rigs with their voluminous spinnakers produce performance, but the indications are that they may not be efficient on the basis of area, spinnakers would appear to be the wrong shape to produce the most powerful vortex lift. There is scope for a new style of off the wind sail that produces good vortex flow.

THE FUTURE

Sail Outline. Triangular (Bermudan) mainsails and jibs by no means represent the optimum shape The ellipse can be considered near the theoretical optimum, when heeling moment is not important; rectangular or trapezoidal sails more nearly reproduce its associated pressure distribution (and hence downwash velocity). The Lateen and Crab Claw rigs are shown to have a good basic performance, but have drawbacks for short tacking. The sprit sail is basically rectangular but, like the Bermudan, it has relatively large twist and uneven camber. Some thought should be given to better control of the setting of the sails on these types of rigs.

Crab Claw Rig. The efficiency of the Crab Claw (which offers control of twist and excellent tip vortex properties) was so marked that it was decided to undertake further research specifically into this rig. Four new model sails were made, with varying leading and trailing edge profiles. A cut–out concave leach appears more effective than a straight one as it encourages the main trailing vortices to spread towards the ends of the spars. The further the tip vortices are apart (increased span) the lower the induced drag.

It will be seen from the graphs that the Crab Claw rig is generally superior to all other rigs when off the wind. Further tests varying the sweepback angle from almost horizontal to near vertical were carried out. In general terms, this confirmed the promise shown by the initial tests, to the point where the Crab Claw planform produced a C_x/C_y ratio which promises to be as successful close hauled as it had already proved to be when reaching and running.

Chinese Junk Rig and Squaresails. None of these tests looked at the Junk rig or the squaresail. There may be some subtle aerodynamic efficiencies in these sails that has yet to be discovered.

With a little taper towards the head of the sail and a series of separately sheeted battens to control the sail shape, the junk rig approaches the ideal planform, incidentally makes reefing simpler. A test programme on this and other non-yacht rigs could be interesting.

The Sailboard Rig. This is almost certainly the only new rig to be developed recently to a level of operational efficiency comparable with current yacht and dinghy racing rigs. The main disadvantages for larger boats of this type of rig is the total lack of any way of lowering or reefing the sail. The style needs adapting for more stable craft and for boats that cannot come back onto the beach to change sails.

The sailboards have developed a single sail because of practical handling difficulties. This does not mean that a two or more sail rig might not be more efficient for other styles of craft.

Wingsails. These are still a very specialised field and the development has been in the hands of too few teams for it to be likely that anywhere near the optimum has yet been reached. The main drawback is their fragility which makes it difficult and expensive to push these systems to the limit. This lack of robustness means that most cut-and-thrust racing classes have given abandoned wing sails as impractical, expensive and irrelevant. Maybe the wingsail enthusiasts will come up with more practical versions without foregoing their theoretical efficiency.

The Racing Rules. These will continue to dominate the development of any sail propulsion system since most competitors are more interested in winning races within a particular rule system, than strive to make more efficient and practical rigs as such. Cruising rigs are developed for ease of handling and are rarely tuned to any real level of efficiency, since they are not raced often or seriously enough to sort out the true performance.

As the sailboards have shown and racing yachtsmen have always known, fine tuning can add as much as 50% to the effective power of a rig. Any new style of rig will have to compete directly with the high level of efficiency achieved within the limitations of current Bermudan/spinnaker style of rig.

FINAL COMMENT

There is no one style of rig for maximum efficiency in all conditions.

It is a matter of matching the requirements with the advantages and disadvantages of each option and in the end it usually means being governed by experience and using equipment and materials that are currently available. It is easier to use a standard type of sail, as almost any alternative style of rig requires the development of new technologies and fittings. This is the inevitable penalty for overcoming the inertia of the established ways of doing things and trying to develop something different.

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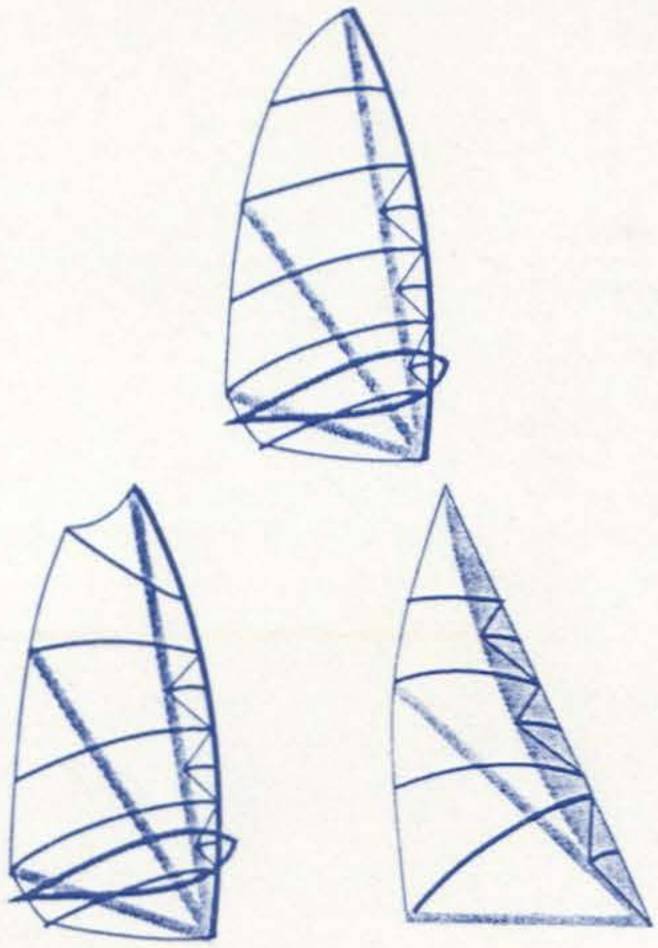

Rig Efficiency

Examines the effect of aspect ratio, camber and twist
on the potential power of a number of rigs –
Bermudan, Lateen, Sprit, Gunter, Dipping Lug and the Polynesian Crab Claw,
as well as Schooner rigs for working ships,
all with various types of modification.

Wind tunnel test reports indicate the potential driving force available
from these rigs from close hauled to running and
the effect of the efficiency of the keel
on the overall performance of the rigs is also demonstrated.

A comparative assessment of the advantages and disadvantages
of various rigs is made and
some explanations as to why certain rigs maybe superior.

The refinements in sailboard rigs
that have made 40 knots possible are also discussed.

The current style of Bermudan racing rig
does not appear to be a particularly efficient,
despite all the devotion given to it over the last seventy years or so.
Other styles of rig show significantly more power under most conditions.