SAILING THEORY

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EDITORIAL

June, 1960

This publication by Charles Satterthwaite was originally published by the New Zealand magazine SEA SPRAY through the courtesy of whose editor John Malitte we use it. It was originally called *The Well Tempered Sailing Craft*, to emphasize the fact that it is mostly concerned with the practical application of the theory of sailing to the design of yachts as well as their handling.

The field covered here has never been quite so well covered before and I feel that this publication is one of exceptional merit and value to yachtsmen. To deal with both the theory and practice of sailing in such a short space is indeed difficult and it has been most successfully done, in my opinion.

This publication may make difficult reading to some but the effort of understanding it completely will be very amply rewarded in increased knowledge and pleasure in sailing boats. Every time I have read it, I have appreciated some fresh fact about sailing craft and I hope it will be of equal value to members and others.

The Yacht Wind Tunnel. As reported in our last publication, on the suggestion of Dr. Davies, Universities and Technical Colleges are being approached to see if they will take a full sized Yacht Wind Tunnel under their care. However, there is both space to erect a model yacht wind tunnel of some 8 feet in height at Woodacres and a caravan for the accommodation of members and their families who may want to erect one. We also have a design for such a tunnel made by Messrs. Gerry, Adams and Dumpleton as well as that of publication No. 24, both of which could be made. If therefore, anyone wants to do this most valuable work and, at the same time provide a seaside holiday for his family, will he contact me ?

"*Catamarans and Outriggers*, 1960" Designs and descriptions of multihulled craft for this publication should now be sent in.

In *A.Y.R.S.* 27, *Cruising Catamarans*, the statement about the Santa Monica Race was incorrect. In this race *S'Cat* was the first boat to finish in a mixed fleet of over 80 boats, beating both *Aikane* and *Dreamer* by 20 minutes, boat for boat. Both *S'Cat* and *Aikane* have deep U asymmetric hulls, while *Dreamer* has semi-circular sections. The winds ranged from 3 to 9 knots in velocity. Half the distance of 25 miles was a dead beat ; the rest, a reach. At the end of the windward leg, *Dreamer* was a mile ahead of *Aikane* and even with *S'Cat*. On the reach however, *Aikane* closed the gap and finished only half a length behind *Dreamer*. The three Rudy Choy-Warren Seamen craft *S'Cat* (27'), *Aikane* (46') and *Foamey* (24') all have to give time to the 44' *Dreamer* in a handicap based on past performance.

JUMPAHEAD

In publication No. 28, *Catamarans* 1959, exception has been taken by the *Jumpahead* Class Association to remarks, which were :—

" Its speed is, if anything, only the barest fraction worse than *Shearwater III* but it carries more sail area. One can say that the hull resistance is definitely greater than that of *Shearwater III* as it is the same weight."

Bill O'Brien, *Jumphead's* designer gives his opinion as follows :—

(a) A round, low wetted surface hull is superior for a given driving power (sail area) up to approximately 14 knots.

(b) But above this speed, the simple flat bottom is far superior when reaching, a compromise of deep V changing to flat bottom is superior to the round on all points in heavy weather, sail area for sail area.

Bill O'Brien's evaluation is, of course, a more perfect statement of the case than the summary of *Catamarans* 1959. In practice, Chris Hammond in a *Jumpahead*, beat the best two *Shearwaters III* (John Fisk and Roland Prout) at Hayling Island in 1958 in a very strong wind.

In strong wind *Reaching* at the *One-of-a-Kind* races (1959) at Westcliffe-on-Sea, the *Jumpahead* was faster than the *Shearwater III* in the maximum speed reaching trials.

Summary. *Jumpahead* is shorter and heavier than *Shearwater III*. She has more sail area to obtain equal performance in light airs.

In strong winds *Jumpahead* can be faster than *Shearwater III*.

SAILING THEORY

By C. A. Satterthwaite

Part I

Introduction

The human qualities attributed to ships, and in particular to sailing ships, probably arose from the subtle peculiarities of their antics amidst the waves and the winds. From time immemorial, ships have been referred to as female — no doubt often with female dogs in mind — and it is perhaps the uncertainties associated with their motion that has made this traditional. On the other hand maybe it was the cost of their rigging ! The behaviour of a ship in a seaway has always been one of the real wonders of this world, as something at once beautiful, inexplicable and often inspiring. In the Book of the Proverbs of Solomon, Agur the son of Jakeh declared it to be beyond his comprehension, and although in this respect modern yacht designers should be wiser than he was, there is still a lot that remains imponderable about a ship's motion.

In other related sciences of more direct economic value to modern life, research work has progressed apace with the result that we are able to bring new trains of thought to bear on the ancient art of sailing. The mellow light of a dawning knowledge may begin to shine in a few places hitherto darkened, I fear, by not a little humbug !

" *Balance* "

Quite one of the most interesting aspects of the way of a sailing craft is that described as " Balance." It is also one of the most important criteria of a ship, since it is the first quality that will commend or condemn her in the eyes of the sailor. Good balance in a yacht implies freedom from all objectionable tendencies, whatever the sailing attitude, conditions and motions, but not at the same time a lack of sensitivity or an inhability to look after herself at least for a limited period. It is, if you like, a definition of essential sanity in a ship. As our vegetables are balanced in the scales, so, in the midst of the seas, is the sailing craft balanced between wind and water. However, whilst a state of poise as determined by the grocer is easily recognised, the mechanism of balance afloat is not nearly so obvious.

Every sailor of any experience knows, and avoids, the sort of boat castigated as " hard-mouthed." Her behaviour is characteristic and was once a common feature of small sailing craft. As she heels when close hauled she consistently luffs into the wind's eye, and

Fig. 1. Drawing of a badly balanced yacht.

always needs plenty of weather helm to keep her somewhere on course. If caught by a sustained squall she may easily take charge, ramp up to the wind, and put herself in irons to an obligato of flogging canvas, crashing boom and thumping blocks. The same craft when before the wind yaws all round the horizon — a helmsman's nightmare! This is an extreme case of course, but there are many otherwise excellent craft spoilt by a tendency in some degree to "wildness" of the above description.

On the other hand, the happy vessel that possesses good balance is equally well known and usually quite outstanding. She floats, as it were, on the worship of her lucky owner, and enjoys immortality in the memories of her crew. She is light on her helm, literally finger light, but yet she has a positive "feel." She is responsive on any heading, at any speed, even under reefed canvas, and in restricted waters, bringing up or getting under way. At sea she may be left to look after herself with the certainty that she will behave under all weather conditions.

Balance is then the factor that distinguishes the well tempered vessel from the ill mannered. Lack of it means a hard working and almost certainly a relatively slow boat, whereas possession of it represents everything that contributes to make a sailing craft a delight and satisfaction to handle.

The aim of this study is to establish the criteria of balance, and to find out how it may be ensured in a design. There does exist a lot of information on the subject by various authorities, ranging in scope from random observations to such controversial theory as that of "Metacentric Shelf" advocated so ardently and successfully by the late Rear-Admiral Alfred Turner. I hope to show that by careful correlation of all this work it should be possible to establish a sound theory of balance without the flaws and fallacies apparent in some of the previous explanations.

In the days of not so long ago when it was customary to build from a model and not a set of lines or table of offsets, the possession of good balance was dependent entirely on the eye and experience of the builder. If he was lucky or a very experienced sailor as well as a shipwright, the vessel he created became a legend as a slick sailer, but if not, then often expensive alterations became necessary to make a passable sailing craft out of her. Quite frequently extravagant bowsprits and sail plans had to be rigged in order to exert adequate control over the vessel. Even now, a set of lines could be drawn both pleasing to the eye and satisfying the Rating Rules, but representing a real sea cow of a boat that pulls her helmsman's arms out. What a pity to waste good time and materials on such a tub !

It is often distressingly obvious that a boat is free to move in all directions, and she may in fact yaw, roll and pitch — to consider rotary motions alone. We can exert direct control over yawing only, by means of the rudder. Over rolling and pitching we have no such influence. There does exist an indirect relation between all three such motions however. For example, rolling in a seaway may induce yawing, and so too may pitching. It is characteristic of badly balanced craft that these indirect effects are very marked, whereas in a well tempered craft they are negligible, or at most only minor matters of temporary trim, a mere pressure on the tiller, or the easing of a sheet.

We may say then that balance will be manifest primarily through the rudder, and the less use we have to make of it to maintain the desired course the better is the inherent balance of our "dream ship."

It may well be noted here that a poor state of balance implies a slower boat, since the continual yawing induced will spill wind from the sails and thus lose driving force, and the constant rudder movements will create extra water drag. Moreover, if such action is necessary to curb inherent yawing tendencies, it must mean so much less rudder movement is available and effective for manoeuvring the vessel, and generally, too, that excessive tiller force is required to apply it ; with the inevitable discouragement of the steersman, possibly bruises on his ribs, and poor steering in any case. One thing leads to another. We aim to balance our craft so that rudder movement is almost wholly reserved for steering and not wasted by being used as a neutraliser of bad habits.

The Nature of " Balance "

Consider a sailing craft in a steady state of motion, over a calm sea, with a steady sailing breeze. (Idyllic no doubt, but even under more normal conditions, similar principles can be applied at any given instant of time.)

The conditions must obtain that : The Sail forces and moments due to the wind velocity *as felt by the vessel* = The Hull forces and moments generated by the *resultant motion* of the vessel through the water.

For, if this were not so, an unbalanced force and/or moment would exist, causing a change to occur in the state of motion of the vessel until such an equilibrium was eventually achieved. This equation in fact represents a fundamental truth as applied to the steady motion of a sailing craft.

A diagram in Part II of this publication will show views of the craft in question, sailing to windward, with the principal forces and moments indicated. *Anything* that affects any of these forces or moments in either magnitude or direction will upset the equilibrium and cause the vessel to change her attitude to achieve a new position of equilibrium. This in turn of course, may immediately be changed yet again by the helmsman applying sufficient rudder to counteract the original disturbance and thus maintain the heading. However, if the disturbance was drastic enough, or the vessel a badly balanced specimen, we may have to call the watch to tend the sails before we can restore the original course, or perhaps in the latter eventuality. take prompt action with both helm and sails before she takes charge and damage results.

It is my hope that this introduction will enable the reader to recognise the problem of balance, and understand that good balance is highly desirable in all sailing craft. In the next part of this article I will consider the implications of the forces shown on the diagram and how their relative position influences the boat. From which we may be able to derive a better explanation and analysis of the balance of sailing craft than has yet found general acceptance.

Part II
THE FORCES CLOSE HAULED

Possibly the sight of Figure 2 has provoked in most folk a severe attack of spine chilling creeps — similar to the sensation I experience

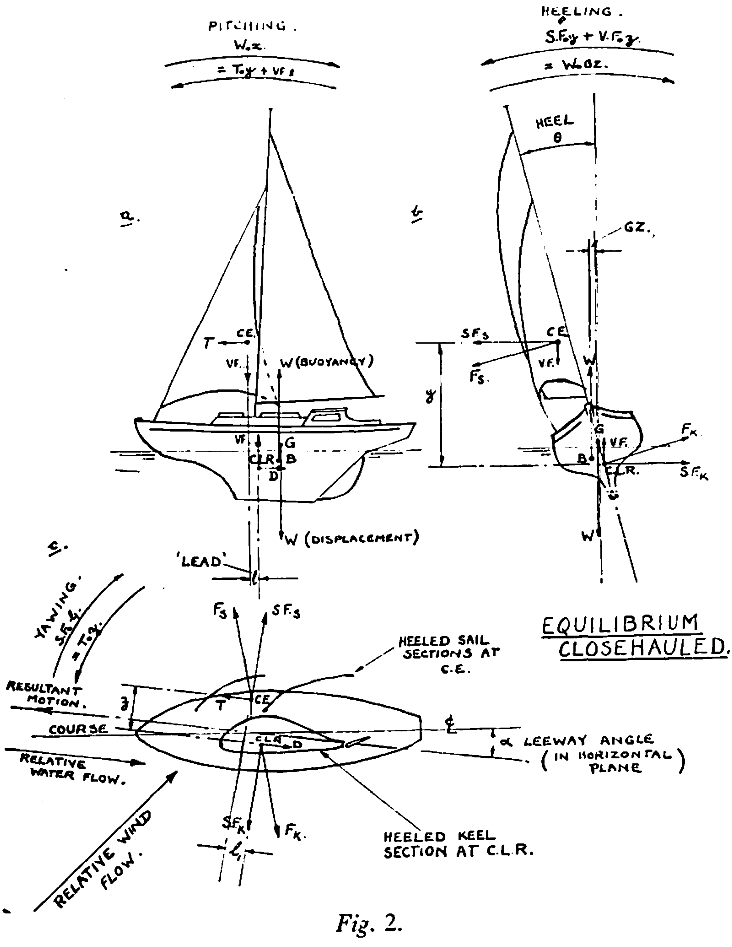


Fig. 2.

whenever I happen to consult a book on first aid ! However, the fascination is not to be denied, and we are compelled to carry out an analysis of the diagrams no matter how repulsive they may appear.

The object of the figure is to show concisely and in all three dimensions the main forces and moments resulting from the wind flow over the sails, and the water flow past the hull.

The engineering marvel of the aeroplane has made everyone familiar with the idea of the aerofoil. The fact that a wing can generate a " lift " force enabling flight to be achieved and sustained is now common knowledge. Sails are special types of aerofoils, namely thin cambered plates of canvas, and they generate " lift " forces horizontally instead of vertically. They have many physical differences when compared to aircraft wings but the principle of operation is precisely the same.

Not quite so well appreciated, but in fact merely another aspect of " aerofoil action," is the hydrofoil action of a boat's hull in the relative water flow. Unfortunately, the general form of a ship's hull does not lend itself to making an efficient " aerofoil " section, since it is not designed primarily with that end in view. For hydrofoil action therefore we rely on fin keel, centre-board or leeboard, all of which devices resemble more closely an aircraft wing and generate a " lift " force corresponding to that developed by the sails.

We shall see that the shape of the hull, and the manner of its reactions as a hydrofoil, decides whether the craft is well-tempered or not.

Examine Figure 2 with a more discerning eye. We have three views, a, b, and c, showing sheer, draught, bow view and plan view respectively, of a nice little sloop. Indicated on each view are the estimated positions and directions of the forces due to both wind and water with some idea of their effects as pitching, heeling and yawing couples.

The whole complex pressure system developed by the passage of the relative wind over the sail plan can be reduced to correspond to one resultant force, " Fs," having the same total effect, and acting at a point called the " Centre of Effort," C.E., on the figure. Figure 2b shows that Fs acts approximately at right angles to the mast, and Figure 2c shows how Fs relates to the relative wind flow.

In the same way, the equally, if not more complex system of pressures set up by the relative water flow past the hull, may be compounded together to give a single resultant force, " FK," acting at a point (corresponding to the C.E. of the sail plan) known as the " Centre of Lateral Resistance," C.L.R. of the hull.

The Equilibrium

Figs. 2b and 2c locate F_K and you will notice that in Fig. 2c the horizontal components of F_S and F_K and equal and opposed to each other in the same vertical plane. This condition must follow directly from the primary equilibrium conditions mentioned in the Part 1, namely, " Sail forces and moments due to the relative wind flow, equals the hull forces and moments generated by the relative water flow,"

The C.L.R. is not usually spoken of in the context I have used above. To the yacht designer the textbooks define the C.L.R. as the centre of the area of the underwater profile.

This we will call the " conventional " position for it, and bear in mind that its correct position is as shown in Figure 1. Similarly the C.E. is conventionally taken as the centre of area of the sail plan, but, as with the C.L.R., this is not quite true, and the C.E. shown in Figure 2 is at the real position which is somwhat forward of the centre of the area.

We can better appreciate the effects of the forces F_S and F_K if we resolve them into components, parallel to, and perpendicular to, the direction of the resultant motion of the boat. There will be three such components in each case to describe completely the effects of F_S and F_K ; one in the direction of the resultant motion, one horizontally perpendicular to it, and one vertcially also perpendicular to it. Thus F_S is equivalent to the " thrust " force, T ; " side " force, SF_S ; and vertical force, V.F. F_K similarly is equivalent to the " drag " force, D ; " side " force, SF_K ; and vertical force, V.F.

Since we postulated that our little ship is in equilibrium, sailing along at a perfectly steady rate, thus we can say that $T = D$, $SF_S = SF_K$ and $VF = VF$.

Note the relative sizes of SF_S and T. Most of the force generated by the sail plan, F_S, is wasted in side force, SF_S, and in fact the ratio T/SF_S is a measure of the efficiency of the sail plan on this heading. Hence the necessity for the fin and hull to develop an opposing side force, SF_K in the correct position to balance the vessel. If it were not for this characteristic of the sail plan we could simplify our hull design immensely. As it is, hydrofoil action is essential for any degree of weatherliness.

It is clear that the CE of the sails will always be above the CLR of the hull. There are therefore bound to be pitching and heeling couples formed by T and D, and by the side, and vertical forces as shown in Figs. 2a and 2b respectively. In both cases, of pitch and heel, the moments of these couples are balanced by the vessel adopting a suitable trim and heel to produce reacting moments due to displacement of the centre of buoyancy, " B " from its static position in vertical line with the centre of gravity " G."

We sail to windward then with our nose slightly depressed (like many humans too !), and at an angle of heel. The exact extent of both inclinations being determined by the shape of the hull and the displacement (" W," the total weight) of the boat.

Therefore, in Fig. 2a, the nose down effect of the sail thrust Ty and vertical force VFl is equalised by a slight forward movement " x " of the CB such that $Ty + VFl = Wx$. Note that T and VF are small forces in comparison with the displacement W, but that y is a great distance in comparison to X. Similarly equilibrium in heel can be seen from Fig. 2b to be achieved when $SFy + VFz = W\ GZ$. Where GZ is the righting arm of the transverse stability moment and is a much smaller distance than either y or z, the arms of the heeling moments due to side and vertical forces respectively.

Fig. 2c is the most significant from the balance point of view, and from now on we will assume the stability conditions indicated in Figs. 2a and 2b as mentioned above to be met, concentrating our attention on the horizontal planes shown in this plan view. I say " planes " because this little diagram is composed of two horizontal sections, one taken through the sail plan at the CE and one taken through the hull at the CLR. We notice that the CE lies well to one side of the fore and aft axis of the yacht, whereas the CLR lies in the other, and their athwartships separation (which we measure as " z ") depends on the angle of heel of the craft, the more she heels the further apart move the CE and CLR.

Considering for a moment the couple formed by the thrust T and drag D, we see that they exert a luffing moment $= Tz$ say, which is of course precisely counteracted by the couple formed by the side forces of moment SFl'. That is how I have drawn it in the Figure 2c, and this will be true providing the CLR and CE are in the relative positions shown.

The " Lead "

Whence we see that " l' " is a measure of the " lead " of the CE over the CLR that is necessary to ensure the equilibrium of the craft on this heading. The actual lead is measured in the fore and aft direction shown in Fig. 2a as " l." The relation between l and l' is, $l = l', \cos \alpha$ where α is the angle of leeway.

The actual lead l corresponds to the " conventional " lead which is given as the advance of the conventional position of the CE over the conventional position of the CLR. The conventional lead is decided by rule of thumb and most textbooks quote values for it applicable to various types of yacht, which experience has found to be successful. Since the value of the actual lead " l " can only be found as the result of extensive tests, there is some justification for the use of guesswork in positioning the sail plan of a yacht in the first instance, but we must be clear that in this analysis we always refer to the actual lead and to the correct positions of the CE and CLR — even though we cannot — as yet — lay our fingers on them. Practice versus Theory !

It looks then as though this " lead " is a somewhat critical dimension, since we cannot establish the equilibrium of forces and moments shown in Figure 2 unless the CE and CLR fall in the relative positions indicated. In fact when close-hauled the lead must adjust itself so that the horizontal components of F_S and F_K are in the same vertical plane, in the manner shown in Fig. 2c. This adjustment will be made quite automatically by the vessel herself altering the leeway angle α, until an equilibrium is reached. Further alteration may be deemed necessary by the man at the helm and the hands at the sheets until the crew is satisfied with the heading and the set of the sails while the craft is satisfied with the leeway angle and speed necessary to ensure that the conditions of Fig. 2c are fully met. At the same time minor adjustments in pitch and heel will also occur to suit Figs. 2a and 2b, but clearly these must not have drastic effect on the lead of the CE over the CLR for the boat to be balanced, as we shall soon see.

It is possible to discuss variations on the main theme of Figure 2 endlessly, to no real purpose, and perhaps, at present, only to confusion of the issues involved; which are quite complex. In practice varying conditions are met by automatic adjustments of helm and leeway angle, heel and pitch so as always to seek the ideal equilibrium we have just analysed.

It is next our purpose to make sure that the adjustments required from both craft and helmsman to keep the peace amongst the forces and moments acting on the sails and hull are really only adjustments ; and that excessive movements of craft or helm are not necessary to maintain equilibrium. The latter may fairly be described as an " objectionable tendency," making the craft hard-mouthed in consequence of it.

This leads to the consideration of the control we have over the positions of the CE and CLR as we sail, and what happens to these centres when the craft pitches, heels and yaws in a seaway.

PART III

The Sail Force

We will now leave the general conditions for equilibrium close-hauled, and take a more particular look at the ingenious mechanism that enables us to harness the wind to propel the boat. In order to appreciate the state of balance summarised by Figure 2, we must consider the general characteristics of sails, so that the behaviour of the total resultant sail force, Fs, as the vessel yaws, heels and pitches, as the trim of the sails is altered, and as the relative wind changes in both speed and direction, may be estimated. We can indeed only estimate, as up to the present there is little consistent experimental work available on which to base a scientific study. This, in spite of the impression that prevails in some quarters, that the characteristics of sails have been exhaustively examined and no improvement is possible !

Manfred Curry presented a good deal of experimental evidence in his famous book " Yacht Racing," based largely on the previous work of Eiffel ; but although his diagrams illustrate his arguments they are not quoted in sufficient detail to permit of the information being correlated with other work. Some more modern authorities present information that is interesting, but not any more comprehensive. This lack of clear cut quantitative data on sails is most irritating and a reproach to modern sailors.

Aerodynamic theory concerns itself in great detail with the behaviour of the relatively thick aerofoils suitable for aircraft, but cares very little about the thin cambered plates corresponding to the sails we use on boats. Still less is known of the combinations of such plates which make up the complete rig of a sailing craft. The science of modern aerodynamics too is more concerned lately with very high speeds where conditions are in no way comparable with those obtaining at the slow speeds customary at sea. However, the fundamentals of slow speed aerodynamics are applicable equally to sailing craft as to aircraft, and by analysis of the meagre data that is available we can make an intelligent prediction of the performance to be expected from sails of at least one type.

Theory, and practice, show that the magnitude, direction, and point of application of the total resultant sail force, Fs, will depend on the following principal factors :

a. The angle, measured in a perpendicular plane to the mast, at which the relative wind approaches the sails. I call this the " angle of attack " of the sails, and it determines the sail's characteristic.

For a single sail it may be measured most conveniently at the boom, (α_B in Figure 3b).

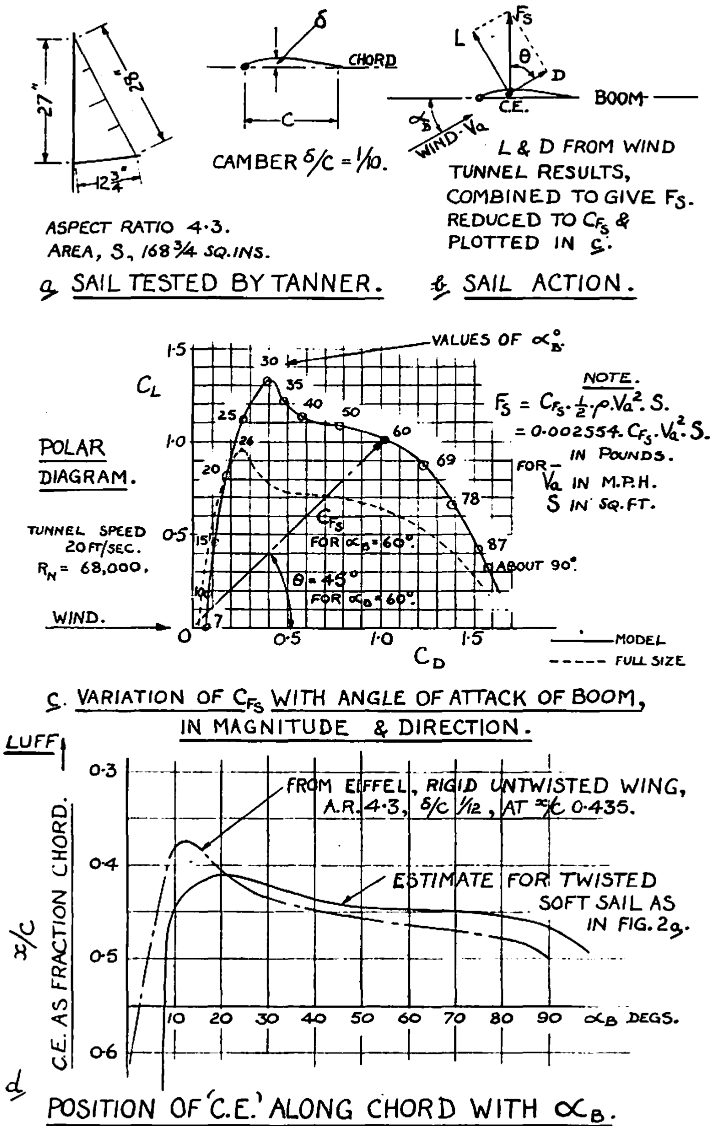
b. The speed of the relative wind, Va, measured in the *same plane* as is the angle of attack ; and the area of the sails. S. The relative wind speed has considerable effect on the magnitude of Fs, which increases as $(Va)^2$. The area of the sails increases Fs in direct proportion. We may therefore say that Fs is proportional to the product of $(Va)^2.S$.

c. The shape of the outline of the sail in elevation. This is measured by the relation between the length of the luff of the sail, and the mean chord, or straight line distance from luff to leach perpendicular to the luff ; and is known as the " Aspect Ratio." For any given sail the aspect ratio is fixed and not a variable in the same sense as is the angle of attack or the wind speed. Physical limitations of a yacht's rig and Rating Rules have settled the aspect ratio of the sails of the majority of small sailing craft at about 4.0. It may be noted that the higher we can make the aspect ratio of a sail, providing it will stand and set properly, the more efficient it could be to windward.

d. The camber, or " flow " of the sail in cross-section. This is measured by taking a reference chord line from luff to leach, as above, and finding the maximum perpendicular distance from it to the sail section profile. The camber is an important aerodynamic characteristic. A flat sail is very inefficient, and, as the camber increases, from the flat sail case, so the magnitude of Fs increases at any given value of the angle of attack.

However, a highly cambered sail means that Fs is inclined in such a way that the aerodynamic drag is too high in comparison to the thrust we get when close hauled, i.e. the ratio of T to SFs is too small to be useful. High camber also promotes excessive movement of the position of the C.E. with changes in angle of attack. From Figure 2, it can be seen that any movement of the C.E. fore and aft must mean the complete upset of the equilibrium and a change in heading, speed and leeway will be necessary before the craft settles down again. There is an optimum value for the camber for which a sail could be the most efficient on a windward heading, but, as any sailor knows, sails in fact vary in camber, depending on their age, cut, use and individual adjustment.

e. The density of the air and the surface roughness of the sails. For our purposes it is sufficient to take the density of fresh sea air as constant, and also to ignore any effects of the surface finish of the sails. The variations due to these factors are, in the case of the density of the air, negligible ; and in the case of the finish of the



27"
28"
$12\frac{3}{4}$"
ASPECT RATIO 4·3.
AREA, S, 168¾ SQ. INS.
a SAIL TESTED BY TANNER.
δ
CHORD
C
CAMBER δ/C = 1/10.
L
Fs
θ
D
BOOM
C.E.
αB
WIND·Va
L & D FROM WIND TUNNEL RESULTS, COMBINED TO GIVE Fs. REDUCED TO CFs & PLOTTED IN c.
b SAIL ACTION.
VALUES OF αB°.
NOTE.
Fs = CFs·½·ρ·Va²·S.
= 0·002554·CFs·Va²·S. IN POUNDS.
FOR – Va IN M.P.H. S IN SQ. FT.
CL
POLAR DIAGRAM.
TUNNEL SPEED 20 FT/SEC.
RN = 68,000.
WIND.
CFs FOR αB = 60°.
θ = 45° FOR αB = 60°.
ABOUT 90°.
CD
MODEL
FULL SIZE
c. VARIATION OF CFs WITH ANGLE OF ATTACK OF BOOM, IN MAGNITUDE & DIRECTION.
LUFF
C.E. AS FRACTION CHORD.
x/c
FROM EIFFEL, RIGID UNTWISTED WING, A.R. 4·3, δ/c 1/12, AT x/c 0·435.
ESTIMATE FOR TWISTED SOFT SAIL AS IN FIG. 2a.
αB DEGS.
d POSITION OF 'C.E.' ALONG CHORD WITH αB.

Fig. 3.

canvas of the sails, also of minor significance, providing there is no abnormal roughness, torn batten pockets, etc.

Wind Tunnel Results

Considering now a given type of a Bermudian sail as in Figure 3, we can reduce the major variables to, the angle of attack α_B ; the relative wind speed, Va ; and the sail area S. Students of Manfred Curry will recognise the form of the information given in Figure 3, which is an attempt to portray, concisely, the behaviour of a typical Bermudan type of yacht's mainsail. The data given was drawn principally from a paper by T. Tanner, printed in the Royal Aeronautical Society Journal for October, 1930, with extra evidence supplied by Eiffel, Curry and Davidson. Tanner made a wind tunnel study of the model sail shown in the figure, but, unhappily gave no information about C.E. positions at the various angles of attack at which he took readings. Actually, Tanner's model appears to have been a proper miniature canvas sail, so that the effects of the variation in camber, and the sail twist from foot to head must be included in his test results. He fails to comment on these features, however, and does not indicate the value of the sail camber at any point whatsoever. I have had to compile the graph, Figure 3d, therefore, assuming a mean camber of $S/C = 1/10$ from Tanner's sketches and using the results quoted by Eiffel for thin cambered plates, plus a bit of guesswork to allow for variations in camber and for sail twist. It is my fond hope that Figure 3 is as close an estimation of the characteristics of a single typical Bermudan type sail as can be found in the classical literature on the subject.

Tests made in wind tunnels nearly always have to be corrected in some degree for " scale effect " before the results may be considered to reflect full size characteristics. This is because, although the model is so much smaller than the full size yacht's sail, the air used in the tunnel is the same " size " as that used at sea. In Figure 3c, the full line shows the model results and the dotted line gives an estimate of the corresponding full size characteristic.

The information given in Figure 3 may be related to Figure 2 in the following way. For a given angle of attack of the boom, α_B (corrected for the angle of heel), the value of CFs may be read off the curve of Figure 3c, for model or full size as required ; and the corresponding magnitude of the total resultant sail force, Fs, found by use of the equation given namely Fs=0.00255.CFs,(Va)S lbs., where, S is the sail area in square feet, and Va is the relative wind speed in m.p.h. (also corrected for the angle of heel). The angle, θ, read direct off the figure will give the direction of Fs relative to the direction of Va. We can now evaluate the thrust, T. side force, SFs. and vertical force, VF, once we know, or assume, the course of the boat and her leeway angle. This may be done by plotting on Figure 3c the directions of T and SFs as shown in Figure 2c, and completing the rectangle of which Fs forms one diagonal. Location of the centre of effort " C.E." follows from Figure 3d in terms of the distance of CE from the mast, at the given angle of attack. Thus a complete picture of the magnitudes, directions and point of application of sail thrust, side force and vertical force for any value of the angle of attack ; vital information from the " balance " point of view ! However, Figure 3 applies only to a single Bermudan mainsail, whereas Figure 2 is clearly a sloop-rigged craft having both jib and mainsail. Reference to Figure 4 will show the same information for a cat-rigged boat, such as a Finn, giving figures taken from Figure 3 and illustrating all the terms used. The angle of heel has been assumed zero for

CAT-RIGGED CRAFT

Sail Area 300 *sq. ft. Boom Trimmed to* $\alpha_B = 26°$

Relative Wind, Va = 15 *m.p.h.*

From Fig. 3*c*. CFs (*full size*) = 0.975.

$\therefore$ Fs = 0.002554.0.975 (15).^{2} 200 = 112 *lbs.*

$\theta = 75°$, *and from Fig. 3d, C.E. is at* $x/c = 0.415$

If hull permits sailing at 35° *to Va, making* 3° *Leeway, then thrust,* T = 44 *lbs. and Side Force,* SFs = 103 *lbs.*

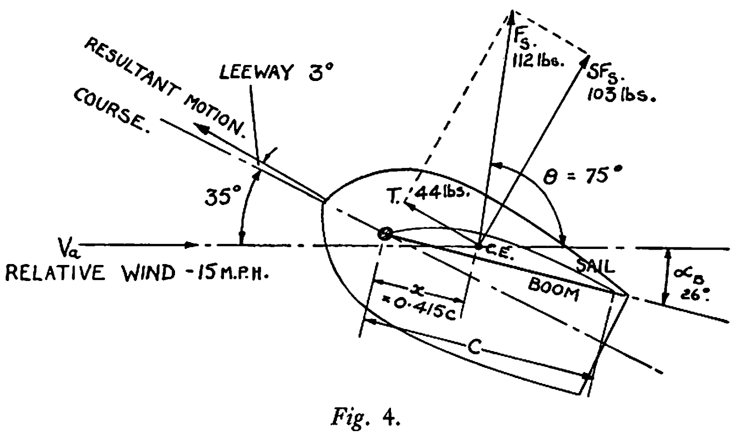


Fig. 4.

simplicity, and the angle of attack has been taken as 26° which corresponds to " a good full " and not headed hard on the wind. Figure 3c shows that for values of α_B of 7° or less the sail is " back winded," but is most effective to windward at about 18 to 20° (model scale), at which angle a good helmsman would instinctively try to keep her. In fact the angle of attack would vary between say, 10 and 20°, quite apart from variations due to rough water and evasive action for random motor boats, etc. ! For such a range of angle of attack the C.E. position varies correspondingly from about 0.45 to 0.415, i.e. it moves forward as the vessel bears away up to $\alpha_B = 26°$; then it would move slowly aft again if the helmsman bore away any further.

What now of the little sloop of Figure 2 ? How can we provide the same information for a rig of two sails, as we have for a rig of only one ? Tests have been carried out on such rigs in full size. The classic study of Warner and Ober, " The Aerodynamics of Yacht Sails " referred to by Curry and the work of Davidson on 6 metre boats, provide a good deal of interesting information. However, we cannot make as compact a diagram for the sloop, or any other multi-sail rig, as has been done for the single sail.

The Sloop Rigs

Figure 5 (Page 20) shows some results of tests mentioned on sloop rigs. The information is necessarily confined to the closehauled condition only, where the two sails may be treated as making up one aerofoil, having a slot in it where the jib overlaps the luff of the mainsail, and the sheets remain *UNTOUCHED.* As soon as the heading of the craft is freed at all off the wind, then the consequent retrimming of the sails will alter their mutual geometrical relation. Therefore the simple picture of Figure 3c cannot be plotted for a multi-sail rig. As regards the C.E. position, Figure 2 makes it clear that the C.E. of a sloop may well lie forward of the mast, and therefore the convention of Figure 3d, for fixing its position for a single sail is no longer realistic. Instead the C.E. position will be considered in relation to the bow of the craft, and as a proportion of her overall length from the bow. Similarly, defining the angle of attack by the boom angle is inconvenient, and we will take the angle of the fore and aft centreline of the boat in relation to the relative wind as being a better criterion for the whole rig. Altering these definitions thus in no way invalidates the previous reasoning, and whatever the rig, whether made up of soft canvas sails, fully battened sails, Chinese lugsails, catboat, cutter, yawl, ketch, schooner, brig, barque or ship, we can reduce its effect to a single resultant sail force acting at a centre of effort, and, when

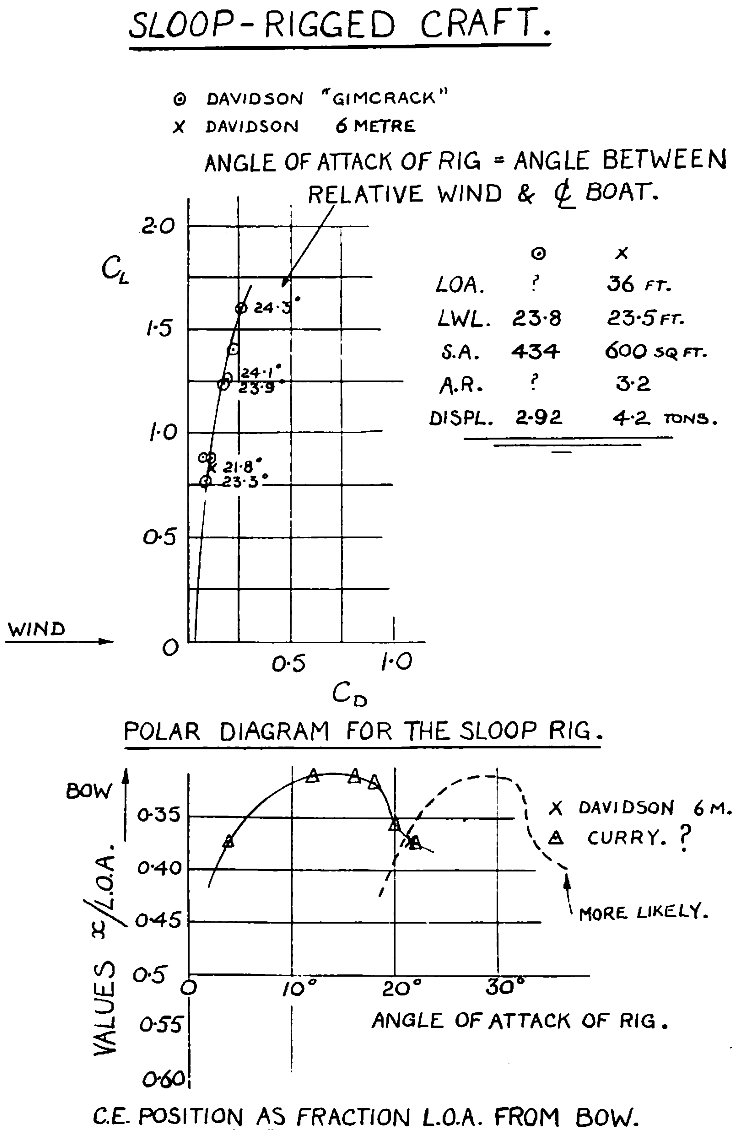


Fig. 5. C.E. position as fraction L.O.A. from Bow.

closehauled, expect to find very similar characteristics to those shown in Figures 3 and 5 ; providing, always that the individual sails are *not* retrimmed. Particular rigs will show peculiarities, some giving good thrust when high on the wind, others poor thrust and excessive side force. The merits of each must be examined in conjunction with the purpose for which the individual craft is being designed.

Giving some thought now to conditions other than closehauled. A point to note is that from a heading on the wind (Va at say 18-26° to the centre line of the boat) to a reach (Va about 90°) the individuals sails will be TRIMMED to act as aerofoils with an individual angle of attack to the relative wind that will show no significant variation. Sails without booms or battens will increase in camber as the sheets are freed, and the angle of twist of a soft sail will increase as the tension

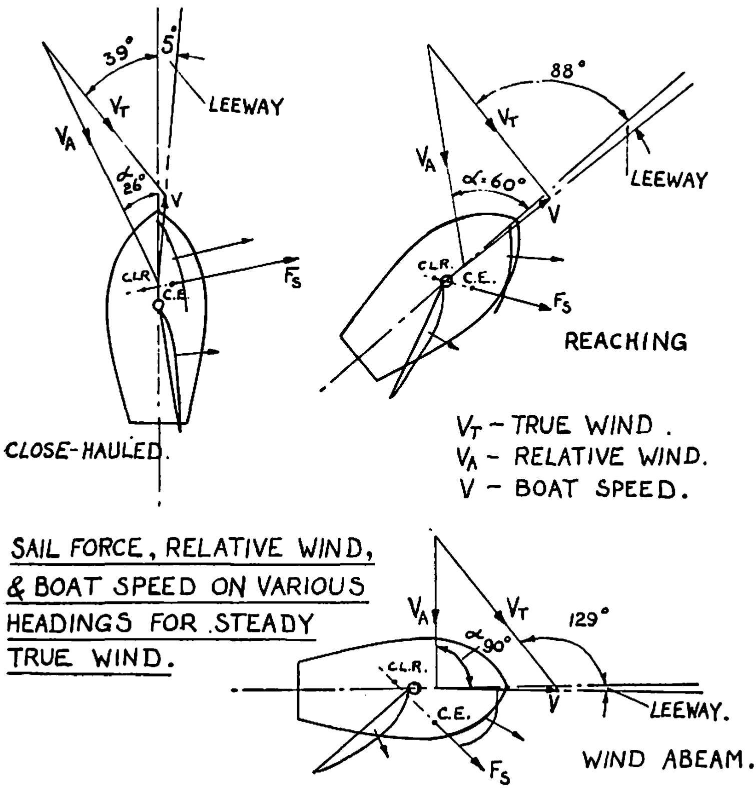


Fig. 6.

on the sheet is released. To a first approximation however, the position of the C.E. in each sail, being dependent on the angle of attack, will remain relatively steady (Figure 3d) and individual sail forces will preserve a fairly constant relation to the angle of attack although modified in magnitude by the speed of the relative wind, and to a second order by the changes in camber and twist. The change in speed of the relative wind with heading will be the major variable, and as the sail trim is altered so the relative wind affecting individual sails will vary. The mainsail, for example feels the wind as determined by the jib set ahead of it, and knows no other influence until the craft is headed well off before the wind. The total resultant sail force Fs, will, however, swing round relative to the boat as the heading varies away from closehauled as shown in Figure 6.

Reverting to the closehauled condition it is now expedient to point out the effects of yawing, heeling and pitching on the angle of attack of the rig since, as has been demonstrated, this angle is of vital importance in locating the sail forces.

Clearly, yawing will decrease the angle of attack when luffing until the flogging of the headsails reveals that the value of α B has decreased below the 7° or so set by Figure 3c ; and increase the angle of attack when bearing away. As the craft heels from the upright over to leeward, the angle of attack will decrease until it is, theoretically speaking, zero when she is on her beam ends. In fact, at extreme angles of heel the sail plan will be in the lee of the hull, and of little use for this reason alone. Tests by Davidson have demonstrated that angles of heel in excess of 20° are detrimental to windward performance, so that for the purposes of this analysis 20° is the practical limit. Pitching will have no long term effect on sail characteristics since its magnitude is small in comparison to heeling and yawing, and, unlike heeling, it is not a permanent condition of the vessel but an oscillation about the level trim position.

Windward Sailing

Finally consider a typical sailing craft on a windward heading. She is — or should be — in the charge of the helmsman, and he will be concentrating in an endeavour to maintain the vessel at a constant angle of attack to the relative wind. This he judges as best his experience dictates, and he directs the crew so to maintain the trim of the sails that the angle of attack stays at the value he considers to be the optimum for the best speed made good to windward. The tendency is therefore for the sail force and its point of application to remain as steady and constant as the activities of the crew can

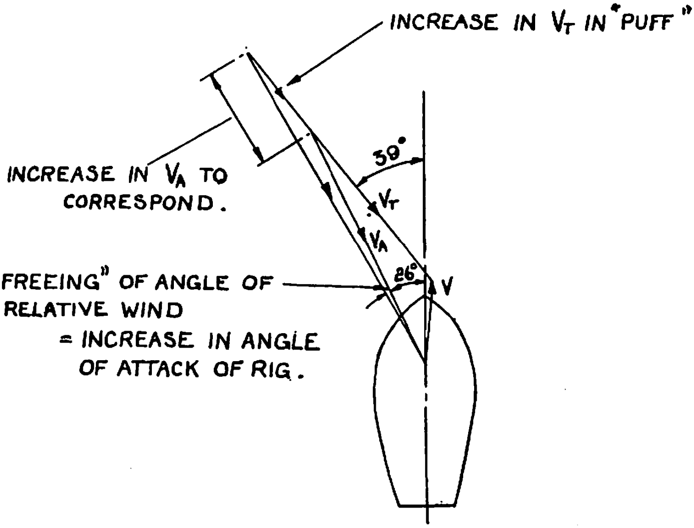


Fig. 7. Wind velocities at instant of sudden increase in Wind Strength.

achieve. Consider the sequence of events when the craft meets with a squall, i.e. a temporary increase in the speed of the *true* wind. This is quite the usual state of affairs as any sailor knows. The effect of a sudden increase in the speed of the true wind, VT, will mean not only an increase in the speed of the relative wind, Va, but also that Va will alter in direction to become " freer " — see Figure 7. Thus the angle of attack of the sails will suffer a temporary increase, say from 20° to 30°, whereupon the C.E. will move forward (as shown in Figure 5). The boat then responds to the puff by heeling, thus decreasing the angle of attack and relative wind strength and the C.E. tends to travel back towards its original position in the sail plan. Meanwhile the helmsman sensing the change in relative wind and the angle of heel, has " sprung a luff," instinctively reducing the angle of attack (and heel) anyway — gaining to windward of course, and so again keeping the C.E. in about the same relative position. There is therefore a good deal of control — both conscious and inherent over the C.E. position which tends to be stable about a mean position in the rig such as is shown in Figure 2.

From this study of sail aerodynamics, brief and incomplete though it may be, enough evidence can be obtained to show the behaviour of the total resultant sail force and its point of application for the closehauled sailing condition of any typical small sailing craft. Clearly the C.E. of a sailplan is not to be found at the centre of area of the sails as is commonly taught. It is not even at a fixed position in the rig, but, as has been shown, enjoys a certain limited licence to wander to and fro at the discretion of the ship's company and the dictates of the wind and sea.

Our attention turns next to the corresponding reactions of the hull in the water. From these we want to determine what sort of shape will best ensure that the C.L.R. shall keep in step with the C.E. so that the conditions of Figure 2 obtain, without extremes of motion, and the craft thereby qualifies as being truly well-tempered.

PART FOUR

Those of you patient readers who have survived Part III, must be wondering what can possibly come next ! But not to worry, we have broken the back of the abstruse technicalities, and this study can be completed without introducing any really new ideas on sailing craft.

The Hull Forces

In general with this problem of the balance of a sailing boat, we move in the land of the blind. As everyone knows, even a one-eyed man is king where nobody can, or will see ; so that this is one case where a little knowledge can be a great help. In recent years there have been at least two instances where some idea of the balance characteristics of a sailing vessel would have saved much hard earned money ; and indeed, for one lonely voyager would have made for happiness instead of misery.

The habits of sails when spread to the wind have been well aired (?) in Part III, where, in particular, it was shown that on a closehauled heading, variations in the movement of the C.E., and total resultant sail force F_S, tended to be small. With this knowledge in mind, a renewed study of Figure 2c shows that the vital requirement of balance, namely that F_S and F_K must lie in the same vertical plane, can be further enlarged upon. It is clear that when the C.E. wanders in the course of normal sailing, and F_S varies correspondingly in the manner outlined in Part III, then the hull C.L.R. MUST move and

FK alter in correspondence to maintain the balance conditions of Fig. 2. It has been shown too that variations in wind strength cause corresponding variations in the angle of attack of the sail plan, due both to changes in the apparent wind direction and to the resulting changes in angle of heel of the craft, and hence variations in Fs and the C.E. position in accordance with the data of Figs. 3 and 5. Therefore for these very same alterations in wind strength and angle of heel, the C.L.R. of the hull has to move to correspond with the C.E. at any instant, also the keel force FK must equal Fs and lie in the same vertical plane. If the hull cannot fulfil these conditions then the craft will not be able to sail on the heading in question. In fact, it is likely that the hull could be made to comply with the conditions of balance by manual adjustment of the C.L.R. position by use of the rudder. However, we aim to keep this use of the rudder to a minimum, achieving the balance desired as far as is possible by suitable shaping of the hull.

It should be noted that this is a problem of design, since once a hull is built it cannot be altered in shape to anything like the same extent as the sail plan. It is easier and cheaper to alter the mast position than to rebuild a hull, and therefore it is obviously important to have some criteria to judge the balance characteristics of the hull of a craft, and also to be able to guess at the probable habits of the C.L.R. during the early design stages.

The mechanism whereby the hull is enabled to comply with the balance conditions above described, is that known as "hydrofoil action." This is exactly analogous to the aerofoil action of sails already discussed at length in Part III, although somewhat complicated by the less easily analysed conditions that prevail. Instead of considering the forces due to the action of airflow on the sails, we now consider those due to the action of the water flow on the hull. The same rules apply, and this hydrofoil action may be analysed and shown by a Polar diagram in the same way as in Figs. 3 and 5 (see Part III) for the case of sails. However, it so happens that there is not at present sufficient data available to present such a diagram for a representative type of yacht's hull. Davidson gives a figure from his six metre experimental results, but this yields only a single point to correspond to the test result marked as "x" in Fig. 5. As one swallow does not make a summer, neither does one test result serve to outline the hydrofoil characteristics of a boat's hull. It will be necessary therefore to examine this matter from a general point of view, quoting the known characteristics of aero- and hydrofoils as the result, mainly of aircraft research work. In fact we need now but little additional information to deduce what is required of a hull design to ensure reasonable balance with the sail plan and thus to secure a well tempered craft.

The Movement of the C.L.R.

Since, as has been seen in Part III, the C.E. movement is, in general, quite small, the range of movement expected from the C.L.R. must also be small. The limits of the movement of the C.L.R. must correspond to the range of movement of the C.E. as shown by Figs. 3 and 5 (say from 0.3 to 0.45, i.e. 0.15 of the overall length of the craft). When movement of the C.L.R. occurs, due to the action of wind or sea on the attitude of the yacht, we want it to be in the right direction and of about the correct amount to follow the C.E. so that either no rudder action, or at most only a little such action, is needed to maintain the heading. If, as a result of wind and sea, the C.L.R. movement tends to be extravagant and out of proportion to that of the C.E., the yacht will be hard mouthed and require the excessive rudder action descrbied in Part I. Just how is it possible to find out whether a proposed design will exhibit a moderate and favourable C.L.R. movement or an extravagant one? It is suggested that this may be done by drawing and examining the shape of the heeled water planes of the hull, an example of one of which is shown in Fig. 2c.

In considering this idea, it is most important to remember that yawing occurs in the horizontal plane. It is necessary therefore, to be concerned with the shape of the sections of the *heeled* hull and keel taken *horizontally* and to consider their reaction to a corresponding horizontal water flow. (Although the water flow about the hull will not generally be horizontal, especially close to the surface, but for a start, this may prove to be a sufficiently accurate approximation). In this way a relation can be seen between the effects of heeling on the horizontal water-plane shape, and hence in the water-forces resulting by reason of hydrofoil action, in the horizontal plane and tending to cause the craft to yaw.

The Production of Laterul Resistance

Fig. 2c illustrates one such horizontal water-plane through a heeled hull. For the time ignore the rudder section shown, and consider only the actual hull shape that results. It can be seen how the angle of heel has produced an asymetrical water-plane shape, whereas everyone knows that when upright, sailing craft are designed and built to have symetrical hull water planes. Thus the hull when heeled forms crude "aerofoil" shapes by its horizontal sections and advancing these shapes through the water at suitable angle of attack (leeway) will generate hull forces in opposition to those due to the sails. See Fig. 2 once more. These hull forces act of course at the C.L.R., the desired behaviour of which has already been defined above. Now, will this desired behaviour of the C.L.R. namely to follow the movements of the C.E., always be inherent in the asymetrical hydrofoil shapes of the heeled hull? Not necessarily. However, by considering the general characteristics of aero- and hydrofoils it is possible to define the *type* of shape that will be the most favourable, and also to point out the characteristics that will be the least conducive to good inherent balance. Confirmation of these considerations can be obtained from experience, and could be got from a series of towing tank tests on various hulls, if someone could be found to do them !

Davidson has pointed out that the hull of a sailing craft has three functions to perform, (a) to displace sufficient water to support the total weight of the complete vessel, (b) to have lateral stability to support the sail plan and (c) to act as a hydrofoil for the generation of FK. I would add a fourth function, (d) to have sufficient accommodation space below and on deck. Thus, in contrast to the sails, whose sole function is to generate sailing thrust, the hull has to be a jack-of-all-trades, and because of this its efficiency as a hydrofoil is comparatively low. The bulbous heeled water-plane of Fig. 2c is indeed a poor shape for hydrofoil action. However, remember that this is only one such section and the others of the fin keel below will be of a more favourably shape. Hence the higher efficiency of fin keels, leeboards, centreboards and similar thin devices for weatherliness and also the relatively poor qualities of the old sailing warship hulls. Lack of efficiency as a hydrofoil is made up for to a large extent by the greatly increased density of water as compared to air (about 800 times) and hence even at the slow water speeds compared to the wind speeds (about 1/5th say), the hull is enabled to generate hydrodynamic forces comparable to those of the sail plan. Hence it is possible to achieve the desired balance of Fs and FK at the low water speeds and at a reasonably small angle of attack or leeway angle. Obviously the smaller the leeway angle at which the hull will generate sufficient hydrodynamic force, the more weatherly will the craft be.

Having appreciated this light on the hull of a sailing craft as a hydrofoil, it is possible to go to the well established general knowledge on such devices and to define the principal characteristics required of the heeled sailing craft for efficiency to windward and for balance in a seaway.

Firstly — it is interesting to notice that the heeling that necessarily occurs when sailing to windward (see Fig. 2 yet again) is undesirable from the viewpoint of crew comfort and sail efficiency, but is highly desirable in order to produce asymetrical hull water-planes that will be more efficient as hydrofoils than the symetrical upright water-planes could be.

Secondly, the asymetrical sections so produced by the angle of heel must be of good clean fair outline, especially those of the fin keel. The hull sections themselves cannot always fulfil this requirement.

Thirdly, a reasonable camber is desired as in the case of a sail (see Part III), so that FK may be generated at a small angle of leeway, and at the comparatively slow water speeds.

Fourthly, excessive camber is to be avoided, for the same reasons as excessive sail camber is undesired, since it means high water drag and excessive fore and aft movement of the C.L.R., making balance difficult to attain without use of the rudder. Furthermore, as the craft heels, any progressive change in camber of the heeled water-planes that becomes extreme will lead to violent C.L.R. movement and consequent bad temper.

Fifthly, if the chord line of the heeled hull water-planes becomes inclined to the direction of the original fore and aft centre line of the hull, as the angle of heel increases, it means that the angle of attack of the hull as a whole has altered, and consequently the C.L.R. will move in the fore and aft direction and upset the balance. This effect follows the same typical pattern as shown in Figs. 3 and 5 for the movement of the C.E. of sails with change in angle of attack, although for the relatively much thicker sectional shapes of the hull, the peak on the curve will not be so marked.

This last item accounts for the basic cause of a craft luffing, or more rarely bearing away, when heeling on a windward heading. It is also responsible for seriously aggravating the yawing of a craft when rolling downwind in a seaway. This too is the fact groped for by Turner in his famous " Metacentric Shelf " balance theory, of which we will discuss more later on. Barnaby in his book has mentioned this dynamic aspect of sailing balance and shows a diagram of heeled hull water-planes, but does not pursue the argument to the conclusions reached here.

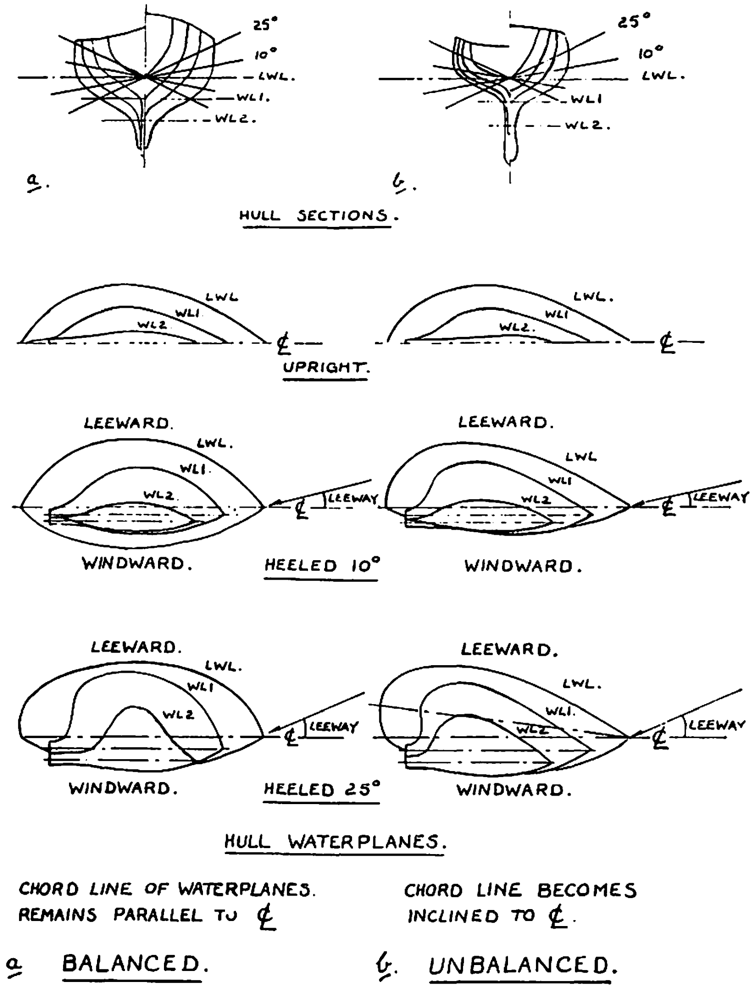


Fig. 8. Hull Characteristics

To illustrate this discussion, Fig. 8 shows upright and heeled water-planes of two craft. 8a is balanced and 8b is unbalanced.

To sum up — for small and favourable C.L.R. movement and hence a Well Tempered Sailing Craft, the hull must be of such a shape that, on heeling, it shows horizontal, asymetrical, waterplanes that are clean and fair in outline, have a moderate camber and do not change camber or angle of attack excessively as the angle of heel changes.

Then the change of attitude the vessel adopts to accommodate changes in wind speed will only cause small C.L.R. movements, compatible with those of the sail C.E. and she is therefore tolerant of a wide range of movement without exhibiting any vicious yawing tendencies.

The Effect of Rudder Angles

Finally, what about the effect of rudder? The action of the rudder is to produce an alteration in the effective camber of the hull

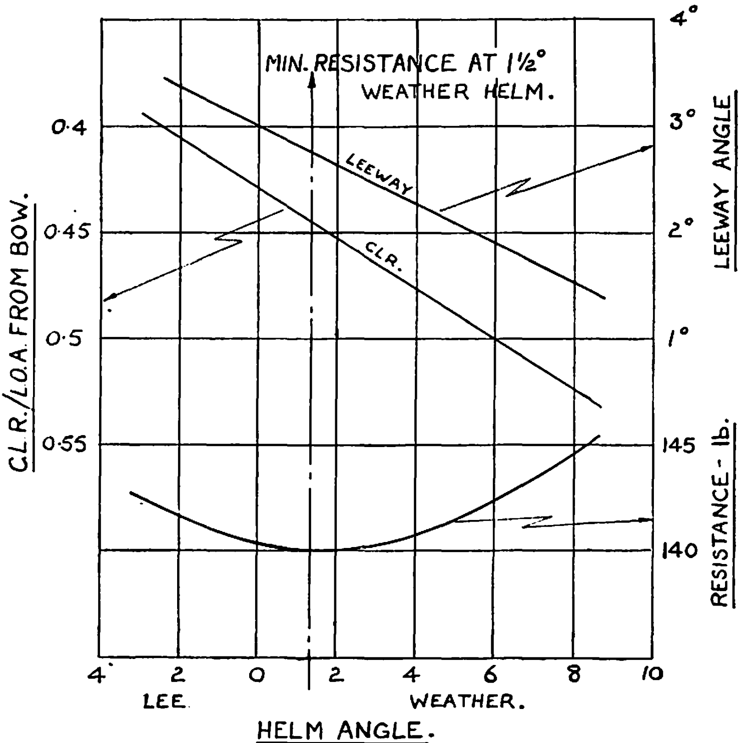


Fig. 9. Effects of Helm Angle on 6 metre hull, at 5.9 kts. and 20° Heel, Davidson

and fin keel. Reference to Fig. 2c shows that the rudder is there shown deflected to leeward (corresponding to weather helm) and that this results in an effective camber on the heeled water-plane, increasing the deflection of the water-flow and thus increasing the magnitude of FK in proportion. However, the rudder angle inclines FK more aft in direction indicating an increase in water drag, and also moves the C.L.R. aft from the position corresponding to " no helm." By this latter action, the rudder acts directly as a balancing device, enabling the C.L.R. to be moved forward for lee helm, and aft for weather helm, until balance is achieved and the craft holds the desired heading. Fig. 9 is taken from Davidson's test results and shows the extent to which the rudder can influence the C.L.R. position. It also shows how weather helm reduces the leeway angle and how excessive helm increases the resistance to motion — or water drag. Clearly it is advantageous to arrange for balance to be achieved under conditions of slight weather helm since, as mentioned above, this gives a worthwhile increase in FK corresponding to the effective camber so introduced, and thus the craft can balance the sail force at a smaller angle of leeway and make better speed to windward.

This is essentially all the dynamics of the theory of sailing craft balance. So far it can only be substantiated by experience and analysis of the lines of craft of known temper. This we will do for two distinct craft of well known characteristics. However, before concluding it would be as well to examine some of the dogmas of " lead," and to try to reconcile Turner's " Metacentric Shelf " theory with the ideas expressed in this publication.

PART FIVE

Methods of Balance

In this section the results of the discussion of Part IV will be correlated with other methods that are in use to attempt to obtain a well-tempered craft. A perusal of the many classic books on yacht design shows that there is frequent mention of the desirability of matching the bow of a craft to her stern. To mention the point is as far as many such authorities go, and of the older classics, it is perhaps Dixon Kemp who retails the most sense on the question of hull shape for good balances. Generally systems of hull shaping seem to fall into three categories, as enumerated by J. Laurent Giles in an article on " Balance " contributed to the Yachting World Annual, 1954 ; these are :

(a) The " Balance Section " system dating from the 18th Century.

(b) The " Metacentric Shelf " system of Engineer Rear Admiral Turner.

(c) The geometrical system of Malden Heckstall-Smith.

Taking each of these in turn comment may be as follows :

Balance Section Method

(a) This is the method of so shaping the transverse sections of the hull at bow and at stern that, when the vessel heels the moments of the volumes of the immersed wedges equals those of the emersed, and therefore the centre of buoyancy suffers no fore and aft movement. The vessel therefore suffers no change in trim as she rolls, in theory anyway. The hull shape is subject to a definite control to achieve this condition, but this cannot be said to be an equally definite control over the balance characteristics of the craft in yaw. It is axiomatic that moments in one plane, such as the longitudinal in this case, cannot have direct influence in another plane at right angles, in this case the horizontal yawing plane. A little thought will show however that the shape of the heeled waterplanes, and the inclination of their chord line (as in Figure 8), is influenced by variation in the transverse section shape that may be made under this system, and therefore there is some indirect influence on the hydrofoil action of the hull.

Whether this influence is favourable or not to balance in yaw is not obvious from consideration of the fore and aft movement of the centre of buoyancy above, so that this method cannot be a comprehensive or direct assessment of temper. It is customary to design so that there is the minimum possible fore and aft movement of the C.B. as the craft heels anyway, quite apart from balance considerations, so that the conditions of the " Balance Section " system are a part of design procedure, but, only a part.

Practical experience shows that quite small changes in trim (induced by shifting internal weights), may make appreciable changes to balance characteristics. This gives a method of adjusting the balance of a craft at any one particular angle of heel, but of course give no guarantee, that as the heel varies the balance will remain unaltered. It indicates, too, that for some craft the changes in hull waterplane shape occurring as the result of small changes in trim have large effects on the C.L.R. position, and therefore, of the lead of the C.E. over the C.L.R. It is considered that badly balanced craft are particularly susceptible to change in trim, and that a well-tempered design following the principles of Part IV would not exhibit such drastic changes in C.L.R. position.

Metacentric Method

(*b*) The most notable and perhaps the most controversial theory extant is that propounded by the late Engineer Rear Admiral Turner, and called by him the " Metacentric Shelf " system. In discussing the principle of this theory it is only fair to get the perspective correct and give Turner the credit for a system that produced well balanced sailing craft and particularly model craft, in which field his designs were supreme before the days of the Vane type of automatic steering gear. For a description of this method as applied to models, but with many discerning comments on full size craft, the reader is referred to articles by Turner in the " Model Engineer " from June 2nd, 1927, to April 18th, 1929, inclusive. For the application of the method to full size yachts, refer to Harrison-Butler's " Cruising Yachts, Design and Performance." The writings of Turner mentioned above are worth reading for their direct sailorly common sense alone, apart from the famous balance system so ably described therein. Harrison-Butler's book gives the detailed procedure for the Metacentric Shelf analysis. but does not venture on deep criticism. There can be no doubt that Turner hit upon a fundamental truth because his system has produced craft that are good, and in some cases, exceptionally well balanced. Unfortunately the theory behind it is based on an absolute fallacy, namely, that heeling moments due to hull displacement can have direct influence on yawing moments —the same mistake in basic mechanics that upsets the " Balance Section " system above. Turner insisted that hull balance was a static affair and gave no consideration to the dynamics of the hydrofoil action of a hull, although he was quite aware of the aerodynamics of sails.

Shorn of the descriptive matter and erroneous assumptions, the principle of the Shelf analysis boils down to this — that the desired state of hull balance may be achieved by so disposing the heeled immersed sectional areas of the hull that their respective centres fall " symetrically " about a vertical plane drawn parallel to the original fore and aft centre line.

To discover just how these centres are related, the hull is divided up into stations equally spaced between the ends of the L.W.L., and taking each transverse section in turn, the centre of area of the heeled immersed portion is found. The horizontal distance between the centre so found and any convenient vertical reference plane parallel to the original fore and aft centre line measured and plotted at the relevant station. A fair curve drawn through all these plotted points will indicate the balance of the hull, so asserts the Shelf Theory. Figure 10 is reproduced from Publication No. 5 of the Amateur Yacht Research Society, " Sailing Hull Design," and illustrates the

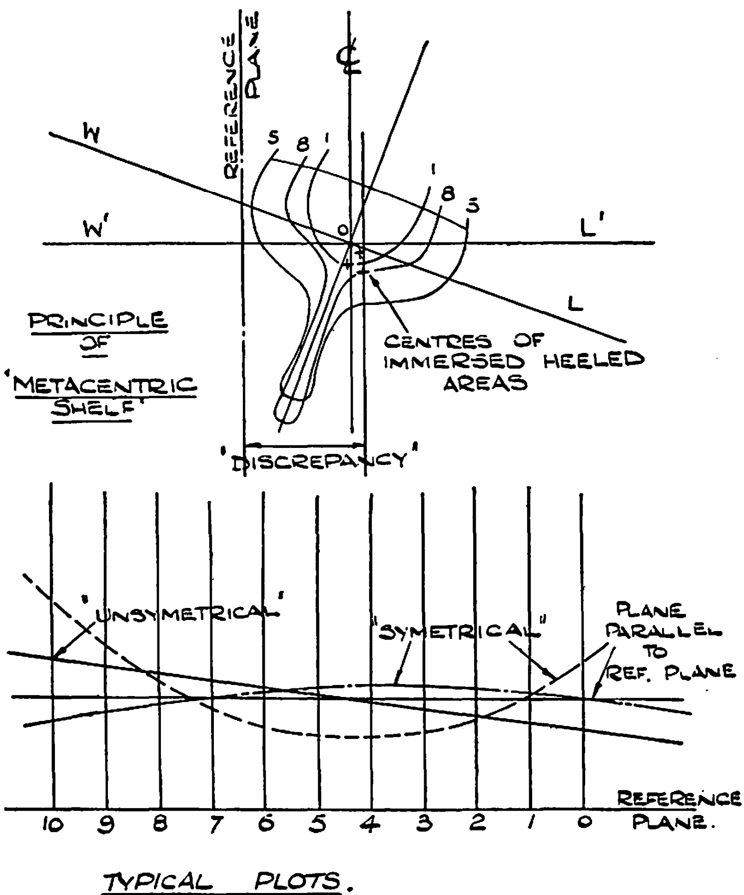


Fig. 10.

procedure just described. It shows three such curves of centres of heeled areas, two " symmetrically " disposed, and one struck " asymmetrically " across a plane parallel to the reference plane and fore and aft centre line. If it is not possible to obtain a condition of approximate symmetry by moving this parallel plane slightly up and down, then the hull is declared to show poor balance such that the craft will be bad tempered. Note that the reference is only used for convenience in plotting and that the curve of centres of heeled areas is assessed in relation to the parallel plane about which it falls symmetrically or otherwise.

It is a fact that hulls showing up well on this analysis have demonstrated excellent balance at sea. Harrison-Butler's " Z " four tonners were well known for their good temper, and have an excellent Shelf analysis. It is also reported however, that other craft of good analysis by the Shelf theory have shown indifferent performance at sea, and alternately some of the poor Shelf analysis have been quite well tempered in practice. There is therefore no absolute confirmation of Turner's principles in fact.

Just what does the curve of centres of heeled areas show ? It is a line, in general a curved line, about which the heeled displacement is symmetrically disposed, equal amounts lying to either side. Thus, if the curve does fall symmetrically about the vertical plane, it can be said that the heeled displacement is disposed parallel to the original fore and aft centre line of the yacht. Intuition might say that this is a reasonable requirement for good hull balance and so indeed it seems, although exact shape as a hydrofoil is not considered, and this is important, as shown in Figure 8, apart from other cogent reasons for the " boat " shape. Compare this requirement of Turner's with the hull balance criteria developed in Part IV of these articles. In considering the curve of centres of heeled areas along the hull. Turner is unconsciously marking the disposition of the heeled hull as a hydrofoil — albeit in a very crude way. A hull displaying the heeled water-plane shapes of the balanced type in Figure 8a, i.e., having chord lines parallel to the original fore and aft centre line will also show a curve of centres of heeled areas disposed " symmetrically " to satisfy the Shelf theory. The converse is certainly NOT true, since a cylindrical rolling pin would show an excellent Metacentric Shelf analysis but hardly produce good hydrofoil shapes in its heeled waterplanes !

Turner owed his success therefore not entirely to his system of balance but also in large part to having a good eye for a fair curve and a seaworthy hull shape. Indispensable qualifications for any designer of sailing craft.

Geometric Method

(*c*) The system of Malden Heckstall-Smith for securing a balanced hull is one whereby the design is built around a master diagonal and an upright L.W.L. shape established by formula. These requirements maintain a geometrical balance in the hull shape, and control over the design is positive. So far no independent assessment of the efficiency of this method in producing a well-tempered sailing craft has been gathered. It is interesting to note that application of Turner's method, described above, leads to the drawing of a fair bilge diagonal, and experimental evidence shows that fair diagonals are one essential for clean water flow. Some eminent yacht designers, Reimers amongst them, design largely on diagonals and Giles has expressed the opinion that a system of design utilising a diagonal of equal shape fore and aft, is conducive to well balanced hull form.

This is all most excellent company, but the method does not attempt a direct influence of the heeled hull shape as a hydrofoil and similarly no direct attention is paid to ensuring small, or no change, of angle of attack on heeling. Such a system of hull balance is incomplete therefore and could only be useful in conjunction with much practical experience of the behaviour of designs built to its requirements.

Comparing the above three methods of hull shaping with the analysis carried out in these articles, it is clear that, of the three, only Turner's Shelf system makes any attempt to assess the hydrofoil action of a heeled hull ; and that is by luck, since the worthy Admiral did not have such an idea in mind. The actual drawing of the heeled hull waterplanes as sketched in Figure 8 is a direct attempt to assess the hydrofoil capabilities of a craft, which, with more experience and the assistance of more experimental evidence, should be capable of development into a method of designing for a definite degree of weatherly ability and good balance. Such a direct approach to the problem is not a characteristic of the other methods in use.

Relation of C.E. and C.L.R.

A few concluding remarks on the subject of the " lead " of the C.E. over the C.L.R. extending the comments in Part II, are appropriate to illustrate the general vagueness existing on this point.

As mentioned before the " lead " usually quoted is that of the centre of area of the sailplan over the centre of area of the underwater profile of the hull. The assumption being that when sailing close-hauled these centres represent the C.E. of the sails and the C.L.R. of the hull respectively. The previous sections and diagrams have shown that this is not true, and that furthermore, both centres can very in position depending principally on the angle of attack of sails and hull respectively. It is unfortunate that insufficient experimental evidence exists at present to enable a reliable set of data to be obtained from which the real C.E. and C.L.R. positions could be estimated for a given design, and hence the relative position of sailplan and hull decided to satisfy the conditions of Figure 2.

Bearing this in mind, together with the earlier remarks in this publication, it is interesting to see what other authorities advise in the matter of the conventional " lead."

The first designer consulted said, quite simply, that the " lead " should vary from 0.05 to 0.20 of the L.W.L. and the " higher the rig " the greater the " lead."

The second authority fairly bristled with figures, distinguishing between centreboard and keel boats, varying the " lead " from Zero to 0.16 L.W.L. and saying that " higher rigs " needed LESS " lead." Full bows and fine runs required more " lead " than hulls with sharp bows, while hollow bows in conjunction with moderate runs needed the least " lead." In general vessels over 100 feet need far less " lead," which remark does tie up with the findings of these articles, since the longer craft will exhibit heeled waterplanes of far less camber than short beamy craft.

A third authority was emphatic that the " lead " should be 0.03 to 0.06 of the L.W.L.

A fourth designer gave 0.02 to 0.10 of the L.W.L. and for beamy scow types 0.15 x L.W.L. Also that the C.L.R. is nearer the bow on a full built ship and therefore the " lead " needs to be increased to allow for this.

A fifth authority did not care what the " lead " was so long as the hull showed a good " Metacentric Shelf " analysis !

Examination of some modern designs shows " lead " up to 0.20 x L.W.L. Photos of the same craft in action often shows quite large angles of helm. Finally Braithwaite in an article to the " Yachting Monthly " of July 1954 entitled " Juggling with their Centres " gives a very frank and factual account of the balancing of four designs, from which the difficulties of deciding on the " lead " with only convention as a guide can be appreciated. Unfortunately he does not show the hull lines of the craft so that analysis as developed here cannot be applied. However, there is a chance that in the near future this will become possible and some valuable additional evidence thus be made available.

To conclude this publication the hull balance of two small modern cruising keeler designs will be discussed, and an attempt make to assess their temper when sailing closehauled.

PART SIX

CONCLUSION

After so much discussion on the complex subject of " balance " in sailing craft, ranging from the general to the particular, and including an attempted summary of the experimental work of many individuals, it is considered most appropriate to conclude by applying the principles enumerated to some typical examples of modern keel type yachts. Initially it was thought that the types chosen should represent extremes of bad and of good balance, but mature consideration indicated that it would be more realistic to confine the examples to successful modern yacht designs, so that some remarks as to their actual performance at sea would be available for comparison with the theoretical background. It is most unlikely that any coherent remarks would be available in the case of a badly balanced boat ! At the best her owner's loyalty would forbid that she be disparaged, and to label her plainly as a bad seaboat may be unfair to her designer, as well as obviously prejudicial to her re-sale value. Figure 8 (Part IV) shows clearly how a badly balanced type would be recognised anyway.

The two representative yachts chosen are illustrated in relevant essentials by Figures 11 and 12. The hull sections are drawn first, followed by the hull waterplanes taken horizontally through the upright hull (at the same proportions of the draught in each case), and heeled at 10 degrees and 25 degrees respectively, reading from top to bottom of the diagrams. Both of the craft have been built and proved to be good seaboats in English coastal waters. Figure 11 is taken from a design by the late Harrison-Butler. It is one he used to illustrate his book, and he " balanced " her strictly according to Admiral Turner's Metacentric Shelf Theory. She does, in fact, show a curve of centres of heeled areas that is practically a straight line parallel to the original fore and aft centre-line.

Figure 12 is taken from the design of a more modern craft by a

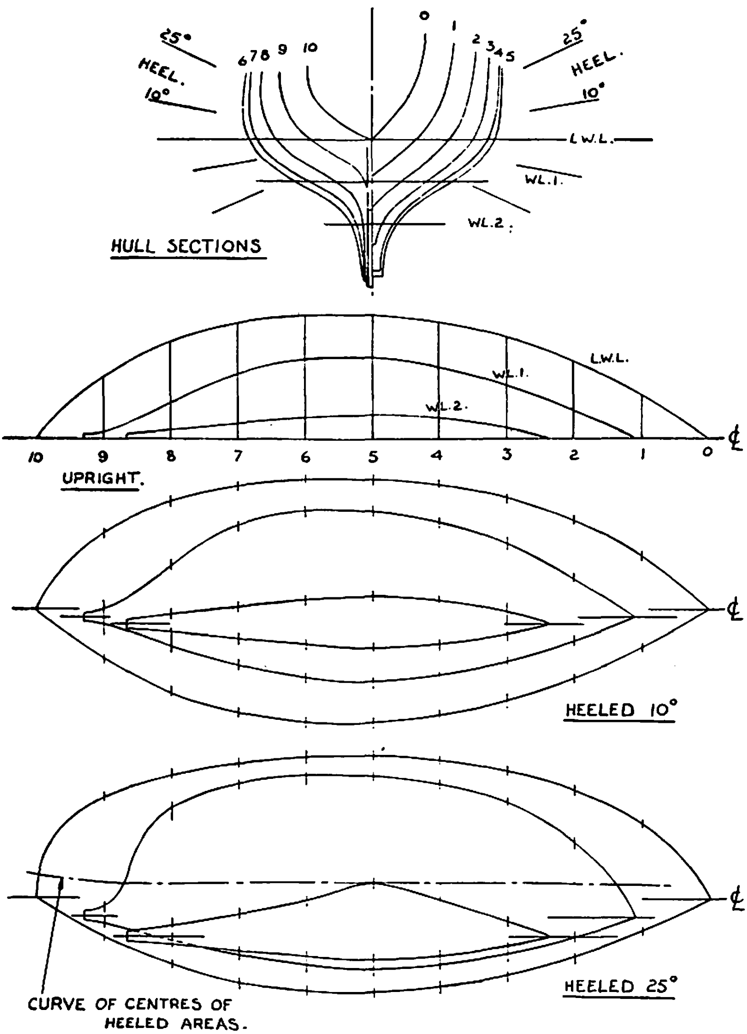


Fig. 11. *Hull Balance of 5.8 Ton Sloop—22 ft. 6 in. L.W.L.*

prominent English designer that, as far as is known, was not balanced by the Shelf system. Her curve of centres of heeled areas shows an "asymmetrical" inclination to the fore and aft centre-line, and therefore, according to the Shelf theory as mentioned in Part V she would be *considered* to be unbalanced. From the conclusions of

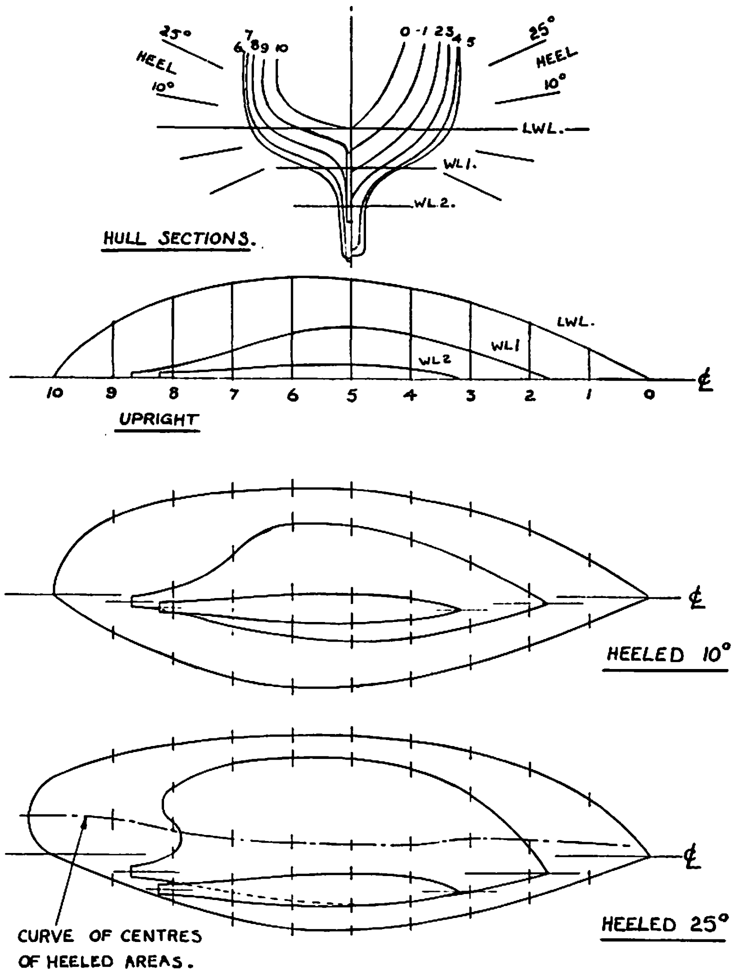


Fig. 12. *Hull Balance of* 3.8 *Ton Sloop*—21 *ft. L.W.L.*

Part IV this is substantiated by her waterplane shapes at 25 degrees heel which show a distinct change in angle of attack and a poor hydrofoil shape at the stern below the waterline, indicating excessive C.L.R. movement.

The profile and sail plans of each yacht have not been reproduced because of space and time limitations, but in each case the rig is that of a stem-head sloop and the conventional " lead " of the centre of area of the sailplan over the centre of area of the underwater profile is 0.163 of the L.W.L. in the case of Figure 11 and 0.083 for the vessel from which Figure 12 has been taken. There is nothing unwholesome about the appearance of either craft ; to the eye of the sailor they would both seem to be most able and acceptable. It is the underwater shape and the hull balance characteristics in conjunction with any remarks available on their actual performance at sea, where the interest lies.

The design from which Figure 11 was compiled suffered a few alterations before finality, and a vessel was built from the plans before the last alteration was made. However, this latter change was only a minor one concerning the disposition of the ballast keel and was compensated by careful re-balance to the Shelf theory. Of the actual yachts constructed to this general design Harrison Butler said, " Three of these yachts were built and I heard good accounts of their behaviour . . . " Nothing more definite is available, but evidently this type is typical of Butlers' designs, noted for their docility in a sea way.

Of the craft built to the design represented by the sections shown in Figure 12 her professional skipper on the delivery trip described her as the " Finest small yacht he had seen or sailed in," and reported that the voyage was made at an average speed of six knots !. " She shows a remarkable ability to windward," he said, " both in the fine conditions then obtaining and in dirtier weather."

Bearing in mind that no designer is likely to include derogatory remarks in a description of his own work, and that the natural jubilation of a hardworking professional skipper in finding a comparatively well tempered sailing craft in his charge after maybe a good many duds may tend to an excess of praise, a comparison will now be made of the two yachts.

Figure 12 shows hull sections indicating a stiffer vessel than that of Figure 11, since the bilge curve is harder. Her draught is relatively deeper and her fin stands out distinctly from the hull body above to a greater degree than in the case of Figure 11. The ratio of ballast keel weight to displacement is about 0.35 for Figure 11, and is 0.42

for Figure 12, therefore in similar conditions craft built to the design of Figure 12 would not heel to the same extent as the Harrison-Butler design. She might seldom exceed say 15 degrees of heel in a fresh wind. Therefore the change in angle of attack of her hull waterplane as she heels to 25° shown in Figure 12 would not be so apparent in practice and she would not need excessive weather helm until the weather became very dirty indeed, by which time windward sailing would be too uncomfortable for efficiency anyway. Note her far better fin shape than in the case of Figure 11. Hence she should show better hydrofoil action and be a weatherly craft, as borne out by her enthusiastic skipper's praise. Furthermore, the slight weather helm necessary to balance her at moderate heel angles (up to 15 degrees say), is conductive to improved hydrofoil action, as explained in Part IV of these articles. She is therefore weatherly on two counts, because of her good fin shape and because of the slight weather-helm she carries. Even at 25 degrees heel, Figure 12 shows that her fin still exhibits a good slim hydrofoil shape although her hull has developed a poor shape and increased its angle of attack a small amount at the water-line, and more below where the knuckle of the counter squats into the water. It follows from this that C.L.R. movement would be excessive when heeling from say 10 degrees to 25 degrees or more. Before the wind when rolling in a quartering sea she is very likely to steer wildly. The delivery trip mentioned by her skipper above was in mainly fine conditions and no doubt she was then at her best. With regard to the claim for her speed, an *average* of six knots corresponds to a speed-length ratio $\left(\frac{V}{\sqrt{L}}\right)$ of 1.3 which is remarkably high. Possibly six knots as her *maximum* was meant and even this is extraordinary for a vessel of only 21 ft. on the L.W.L. and comparatively heavy displacement.

From Figure 12 it is clear that the design could be improved by shaping the stern sections to fair the heeled waterplanes at 25 degrees heel. A small reduction in the change of angle of attack with heel might be beneficial, but lack of more definite experimental evidence on this point precludes further argument at present. At most it is possible to say that the tendency to change angle of attack in the manner shown by Figure 12 is not wholly incompatible with a weatherly craft of acceptable manners. A comparison of tank tests on model of these two designs would be very interesting.

The design by the late Harrison-Butler in Figure 11 shows comparatively poor hydrofoil shape below the waterline at 25 degrees heel and illustrates the deficiency of a hull with no distinct fin. (Compare the heeled shape of WL2 in Figures 11 and 12). Although the angle of attack shows negligible change with heel and she is undoubtedly therefore a docile craft — particularly before the wind — she is not likely to be nearly so weatherly as Figure 12. It is reported that the Z four-tonners by Harrison-Butler ran exceptionally well, no doubt because of their negligible change in angle of attack as they rolled. If anything, Figure 11 could be described as " over-balanced," and a small change of hull shape, sufficient to introduce a small increase in angle of attack with heel would improve weatherly qualities for the reasons discussed above in connection with Figure 12 and also given in Part IV.

Turning attention to the " lead " given in each case for the sailplan centre of area over the centre of underwater profile, what can be learnt ? In neither case does the designer proffer any remarks or opinions. If it is assumed that the conventional " lead " mentioned bears any relation to the real lead shown in Figure 1 and discussed in the earlier articles, why 0.163 of the L.W.L. for Figure 11 and only 0.083 for Figure 12 ? Once more lack of experimental evidence, particularly of the real C.L.R. of hulls, precludes any attempt at analysis. One can refer to the remarks in Part V of these articles and draw some small consolation there perhaps, otherwise this " lead " would seem to have been decided on personal preference alone. It could be argued that, if the hull of a craft is to exhibit the increase in angle of attack with heel, characteristic of Figure 12, then since in this case the C.L.R. moves forward with angle of heel, thus requiring weather helm to restore it to its proper position further aft, then *more* " lead " should be given so that there is less chance of the C.L.R. getting forward of the C.E. and so causing violent luffing. Evidently the values of the " lead " used in these two cases have given no cause for complaint, although this is not to be taken as evidence that no improvement is possible.

Returning to hull line for a final remark, it should be noted that all small sailing yachts will show the general " chubbiness " of waterplane characteristics of both Figures 11 and 12. Therefore the hull waterplanes can be expected to exhibit camber sufficient in itself to promote excessive movement of the C.L.R. with change in angle of attack. Bigger vessels can have slimmer forms so that their hull waterplanes show as much finer in line, and therefore as hydrofoils they do not suffer from such a large proportionate C.L.R. movement and are inherently more efficient. Thus small sailing craft have this built-in penalty of liability to excess C.L.R. movement. However, experience shows that providing it is not provoked by excessive change in angle of attack with heel, it is not an absolute bar to good manners. Beware however of the craft with the lean bow sections in conjunction with a broad flat counter aft, because in such sailing boats as in men, the " mean mouth " indicates bad temper and vicious habits, following on the sort of typical hull waterplanes shown in Figure 8b.

A good deal of personal opinion must necessarily prevail in this business of sailing craft balance. Some like the helm to possess a distinct feel, others prefer complete docility. The former will have the more efficient boat as these articles have shown. Whether the most efficient craft always wins or keeps the sea the best in wild weather probably depends ultimately more on the quality of skipper and crew than on the designer. However, inherent good manners in a yacht will always be desirable and must reflect in the better comfort and therefore efficiency of the ship's company, so that, whatever the weather, both craft and crew remain harmoniously well-tempered.

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