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### EDITORIAL

I suppose that most of my readers will have tried, like myself, to find out how to design a yacht by reading the ordinary books of the simpler kind on the subject. Perhaps they succeeded. I know that I did not. I was therefore delighted to find that, in the manuscript which Charles Satterthwaite sent me, there were all the basic facts of yacht design expressed in the most simple way possible. I found that I could at last master as many of the mysteries as I am likely ever to do.

Unfortunately, the original manuscript would have absorbed too much of the very limited A.Y.R.S. resources to publish in full so that it has been condensed into the short space of this publication. This makes it so that the facts about yachts come closely on the heels of each other.

Readers, who are not already fairly well read about yacht design, may, therefore, have to read this account several times over to get all the hidden inferences. I feel, however, that such an effort will be well worth while and it is quite likely that even experienced yacht designers may find this account of interest.

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# SAILING HULL DESIGN

by Charles Satterthwaite

## INTRODUCTION

The commercial sailing craft is extinct with the exception of the Thames barge and a few schooners in the West Indies and elsewhere, and it is only as a sport that the beautiful art and craft of sailing remains a living thing. For this reason, sailing vessels are only developing slowly while the brains of the nations are concentrating on mechanically driven ships.

The aeroplane has led to a better knowledge of how the sails drive our boats and modern research in hydrodynamics to the understanding of hull form but no consistent programme of scientific enquiry has yet been made with the object of improving sailing craft. Perhaps in the next few years, the spur of International competition, especially the Olympics, will bring this about but, in the meantime, the modern yacht is indebted more to tradition for her shape than to scientific research.

The design of a sailing yacht is no easy matter because it involves not only complex problems of naval architecture but also the often contradictory personal wishes of the owner, the amount of money he is prepared to spend and the comfort of his crew. However, it is a fascinating occupation and, to me, a very satisfying one.

I propose to set out here some elementary ideas on the subject making an attempt to explain the basic natural laws on which the design of sailing craft is based. On the whole, I hope to avoid complex ideas and mathematical formulae to keep the material which I present suitable for the amateur reader. Some of the standard works on the subject are listed at the end for those who wish to go deeper into the matter.

### Section 1

### DESIGN ECONOMICS

Nowadays, money matters and the cheaper the job, the more popular it will prove, always providing it represents sound engineering practice and naval architecture. Time costs money. Material and tools are not so expensive. Thus, we may save by only having essentials and putting purely social and luxury things in their place as auxiliary to the main effort. A good deal of money may be saved on finish. Varnish, for example, is never durable and if neglected, is an offence to the eye. A little extra initial outlay on materials and method to save the everlasting scraping and re-varnishing is a cheaper job in the long run.

The designer has to think of the conditions that the craft he is creating will go through. Rating rules, Tonnage laws or a "bar" at the mouth of an estuary might alter the design or the owner may want a craft which can ride out rough weather with an easy motion like the old-time pilot cutters, or he may want a yacht which will spend her time in deep water running before the Trade Winds. The customer must be satisfied, so that where the owner cannot get what he wants, he must be given the reason.

From the preliminary discussion with the client, we may nearly always form a good idea of the type of vessel required. We are then in a position to check against the local conditions, form an idea of the probable displacement and sketch the sort of vessel we hope will do the job and then again modify it till we feel it is as good as our knowledge will permit. This sketch can now form a basis from which to argue with one's self or customer before starting the design proper.

When the main features of the design and rig have been agreed, the shape of the hull may be laid out to a convenient scale, a sail plan added and, with all the added details of accommodation and fitments necessary to work the ship, there will be a set of plans to hand to the shipwright. The rest of this account will be concerned with the method of working out these plans so that the owner's wishes may be satisfied as far as that is possible.

#### Section 2

### MATERIALS

In former days, the design of a ship was a ritual handed down from shipwright to shipwright and the technical matters were jealously guarded secrets. An East Indiaman, for example, was built to proportions which were invariable and had been schemed out by a process of applied geometry to give a hull of capacity but little hydrodynamic elegance. The same proportions were used to lay off ships of varying tonnage and the construction too, was as inflexible.

Nowadays, we find ourselves in a state of flux. It is still up to us to put our ship together in such a way that it remains in a workable form for a reasonable length of time and have the minimum weight for the maximum of structural strength possible. But our choice of materials is vastly different. The synthetic resin glues have made it possible to build up structural members from thin laminations which are better than if they had been carved out of one huge chunk of wood. Glued joints are better than ones which are nailed, bolted, screwed or riveted.

Scientific construction is to be desired. It is obvious that the traditional methods of boat-building tend to be wasteful of timber and are only partly successful. One often hears of seams opening in the way of the chainplates when a vessel is driven hard in a seaway to windward. It is clear that a continuous skin having the ability to carry stresses and thus eliminate internal framing is much better. Such a skin can be made of resin bonded plywood or fibreglass.

*Wood.* From the structural viewpoint, wood is a material of peculiar gifts. Its strength with the grain is much more than its strength across it. Thus, there is another advantage in using wood in thin laminations since we may dispose the directions of the grain in the various laminations so as to create a material of equal strength in any direction.

The moisture content of timber in its natural state is high but when converted and used, timber gets dryer and shrinks. This may cause serious distortion and even failure of a structure. Thus, we season and shrink the timber before we use it.

Timber is subject to worm and rot unless treated or placed so as to be in a favourable position where such destruction does not occur. Some timbers are very prone to rot and some are amazingly immune. Proper construction and adequate, sensible use of rot-proofing materials will render a timber structure practically everlasting.

Modern glues and modern advances in the art of designing structures have given wood a new lease of life. In my opinion, it will always remain by far the best material for boat-building.

Steel. This is not popular for small craft in the English speaking countries although universal for large vessels. It is a very cold and unkindly material and lacks the comfortable aromatic beauty and wisdom of wood. It is very subject to corrosion and, despite all precautions, it will even nowadays deteriorate quite quickly compared to timbers of boat-building quality. It is harder to repair, if damaged, than timber.

*Alloys.* Light alloys with a high resistance to sea-water corrosion have been successfully used for boat-building. They have not the resilience of steel, their strength/weight ratio is lower and specialised techniques are necessary for their use. Nor have the few yachts which have been built entirely of light alloys yet withstood the test of time.

*Plastics.* Resin bonded glass-fibre has been very successfully used for a wide range of hulls. It seems to be absolutely free of corrosion or rot of any sort and be capable of being permanently coloured to suit one's fancy.

*Composite construction.* Nearly all small craft are of this construction, with steel web floors and reinforcing frames in the way of their masts. Floors, hanging and lodging knees, mast steps and boxes and some frames are better made in metal so that the interior space of the hull may not be taken up with solid lumps of timber. Diagonal strapping to spread the loads from the mast and rigging well over the hulls, is also best made in metal.

### SECTION 3

### STRUCTURE

Our yacht will be built up from many parts. Unless we keep this always in mind, we tend to lose sight of the essential nature of our job and regard it purely as an exercise in draughtsmanship. Let us therefore remind ourselves that our boat consists generally of a backbone, ribs and a skin laid over the skeleton to form the completed shape. The material may be any of those previously mentioned. As we design our hull, we must bear in mind the material we intend to use and the technique we expect from the builder so that when the shipwright comes to translate our tables and drawings into reality, he will bless rather than curse our efforts.

### Section 4

### ACCOMMODATION

It is harder to design the necessary amenities into a small hull than into a large one, though even in the largest of craft there cannot be any deliberate wastage of space. In small boats, such as you and I are likely to own, those few people who are lucky enough to be able to have a craft built will want the most for their money and the fewest frills. The small cruiser needs only a berth, a galley, locker, hanging space, table, two shelves and a stove. This is the bare minimum and the less well off owner could have his yacht built with these and add the rest of the accommodation bit by bit, and even might be able to improve on the original design as a result of his familiarity with the boat as a home.

There are a few principles which combine good hull design with accommodation plans and ensure a strong and efficient hull, often making it a cheaper one.

If possible, it is better to avoid a long coach roof and have a flush deck. This is stronger and cheaper and it makes a deck which is easier to work on. This means reverse sheer in small craft which is not ugly if relieved by a suitably curved rubbing strake to blend it with the waterline. A "Doghouse" is to be blessed. It should give standing headroom over the cabin sole level and, if possible, house the navigator, chart table, radio etc. to form a "Bridge" from which the little ship is run. Having suffered in the fo'c'sle of an 8 meter, headroom 4' 6", I believe such places should be avoided for living quarters.

The galley is usually found well aft nowadays, often to one side of the doghouse, where the motion is least. It should have one big portlight and its own private ventilating system.

Ventilation seldom used to get the attention it deserved so that one is either being well exposed to wind and sea on watch or stifled in a shocking fug of stale air below. Modern accommodation plans are better and recognise the right of the watch below to a share of oxygen.

There are at least three points of importance when planning the "Open" type of interior for a boat which is free from all unnecessary partitions and doors.

(a) Arrange plenty of hand holds of sufficient size and strength so that wherever one is, there is one within reach. This will prevent many an unwanted air trip onto the nobbliest article in the cabin.

(b) Where size permits, I favour at least one watertight bulkhead forward to act as a "Collision" bulkhead in the way of mast and shrouds and designed to be a stress-carrying part of the structure. Aft, I like a bulkhead to shut up the engine in a compartment of its own.

(c) The saloon table is usually far better hinged to a bulkhead or swung from the deckhead above so that it can stow out of the way rather than, as at present, take up valuable floor space.

After cabins, such as were a feature of Stuart yachts seem to be coming into favour. However, a sailing ship is best steered from aft with a tiller in the size of craft we are thinking of so this fashion may not last. An arrangement I have seen in a "Gauntlet" class vessel seems best to me. Here, the cockpit is aft of a small cabin, forwards of which is the companionway arranged transversely. This makes a cabin in which it is possible to have quiet sleep in the watch below, free from the noise of comings and goings in the saloon and galley.

The mast or masts should be stepped on deck so that neither the space below is obstructed by pillars nor the rig distorted to suit the accommodation.

A large enough stove to warm the entire boat often makes the difference between enjoyment and misery. Usually, it is rainwater which spoils a cruise and to be able to go below, change out of soggy clothes and have a brisk rub down in the warmth makes for a happy ship.

The length of cruises undertaken and the type of racing to be followed bears a lot on the accommodation desired. For long voyages, the larder must take up more space than for week-end jaunts only. A boat equipped for ocean-racing in an efficient manner will look a great deal different from one whose economy suffices only for the odd fishing trip.

### Section 5

# BUOYANCY AND GRAVITY

## Every floating body displaces a volume of liquid whose weight is equal to the weight of the body.—Archimedes.

What this law means is that, when we have settled the underwater shape of our hull, we have also defined the amount of water it is going to displace and this gives us the total weight of our vessel.

Fig. 1 shows a vessel floating at her correct L.W.L. (load water line) with all her stores and crew aboard. She has weighed and stowed her anchor and is riding upright with her sails hoisted just before the first puff of wind pays her off on the first leg of a voyage. She is momentarily perfectly upright on a flat surface.

Gravity acts vertically downwards on each and every part of our ship to produce a multitude of little forces, the sum of which equals the total weight of the vessel. The total weight can then be thought of as being one large force acting through a point within the hull, known as the centre of gravity or C.G. as shown in Fig. 1.

Buoyancy consists of lots of little forces too, being the pressure of the water everywhere on the immersed planking. All these forces can also be summed in magnitude and direction to give a single force whose size equals the weight of water displaced by the hull and whose



line of action is directed vertically upwards through a point known as the centre of buoyancy or C.B., also shown in Fig. 1. The displaced volume of the hull can be found quite readily from the lines drawing and converted into the corresponding weight by multiplying by the density. For sea water, 35 cubic feet weigh 1 ton (of 2,240 lbs.).

Figs 2 and 3 show a sheer plan and a cross section of the hull with the C.B. marked on them. It should now be obvious that we



have to arrange our hull weights so that the C.G. falls exactly above the C.B., previously found. When this is done, our vessel will float correctly trimmed fore and aft and with no list to port or starboard.

### Section 6

# RESISTANCE TO MOTION

It is usual to split up the resistance to motion into several headings and deal with these separately. In practice, these all act in unison and have effects on each other, but these mutual effects are of secondary importance. There are three main components :—

- (a) Skin Friction.
- (b) Eddy making Resistance.
- (c) Wave making Resistance.

(a) Skin Friction. Fig. 4 compares (a) the midships section of the "Fair Rosamund"—a slaving schooner of 1832 and (b) that of a



modern 15 ton sloop. It is obvious that the older type had less wetted area in proportion to her displacement than has the modern. From the skin friction angle, therefore, we are worse off with a modern hull than was the rascal who sailed "Fair Rosamund" on the "Middle Passage."

Skin friction is fundamentally shearing action between adjacent layers of fluid, the shearing force being proportional to the viscosity of the fluid and the speed of shearing. The layer of water next to the planking sticks to it and moves as fast as the yacht. Each layer of fluid outside of that one slips on the layer next to it until we eventually find ourselves in free water. Thus, there is a "Velocity gradient" set up next to the planking of the boat within a sheath of water known as the "Boundary Layer." Fig. 5 shows this over a typical length of hull surface.



Initially, the water flows steadily onto the hull at the bows and the boundary layer shows a steady type of flow known as "Laminar flow" where the resistance is proportional to V the ship's velocity. After passing a short distance along the hull, the boundary layer suddenly increases in thickness, laminar flow breaks down and "Turbulent flow" occurs where the resistance is proportional to  $V^2$ , the square of the ship's speed. Laminar flow causes much less skin friction than turbulent flow and Froude, as a result of tank tests, found that the majority of skin friction was due to turbulent flow, so we must keep as much of our hull surface in laminar flow conditions as we can.

The main causes of the transition from laminar to turbulent flow are :

1. Surface roughness.

- 2. An adverse pressure gradient along (and "Waviness" in) the surface.
- 3. The speed of the yacht.

1. A rough hull surface will promote turbulence, obstacles rising sharply from the hull contours breaking up the smooth flow. Skin fittings such as W.C. outlets, water intakes and exhausts behave likewise. Because, however, the layer in contact with the skin moves with the yacht, one should not make too much of a fetish of polishing the bottom. It is enough to have it "Hydraulically smooth."

2. From the bows to about the position of maximum beam, the water flows from a high to a lower pressure which is a "Favourable pressure gradient." The general flow pattern is stable and laminar flow is encouraged. From the maximum beam to the stern, however, the water flows from a lower to a higher pressure which is an "Adverse pressure gradient" and the flow tends to be unstable with turbulence. In fact, transition to turbulent flow probably occurs well forward of amidships. Surface "Waviness" due to a poor shape, not enough frames or too thin plating will cause local adverse pressure gradients which will cause transition in precisely the same way.

3. The speed at which the yacht travels also affects the transition point which works its way forwards as the speed increases.

All we can do to lessen skin friction is to keep our wetted surface to a minimum compatible with other considerations and make it a fair, continuous shape, smooth of finish and with a minimum of skin fittings. We should aim in our design to keep adverse pressure gradient as small as possible and this really means that we should have a long clean run to the afterbody leading the water gently back from the low pressure region amidships to the higher pressure at the stern.

(b) Eddy Making. In this section we shall examine water flows *outside* of the boundary layer. Eddies occur but they are much bigger than the turbulence of skin friction and, though often the two blend, these eddies will be considered separately.

Two definitions and another law are necessary here :

Streamline : This is a line which we may draw in a field of flow ACROSS WHICH NO FLUID PASSES. The laminar flow we have discussed is a streamline flow and the streamlines are drawn in Fig. 5 in the laminar region.

Streamtube: A tube drawn in the field of flow whose walls are composed of streamlines so that the Mass flow throughout the tube remains the same.

Bernouilli's Law: "The total energy content at any and every point along a streamtube remains a constant." This means that, generally, in a streamtube when the speed rises, the pressure falls, and vice versa. Put more usefully, it means that, where the streamlines crowd closer together, there is a fall in pressure. This law does not fully apply in the boundary layer.

Fig. 7 shows some flow patterns about certain shapes. Fig. 7a shows the flow about a THIN flat plate. The first drawing shows it aligned with the direction of flow. Resistance to motion (Rsf) is due to skin friction only and no eddy making resistance occurs because the streamlines are not distorted. At the leading edge of the plate a streamline is drawn ending abruptly. This is the "Stagnation point." The second drawing shows the same plate tilted to the flow so that it has an "Angle of attack" ( $\alpha$ ), of about 5°. The streamlines rise and crowd together over the leading edge of the plate indicating a pressure drop.



Further back, however, the pressure fall causes a slight breakdown of the flow so that eddies tumble off the trailing quarter of the top surface. The eddies blend with the turbulence of the boundary layer. On the bottom surface, the pressure is high because the velocity is lower and instability of flow occurs. The boundary layer is thinner and transition to turbulence is delayed.

Resistance and "Lift." The right hand diagram shows the resultant fluid force, F. This can be resolved into "Lift," L, and resistance to motion, R, perpendicular, and parallel to the direction of flow.

A "Stalled" plate. The third drawing shows the plate at a high angle of attack. The streamlines rise sharply from the stagnation point and try to follow the sloping top surface. They fail and break into a mass of glorious eddies. The plate is then said to be "Stalled." Beneath the plate, the pressure is high and the flow curves sharply upwards under the trailing edge. The right hand diagram again shows F, L and R and we can see how the resistance R has increased and the lift L has decreased as compared with Fig. 7a2.

Fig. 7a4. Here,  $\alpha = 90^{\circ}$  and the plate acts as a dam. The velocity is high at each edge and large eddies form behind it. The resultant fluid force is now all resistance.

Figs. 7b1, 2 and 3 show a cylinder in the flow. The first drawing is of slow speeds and the fluid follows the contours fairly well and the eddies in the wake are small. The second drawing, of medium speeds, shows a marked eddying wake. The third drawing of high speeds, shows violent "Repetitive" eddying where the wake swings to and fro like a happy dog's tail as the eddies are shed first from one side and then the other.

Figs. 7 c, d, e, and f are included to show how fining off the shape aft reduces the size and violence of the wake.

Fig. 7g. This is a shape which might be used for the section of a fin keel. Compared with the three cases of Figs. 7a 1, 2 and 3 above, as the angle of attack,  $\alpha$ , increases, there is a cleaner wake with this shape than with a flat plate, although  $\alpha = 0^{\circ}$ , the value of R is more than Rsf of the flat plate. F is the larger and the ratio of L to R is much greater. In other words, this is a good "Lift" producing section. The streamlines follow this shape better than they do with a flat plate so there is a smoother pressure distribution and, in consequence, a more stable boundary layer. The general flow pattern rises up more and is more deflected downwards which is the cause of the increased value of L. The stagnation point moves aft more as the angle of attack increases.

All the flow patterns which have just been examined show one

FIG. 7. CONTD.

FLOW PATTERNS.



common feature, namely, that the water parts ahead of the object in the stream.

Form resistance. This is a type of resistance whose separate existence is doubted. Fig. 8 attempts to explain the position. Fig. 8a



is the flow pattern in a theoretical, incompressible and inviscid fluid. The arrows indicate the directions and sizes of the forces on it and when these are summed, taking regard to directions as well as magnitudes, they all cancel out and there is *no* resultant fluid force. Fig. 8b shows the same shape in a real fluid such as water. Due to viscosity and eddies, the forces are less and nearly all incline forwards a little. These forces, as opposed to those of Fig. 8a, sum up to give a definite fluid force, F, which is the *total* resistance to motion due to all the sources we have so far considered.

It is within this conception that form Resistance lies but it cannot be said to be an additional source of resistance to motion.

(c) Wave making Resistance. As we increase speed, this rapidly exceeds skin friction, turbulence and eddy making and, at the highest speeds our normal hulls can reach, it is the greatest part of the resistance to motion. Figs. 7 and 8 show that, in general, for good shapes there is high pressure at the bows which causes the water at the surface to rise. A lower pressure is amidships which causes the water to fall below normal level and there is a higher pressure aft which causes the water to rise again. At slow speeds, we get a series of shallow crests appearing along the waterline which, as the speed rises, diminish in number until, at the maximum speed, we find she is sailing on one "Wavelength" only, i.e., there are bow and stern waves and a trough between.

Surface waves travel at a speed which depends on their length and therefore, since the wave system travels with the boat, the wavelength created measures the speed with which she moves. There always seems to be an integral number of wavelengths from the bow to the stern but the maximum economical speed corresponds to the one wavelength condition where the wavelength equals the yacht's sailing waterline length at the time. Overhangs fore and aft make the waterline sailed on longer than the L.W.L.

The creation of these waves demands power from the vessel and this is supplied by the wind. The power required depends directly on the wavelength and on the square of the height of the wave. The height of the waves will depend on the bulk and shape of the hull beneath the water.

It has been noticed from early times that the tendency is for the water to flow *beneath* rather than around a moving ship. Therefore, if we have a deep vessel with steeply rising buttock lines, we will get an uprush of water at the stern which will create a high stern wave. Thus, to keep down the height of the stern wave, we need long flowing bow and buttock lines with the minimum of bulk beneath the water.

Our worthy Editor, in his Two-Hour Design Method, advocates the use of an arbitrary curve of areas which has been taken from some successful yachts. While this practice may produce quite a seaworthy vessel, it should only be used as a rough guide to hull shape. It is much better to consider the fundamentals governing hull shape which lead to clean flow to get minimum resistance, always bearing in mind the patterns sketched in Fig. 7. I do not think that there is any one best distribution of underwater volume which will apply infallibly to all types of sailing craft.

#### Section 7

### WINDWARD ABILITY

Fig. 9a shows a plan view of a sloop sailing close hauled on the starboard tack. The sails are indicated as thin cambered plates. As a result of the air flowing over both the foresail and mainsail, we get a resultant fluid (aerodynamic) force, Fs, as shown, acting at point E, the "Centre of Effort" of the sails.

We want to go in the direction in which our yacht is heading, but the total resultant sail force is trying to move us in the direction of Fs. The force Fs, can, however, be resolved into two components, P and Q, perpendicular and parallel respectively, to the yacht's heading and Q is a small component driving us forward. P, a much greater force, is doing its best to push us sideways. It must be counteracted and we have to rely on the hull to do this. The ratio of Q to P measures the efficiency of the rig on this course. Fig. 9b shows how the yacht



is pressed sideways by the wind, heels and by its leeway angle which is, of course, an "Angle of attack," it generates lateral resistance due to the hydrodynamic action of the hull and fin keel which counteracts the side force of the sails, P. From this drawing, it will also be seen how the heel reduces the effective lateral area as well as the effectiveness of the rig by inclining Fs downwards.

The Fin Keel. A fin keel is a hydrofoil. If we are underway and making some leeway, the keel is presented to the water at an "Angle of attack." As a result of forward speed at this angle of attack, a

lateral force, L, occurs acting to windward in opposition to P whose size will depend on the square of the speed.

Designing for Weatherliness. We have now a choice when designing the hull for windward work. We can rely on plenty of lateral area with the attendant disadvantages of increased wetted surface, skin friction and hull weight or, we can be a little more sensible and fit a moderate fin keel (Fig. 10) shaping it in section as in Fig. 7g to use hydrofoil effect to the best possible advantage.



The effect of the Rudder. The rudder may be used to increase the lift, L, produced by the fin keel as a hydrofoil. When the rudder is set to a small angle  $(3-5^{\circ})$  of weather helm, it gives an effective camber to the fin keel, as shown in Fig. 11, and this increases the lift force.



Centre and Lee Boards. A Centreboard is less efficient than a fin keel because it is a flat plate and where it fits into the boat there must exist a break in the surface with excess turbulent drag. It should be possible, however, to improve centreboards as hydrofoils and even have the angle of attack adjustable. Leeboards are better in many ways than centreboards. Firstly, they can be set to the best angle of attack by suitable chocks on the side of the ship, they can be thick and asymmetrical which produces a larger force for the same size of board and they do not interfere with the water flow on the hull to the same extent. If placed some little way from the hull and sloped at an angle of about  $60^{\circ}$  from the vertical, they can increase the stability of the craft.

Aspect Ratio and Lateral Profile of the Fin Keel. A factor of importance in designing a fin keel shows up in the "End" effects. The "End" here is the lower edge of the fin which is free as compared with the upper edge which is attached to the hull. On the lee side of the hull and fin there is positive pressure and on the weather side, the pressure is low. Some water always flows under the "End" as a result, which destroys some of the hydrofoil action. The broader and stubbier we make the lateral area, as in Fig. 12 (the Thermopylae—a clipper ship), the larger will be this loss. Technically, these effects are related to the shape by the "Aspect Ratio" which is the ratio of the depth (draught) to the mean width (length). The higher the aspect ratio, the more efficient is the fin keel as a hydrofoil.



# FIG.12.

Fig. 13a shows a head on view of a vessel with the lift forces at various levels drawn on it, all of which are equal, which would occur if the section and the angle of attack were the same at all levels.

Smaller free end losses, can however, be obtained by having an elliptical lift distribution as in Fig. 13b. This can be obtained either by having a fin of elliptical lateral profile, or with an arbitrary shape, the fin section can be altered at the various levels to produce lift forces of an elliptical distribution pattern.



# Section 8 SAIL CARRYING POWER

This feature is called "Transverse Static Stability" and is the measure of sail carrying power when close hauled, i.e., "Stiffness," In essence, this depends on the relative positions of the C.G. and the C.B. and how the C.B. moves when the yacht heels. It involves tedious calculations which are not often carried out for yachts.

Consider Fig. 15. This shows a sailing craft hull section containing the two centres both upright and heeled nearly to the covering



board. On heeling, the C.B. has moved down to leeward due to the change in underwater shape while the C.G. is stationary. In Fig. 15b, the total weight of the vessel (W) acts vertically downwards through G and the total buoyancy force (=W) acts vertically upwards through B to produce a righting couple W.GZ. W is constant so the vessel's righting moment is proportional to the size of GZ which varies from zero in the upright position (Fig. 15a) to a maximum and then decreases to zero again usually at an extreme angle of heel such as well over the beam-ends position.

Fig. 16 shows the effect on GZ of variation in the C.G. position in a vertical direction and Fig. 17, the effect of form on the C.B. movement where it will be seen that the flatter the floor the greater will be the movement.

To get the best windward performance, it is clear that we must sail as upright as possible. Fig. 18 shows a vessel upright and also heeled to a small angle by the simple expedient of drawing the new waterline, W'.L'., at an angle to the original W.L. The C.B. has moved from B to B'. The buoyancy acts upwards through B' perpendicularly to W'.L'. and cuts the original vertical centre-line at the point M. It is found that, for all small angles, the verticals through all the C.B. positions cut the original vertical at M.

This point M is called the "Transverse Metacentre" or "Change-point" and, if the C.G. were to fall above it, the vessel would capsize because stability would change from positive to negative.

The "Metacentric Height" is GM and measures the vessel's stiffness or initial stability.

Fig. 19a shows a plank 8" by 2" floating in an unstable way. M lies only just above B and G is above it so the stability is negative. The couple W.GZ tends to overturn the plank and, if it is not held, it will topple over until it floats as in Fig. 19b. It is now immensely stable. M is well above G due to the great movement of the C.B. Rapid movement of the C.B. makes for stability.

Fig. 19b might be taken as typical of a barge which is very stiff at small angles of heel but, should she exceed a certain angle of heel where her deck edge becomes immersed, she is in danger of capsize. In this position the C.B. starts to return towards the original centreline, M comes tumbling down and, when M falls below G, she capsizes. However, by ballasting this type until G is well below B, she becomes the stiffest of boats but she would have a motion which would be very trying on her crew.

A vessel needs adequate freeboard to maintain stability so that her rail does not become immersed too quickly. I think it best to design a vessel so that she will not exceed  $15^{\circ}$  heel in a fresh breeze





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with all plain sail set close-hauled and then give freeboard so that the covering board will reach the water when the angle of heel is  $30^{\circ}$ .

Fig. 19c shows the same plank with its lower half cut to a V section and the displacement reduced to half to allow the same L.W.L. to be used. We see that the metacentre has soared to twice its previous height above B and the plank is now stiffer than ever. Thus, rise of floor may increase stiffness.



FIG. 19.c.

Longitudinal Stability. This can be examined in a very similar way to transverse stability, the same principles being applicable. The longitudinal metacentre is very much higher than the transverse so it takes considerably more force to pitch a vessel than to roll it.

Generally, a sailing yacht will alter her trim when she heels due to small fore and aft changes in position of the C.B. If this is excessive, the craft trims by the head and digs her nose into the seas. A movement of not more than about 1% of the L.W.L. should be allowed.

#### Section 9

### SAIL BALANCE

Balance is exhibited by a vessel when she responds readily to her helm and does not show excessive changes in her state upon being heeled in a squall so that she either luffs or bears away. Rotational movement about a vertical axis is known as "Yawing."

We do not look upon a vessel as being directionally stable in yaw. When she is once disturbed off a given heading, we do not expect her to return to it. However, it is possible to balance her so that she will steer herself and there are the "Vane" and other automatic steering devices which can create an artificial form of directional stability.

It is conventional to "Balance" a yacht by taking the centre of *area* of the sailplan and the centre of lateral *area* of the underwater shape of the hull and putting the former (C.E.) forward of the latter (C.L.R.) by an arbitrary amount known as the "Lead." Neither the true "Centre of effort" nor the true "Centre of lateral resistance" are at the places so found. Fig. 14 shows where the conventional points are and where the actual ones are more likely to be. When sailing, the two centres will be moving continuously according to the vessel's motion, the skill of the helmsman and flaws in the wind so the precise balance is not likely ever to be achieved but this does not matter so long as excessive helm is not necessary to correct them.

It is conventional to balance a yacht in yaw when close-hauled and assume that she will be balanced running and reaching. However, there may be a tendency to bury the bows when running so it is best not to arrange the rig too far forward.

It will be noticed from Fig. 9a that the true C.E. of the sailplan lies to leeward of the centre line of the vessel. This means that Q acts eccentrically on the vessel forming a couple with the resistance to motion of the hull which tends to turn the ship's head to windward. This effect is made worse by heeling which throws the C.E. out still further to leeward. This tendency is balanced by the weather helm we carry since the effect of the rudder is to move the true C.L.R. aft a little thus increasing the lead of the true C.E. over the true C.L.R.



# Section 10 HULL BALANCE

This is concerned with the mutual balance of the hull sections among themselves. All we have to go on is the "Metacentric Shelf" analysis of the late Rear Admiral Alfred Turner. The theory behind this is incomplete and in many particulars completely false but, using his method, he designed and built such very successful model racing yachts that there can be no doubt that he had hit on a fundamental truth. Harrison Butler applied the analysis to full size yachts and produced balanced vessels which were docile and well behaved.

Shorn of all non-essentials, the analysis is thus : The immersed sectional area of the heeled hull should be disposed so that their respective centres fall "Symmetrically" about a vertical plane drawn parallel to the original fore and aft centreline.

Fig. 20 illustrates the system. A hull is heeled to  $30^{\circ}$ . The centre of each underwater section is plotted and a fair curve is drawn through them. The reference plane is not necessarily the plane



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through M or the plane about which the curve we plot may fall. However, the curve so drawn should be "Symmetrically" disposed about some vertical plane parallel to the original reference plane and if it *not* possible to obtain this condition by moving the plane a little up and down, then the hull is declared to be "Not in balance." Fig. 20 shows some typical plots. Two are approximately "Symmetrically" disposed and one is definitely struck across the plane so that it is "Asymmetric." If the plane we finally draw happens to be the one passing through M, the transverse metacentre, the hull is a "Metacentroid."

It is doubtful why this analysis helps in hull balance. It is my opinion that it is the shape of the horizontal waterline planes of the *heeled* hull which should be examined for balance. If they produce hydrofoil action which causes excessive yawing, then she will be hardmouthed. In an unbalanced hull, the C.L.R. moves excessively on heeling.

Fig. 21 shows balanced and unbalanced hulls viewed from beneath both being heeled to about 10°. I think that it is the pronounced hollow in the shape of the after end of No. 2 W.L. of the unbalanced hull which causes the resultant fluid force to act right forward to produce the excessive weather helm.



# Section 11 SEA KINDLINESS

Some people seem to enjoy having their teeth loosened, plugging to windward in a Channel chop, while others are at home rolling scuppers under in the Trades (happy folk!). For each type, the ideal would be to have vessels with different characteristics. Seakindliness may be defined as the property possessed by a vessel to blend herself into the moods of the sea so as to induce a motion having the minimum of disruption to the physiology of her crew.

The motion of a craft will depend on the total weight and its disposition in the hull whether spread out or concentrated. It will also depend on her shape, i.e., her lateral profile, her bow and stern sections and the way they are blended together. There are six types of motion :

(a) Forward or astern motion. These will appear as the secondary effect of the pitching of the vessel in a long swell.

(b) Vertical motion. In an ocean swell, heaving may cause vertical accelerations of real inconvenience to the stomach. The wide, shallow flaring hull of light displacement like the Colin Archer type is worse than the deep, narrow, heavy hull.

(c) Sideways motion. The vessel is designed to discourage this motion so it is not likely to be violent or severe.

(d) Yawing. When the seas come rolling up on the quarter, as each wave overtakes the yacht, she pitches, rolls and yaws. Rudder movement may make this worse by being too late to correct one yaw and consequently be just in time to accentuate the next one. It is better to let her run off a bit and overcorrect to make up for the diversion.

(e) Rolling. The combination of the period and direction of the seas with the speed of the boat produce what is known as "The period of Encounter." The vessel herself, in still water, if set rolling will swing to and fro at a rate depending on her weight, its disposition in the hull and her form, i.e., whether she is a stiff vessel or not. This is her natural rate of roll. Should this rate of roll, however, coincide with the "Period of Encounter," the amplitude of the roll may increase until she capsizes.

Experience shows that the most damaging and inconvenient part of the motion is that where direction is changed at the end of each roll. Here, the acceleration imposed on the vessel is greatest. Consequently, inertia forces are greatest and should they exceed the strength of any particular part, a chain plate for example, we could lose the mast over the side.

Deep draught vessels with a judicious midships *concentration* of weights can have a very comfortable motion although their sluggishness makes them wet. Shallow draught vessels of reasonable beam with a judicious *distribution* of weights may have an equally comfortable motion and they have the advantage that their form is inherently "Lively" so that they are more adaptable.

(f) Pitching. Due to the greater height of the longitudinal metacentre above the C.G., the natural rate of pitching is faster than that of rolling. A vessel will tend to pitch more violently in a short steep sea. The faster she sails, the shorter will be her "period of encounter" with a head sea so she will pitch more violently when going fast to windward.

General considerations about motion. Long overhangs fore and aft of a broad V section will "Slam" in a head sea and be liable to be "Pooped" in a following one. Deep V sections and canoe sterns give an easy up and down motion which is quiet and comfortable.

### Section 12

## THE SUPPORT OF THE SAIL PLAN

Many and varied, slight and severe strains are imposed on the hull by the mast, the rigging which keeps it up and the sheets which keep the sails correctly trimmed. The mast may be stepped on the deck or keelson, each having problems of design. Bulkheads and metal straps may be used to spread the loads. Loads appear at winches, cleats, horses and fairleads. The strengths of all these parts can only be estimated by experience.

### CONCLUSION

The way of a ship in the midst of the seas has long been a mystery. We now have an idea of *some* of the answers to a *few* of the problems. The mystery goes beyond the arid academic world of the lecture room. Students of sailing craft must be sailormen as well as philosophers with a scientific bent and the solution of all the problems may never be complete in all details. A sailing ship is one of the few creations of man which has the power to teach its designer and builder more than his simple mind can comprehend.

### ACKNOWLEDGEMENT

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