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THE MECHANICS OF SAILING SHIPS AND YACHTS

BY K. S. M. DAVIDSON

A persistent urge for higher speeds under sail has stirred man's imagination from earliest times. Through the long centuries of sailing, the peculiar exhilaration of speed got into his blood. Besides, faster ships always had an advantage over their slower rivals, in both the merchant and military services. Now, when only yachts are driven by sail, the special flavour of making a fast passage without benefit of power and the fun of racing continue to weave their spells. Speed has perhaps an even greater hold today than ever before. The fascination of it seems destined to continue indefinitely.

But all through history the desire for speed has had to be tempered in varying degree to accomplish other ends. Cargo-carrying capacity and sea-keeping ability have tended to demand considerable fullness of hull form, and this works against speed. Thus, looking back a long way, it is not surprising to find that two fairly distinct design trends are distinguishable. In large ships intended to carry cargoes on long voyages, the hull forms became very full, while in small craft intended only to carry a few men on shorter voyages or in fine weather the lean lines of the earliest log canoes were retained. The small craft were relatively faster for their size, while the large ships had wider uses and were able to keep the seas in all reasonable weather.

Modern cruising and racing yachts are descendants of the large square-rigged ships of a hundred years ago rather than of the small log canoes of antiquity. They reflect much the same philosophy as the ships, in the balance struck between speed and other qualities. They have good space below decks, and they are thoroughly reliable sea-boats. Nevertheless, their average speeds size for size are just about double those of the square-rigged ships.

Much of what follows relates to this remarkable accomplishment. The roots lie deep. Many ideas and countless experiments have played a part. The connecting thread is a progressive improvement in the ability to sail close to the wind. Most of the differences of design between the old ships and modern yachts bear in one way or another on windward performance, and windward performance accounts in no small measure for the two-to-one gain in average speeds.

In the main, the modern yacht was evolved from the background of the past. Nor has it yet received extensive study in the light of what is now known about hydrodynamics and aerodynamics. The tremendous activity in these two fields, stimulated by the needs of power-driven ships and of aeroplanes, had not even started when the essential features of the modern yacht began to emerge, soon after the middle of the last century. It is therefore especially interesting to apply modern knowledge and methods of hydrodynamics and aerodynamics to the yacht, to examine what has been accomplished up to this time, and to study the chances for further improvement. A good deal of attention is given to recent efforts in this direction.

The story would not be complete without some mention of high-speed sailing craft, in which space below decks and sea-keeping ability are made secondary and speed is given first place. In small sizes, as has long been known, hull fullness can be greatly reduced without reducing sail area because the lateral stability needed to carry sail can be provided by other means such as shifting the crew to weather. This is the principle of the earliest log canoes and of many modern small craft. Speeds can be increased in this way by something like three times. It is possible to visualize further increases of speed to perhaps six or seven times in sheltered waters if more drastic steps are taken to provide lateral stability or its equivalent.

PART I

There is much evidence to support the statement that, size for size, the average sailing speeds of modern yachts are of the order of double those of the old square-rigged ships. The evidence is sampled in table 1. The term 'size for size' refers to the well-known fact that mere increase of size with no change of design will increase sailing speeds roughly in proportion to the square root of the increase of length. Thus in comparing the speeds of different types of vessels or craft it is not speed alone that counts, but speed in relation to length, or relative speed $V/\sqrt{L}$. Table 1 shows both actual and relative speeds. There is a striking uniformity among the relative speeds for each type, and a ratio of just about one-to-two between the mean values for the two types.

Table 1. *Average sailing speeds*

Date	Type	Average actual speed V (knots)	Length overall L (ft.)	Average relative speed $V/\sqrt{L}$	Remarks	
1492	Columbus	$3\frac{3}{4}$	70	0·45	Good passage	Square-rigged ships
1837	Sumner	$6\frac{1}{4}$	200	0·44	Good passage	
1850	Clipper ships	6	250	0·38	Mean figure	
1902	*Preussen*	7	410	0·35	Mean figure	
1935	*Stormy Weather*	$6\frac{1}{2}$	53	0·90	Good passage	Fore-and-aft-rigged yachts
1935	6 m. boats	$5\frac{3}{4}$	36	0·97	Mean figure	
1935	J-Class boats	$9\frac{3}{4}$	135	0·84	Mean figure	

Columbus's speed of $3\frac{3}{4}$ knots is for his first westward passage from the Canary Islands to the West Indies, 3100 miles in 34 days. He himself seems to have considered this a very good passage, and it is supposed that he must have carried the north-east trades behind him most of the way.

Sumner was the ship captain after whom the 'line of position' method now used generally in celestial navigation was named. Describing the incident that led to his discovering the method, he wrote: 'Having sailed from Charleston, S.C., 25 November 1837 bound for Greenock, a series of heavy gales from the westward promised a quick passage; after passing the Azores the wind prevailed from the southward, with thick weather; after passing longitude 21° W. no observation was had until near the land, ... The weather was now more boisterous and very thick, and the wind still southerly; arriving about midnight 17 December, within 40 miles, by dead reckoning, of Tuskar light, the wind came south-east, making the Irish coast a lee shore....' The distance is about 3300 miles, the time 22 days, the speed $6\frac{1}{4}$ knots. Sumner obviously held fair winds with plenty of strength.

Columbus's and Sumner's voyages probably represent nearly the best performances that could be made by sea-going vessels in their respective eras. Both were by square-rigged ships under favouring conditions. There is no great certainty as to the sizes of the ships, but their lengths cannot have been very far from the figures given in Table 1. The two relative speeds should therefore be directly comparable, and the fact that they are nearly the same suggests that there was not much real improvement in performance between 1492 and 1837.

Contrast these voyages with *Stormy Weather*'s $6\frac{1}{2}$ knot speed in 1935—a hundred years after Sumner. *Stormy Weather* is a modern sea-going yacht, designed for ocean racing or cruising and a thoroughly able sea-boat. On a length of only a quarter of Sumner's ship, she bettered his actual speed by something like one-quarter of a knot, over much the same distance, 3100 miles from Newport, R.I., to Bergen, Norway, in 19·2 days. Her relative speed was twice Sumner's. Further, her passage was made in June, in variable summer weather which included a week of head winds and only two days with the wind free enough for a spinnaker. Nor is this passage to Norway an exceptional one by modern yachts. It is a good passage, but there are plenty of others which are at least as good and not a few that are better. *Bolero*, somewhat larger than *Stormy Weather* but otherwise much the same, averaged

$$\begin{aligned} V/\sqrt{L} &= 0{\cdot}99 \text{ in the 1950 Bermuda race} \\ &\ 0{\cdot}68 \text{ in the 1954 Bermuda race} \\ &\ 0{\cdot}83 \text{ mean.} \end{aligned}$$

The Bermuda race, 635 miles from Newport, R.I., is rather too short to ensure a good averaging out of the weather. But the mean figure for the two races cited should compensate for this, as the first race was sailed in fresh winds and the second in light breezes; the mean is not far from *Stormy Weather*'s relative speed to Norway. Incidentally, the two figures for *Bolero* give an idea of the spread that is likely to occur, and it will be noted that even the lower figure is fully half as much again as the mean figure for square-rigged ships in table 1.

The remaining entries in the table are rather rough mean figures, but they add corroboration. The 6-knot speed given for the clipper ships of the 1850's or thereabouts can be deduced from reports of the 'record' long-distance passages of these vessels—Hong Kong to London, Plymouth to Sydney, and so on—that were considered noteworthy at the time and have gone down in history. The 7-knot speed for *Preussen*, one of the last of the big German square-rigged ships, built of steel, was worked out by her captain from his own long experience and is based upon a goodly number of voyages in the Chilean nitrate run to Europe. The speeds for the two modern racing classes are long averages for day-racing by these classes under all kinds of conditions. It has been said that the J-boats, the large yachts which used to race for *America's* cup before the last war, were the 'fastest all-round sailing vessels ever built'. Table 1 rather confirms the statement, giving them a wide margin of actual speed.

Table 1 includes only wholesome boats, able to keep the seas in all reasonable weather. Even the racing classes listed are remarkably good sea-boats. When the J-boat *Yankee* crossed from America to England in 1935, her navigator, a man of great experience in ocean racing, was loud in his praise of her sea-going qualities. The outstanding feature of sound sea-boats is their reasonably great fullness of hull form, which gives them reasonably high displacement in relation to length. It is characteristic of all hull forms of this sort that their resistance curves take a sharp upturn, due to heavy wave-making, at relative speeds $V/\sqrt{L}$ of only a little more than unity, as sketched in fig. 1. This puts a fairly effective limit on the maximum relative speed that can be reached. For no way has yet been found to avoid the sharp upturn by modifying the hull shape without reducing its fullness, and there is a limit to the driving force that can be developed by the rig even under the conditions most favourable for maximum speed, namely, a broad reach with a lot of wind well abaft the beam. Supposing the wind to be increasing, there will always come a time when sail has to be shortened either to avoid damage to the rig or for some other reason.

The maximum relative speed cannot of course be stated exactly. But if the extra speed now and then added, by coasting down the fronts of following seas, is disregarded, the figure

$$V_{\text{max.}}/\sqrt{L} = 1{\cdot}15,$$

based on overall length, appears to be roughly representative of wholesome boats in general. There are numerous records of clipper ships having logged about 18 knots for perhaps a day or even for 2 or 3 days at a stretch, which on a mean length of say 250 ft. corresponds to a relative speed of almost exactly 1·15. *Stormy Weather* once logged 8·8 knots for about 48 hours, corresponding to a relative speed of 1·20, but this was in big following seas. The J-boats reached

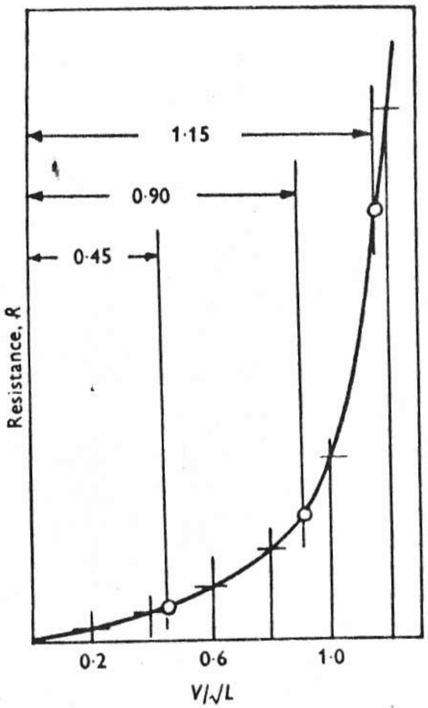

Fig. 1

about 13·5 knots at their maximum, corresponding again to a relative speed of 1·15.*

Maximum relative speeds have therefore remained largely unchanged, while average relative speeds have doubled. Hence the ratios of average to maximum speeds have doubled, increasing

from (say) 0·45/1·15 or roughly 4/10 in square-rigged ships
to (say) 0·90/1·15 or roughly 8/10 in modern yachts.

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* Incidentally, power-driven merchant vessels today do not exceed this figure. The first *Mauretania* at 29 knots had a relative speed of 1·07, the *United States* at 35 knots has a relative speed of 1·11.

These ratios are instructive in their implication for the future. They show that average relative speeds have now been brought so close to the maximum relative speeds set by heavy wave-making resistance that further improvement along the same general lines of development must of necessity be of more limited magnitude. This does not, however, detract from the remarkable advance that has actually been made in the last hundred years or so.

The improvement of two-to-one in average relative speeds cannot in truth be laid to any single thing. Nevertheless, the underlying pattern is clear: a progressive improvement in the ability to carry sail and to go to windward, that is, to make progress against the wind. If there is any one thing that is sure, it is that average speeds of the order of 8/10 of maximum speeds could not possibly be attained unless good progress could be made in head winds.

Looking back a long way into history, surely it was an easy step, once a manageable boat of sorts had been contrived, to think of hanging up an expanse of cloth or woven rushes to catch a favouring breeze. The idea must have occurred quite naturally to almost anyone with the least ingenuity who had experienced the enormous difference between pulling upwind at the oars and drifting gently downwind without effort. Thus it is not surprising to find that the earliest representations of sailing boats show a rig designed to the best advantage for sailing before the wind. A rectangular sail hangs from an horizontal yard, which is slung ahead of the mast to allow the sail to belly out forward. This is the simplest form of the square rig.

It must soon have been discovered that the wind could be brought around somewhat on to the quarter to sail a course a few points away from the wind direction (see fig. 2). The sail could be trimmed to remain about at right angles to the wind. The lateral component of the sail force would be relatively small and would not cause much sidewise drift. But there the matter seems to have rested for at least two thousand years. Eric the Red's ships and William of Normandy's ships had simple square rigs.

Nor was there any basic change until long after that. More masts were fitted, and topsails, topgallant sails, and royals were added as the ships grew bigger. These changes avoided the difficulties of making and handling larger individual sails, but they did not accomplish much else. There is little to indicate that any real advance was made for several centuries in sailing closer to the wind. It was evidently taken for granted that this could not be done. Apparently everyone expected either to wait for fair winds or to take his chances of being blown off course. The effort was devoted to

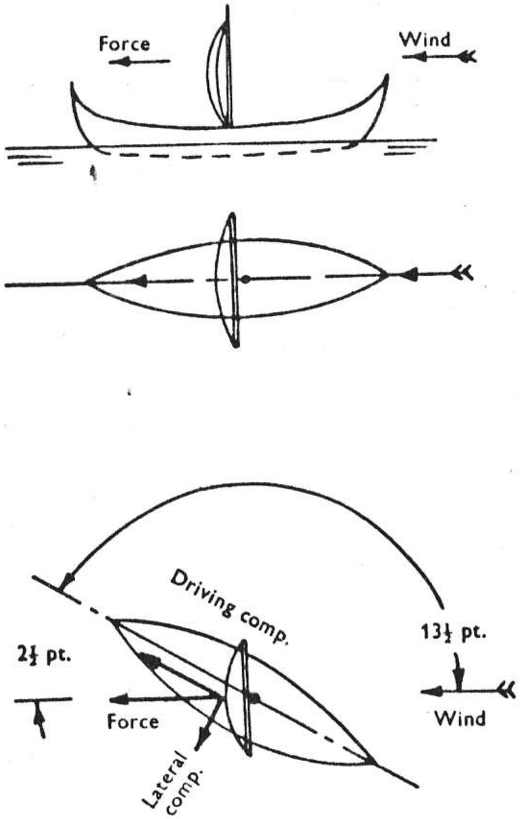
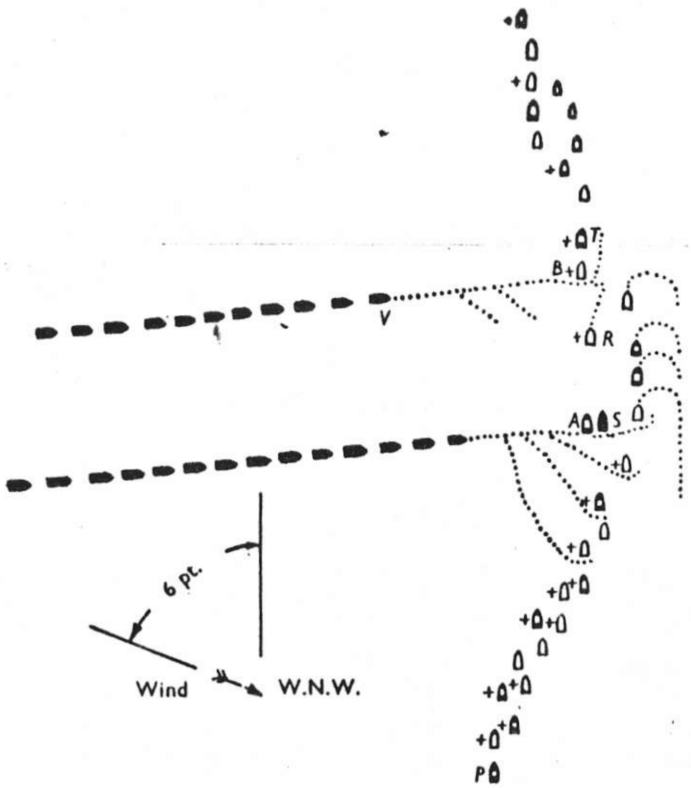


Fig. 2

developing such features as forecastles, after-castles, exaggerated poops, fighting tops and the like, which, far from helping the ships to sail closer to the wind, must effectively have prevented their doing so. To judge by the drawings of ships of the fourteenth to seventeenth century, nearly as much force must have been created by the windage of the superstructure and rigging as by the sails. But of course the force due to windage would act almost exactly down wind and could not possibly contribute to sailing closer to the wind.

It was not much before Nelson's time that the ungainly excrescences of the earlier ships began to disappear. There is plenty of evidence that the advantages of windward ability were obvious to Nelson. They must have been recognized widely in his day. Seaborne commerce and naval power had become large issues, commanding a great deal of thought and attention. Diagrams of the battle of Trafalgar show the combined French and Spanish line at about six points from the wind before action commenced (fig. 3). It is unlikely that six points were being made good. The wind was light, and texts on seamanship of the period and for some time thereafter dwell at length upon the liberal allowances that needed to be made for sagging off to leeward. Seven points would probably be nearer than six as an estimate of the course actually being sailed. But seven points is a very considerable improvement over the twelve points or so which must have been about the best that could be done by the ships of a century or two earlier. Seven points not only avoids losing ground in head winds but permits a little progress to be made to weather. Would Nelson have dared sail to Egypt in 1799, giving up the weather berth in the prevailing westerlies of the Mediterranean, if, failing to meet the French, he had had no chance of getting back to the westward in reasonable time? On the other hand, how much easier would have been his decision to sail east if his ships had been able to make 3½ points from the wind, like modern racing yachts.

Actually, for the same sailing speed, 3½ points produces four times the speed made good dead to weather when compared with 7 points, and twice when compared with 6 points, as is shown by fig. 4. The clipper ships of the 1850's could probably do 6 points as against Nelson's 7 points. Thus the improvement over the clipper ships of two-to-one in average relative speeds which has been effected in modern yachts is consistent numerically with the improvement effected in windward ability. It would be a mistake to read too much into this close numerical correspondence, for windward ability is obviously not all that is required to maintain high average speeds. Windward ability is nevertheless a vital factor. Witness, for example, the Bermuda races that have been cited, in both of which *Bolero* was close-hauled on the wind or nearly so for practically the entire time.



The attack at Trafalgar
21 October 1805

Five minutes past noon

▶ British, 27 ships
▷ French, 18 } 33 ships
▶ Spanish, 15

The French and Spanish ships marked + were taken or destroyed in the action

References

A, *Santa Ana*, Alava's flagship
B, *Bucentaure*, Villeneuve's flagship
P, *Principe de Asturias*, Gravina's flagship
R, *Redoutable*
S, *Royal Sovereign*, Collingwood's flagship
T, *Santissima Trinidad*
V, *Victory*, Nelson's flagship

Fig. 3

Of all the changes that have contributed to the great improvement of windward ability in modern times, probably the most important is the shift from the square rig to the fore-and-aft rig (fig. 5). At any rate it is fair to say that the improvement could not have come about without this shift. For the square rig was quite unsuited to close windward work.

In order to sail on the wind at all, it is evidently necessary that the sail force lie far enough forward of abeam to have an appreciable driving component along the course. This in turn requires, first, that the apparent wind meet the sail at an angle to its mean plane, as in an aerofoil, rather than straight on; secondly, that the lift/drag ratio of the rig as a whole be reasonably high. These conditions apply, of course, to either type of rig.

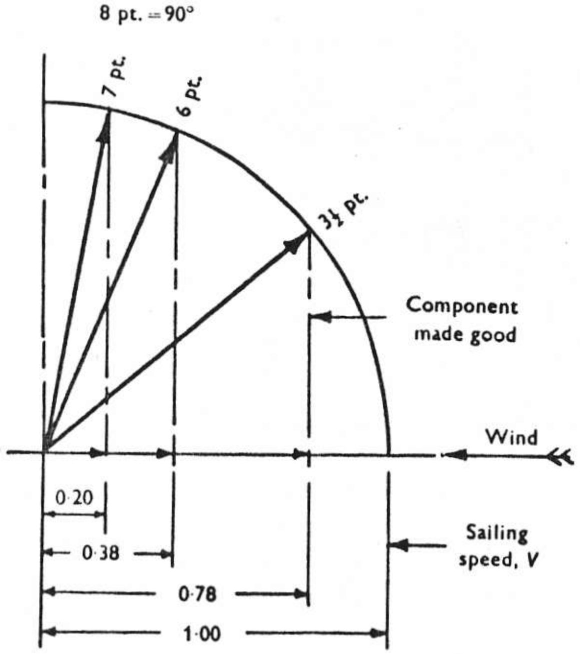
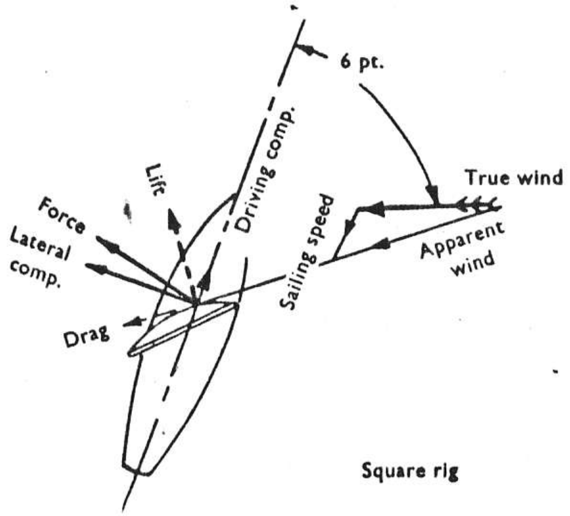
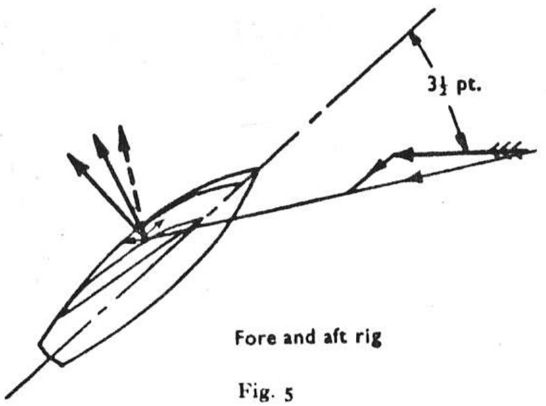


Fig. 4

The basic difficulty with the square rig seems to have been that the weather leech, or leading edge, of the sail could not be set up hard enough to make it stand properly. Not being attached to a spar as in the fore-and-aft rig, there was no way to get a good enough purchase on it to prevent its sagging off badly and very likely coming aback when the ship's head was brought to even 6 points from the true wind, the apparent wind then coming from somewhat farther ahead. Another problem with the square rig, particularly in larger sizes, was to find a way of carrying the weight of the heavy yards while at the same time allowing them to be braced around to more than about 45°. No doubt this problem could have been solved. But besides the difficulty with the weather leech there was the further complication that unless the foot of the sail was cut very high it



Square rig



Fore and aft rig

Fig. 5

would foul against the shrouds when braced around. Six points was for these reasons about the best that could be done with the square rig.

None of the same difficulties plague the fore-and-aft rig. In its modern form the luffs, or leading edges, of the mainsail and jib are supported by the mast and headstay respectively. The mast is, of course, stiff, and the headstay stands well when the sails are sheeted down hard because it takes the whole aftward pull of the mainsail and carries a lot of tension.

In its essential features the fore-and-aft rig is by no means new. Its development can be traced from a long way back. The essential features are the full support of the luff and the fact that the sail is abaft the shrouds instead of ahead of them and can therefore be flattened in without limit. These features were present in various forms of the lateen rig which existed at least six or eight hundred years ago. The lateen rig can itself be considered a fairly direct development from the square rig. It involved only two basic changes, namely, slinging the yard under the shrouds instead of above them, and then canting it until finally the sail became triangular instead of quadrilateral. With these changes both sides of the sail could meet the wind, on alternate tacks. This meant, however, that whereas the sail could belly out away from the mast on one tack, it was blown against the mast on the other, as shown in fig. 6. Hence the sail had a single smooth camber on one tack, but was less effective on the other tack because it was 'cut' by the mast into two shorter cambers. Possibly the idea of actually splitting the sail into two parts, to form mainsail and jib, evolved at about this point in history. The overall configuration of the lateen rig, which was quite a good one from a modern point of view, would not thereby be much altered and the performance would become the same on both tacks. In addition, the chafe of the single sail against the mast would be eliminated.

Whatever the true historical sequence of events, the fore-and-aft rig was certainly well known in smaller boats when the square rig was still in its heyday for large ships a hundred years ago. In fact, all of the square-rigged ships of that time carried jibs and mainsails of the fore-and-aft variety in addition to their square sails. There were many jibs and these were supplemented by triangular staysails between the masts. There was at least one 'mainsail' called the spanker, on the mizzenmast. Indeed, the gradual shift from the square rig to the fore-and-aft rig was already well under way.

Why was the shift to the fore-and-aft rig so gradual? It cannot have been for any lack of appreciation of the need for increased average speeds. The large square-rigged merchant ships were already being hard pressed by the early steamships and speed was the order of the day. Moreover, the ability of the steamships to make progress in head winds was being urged as a strong point in their favour.

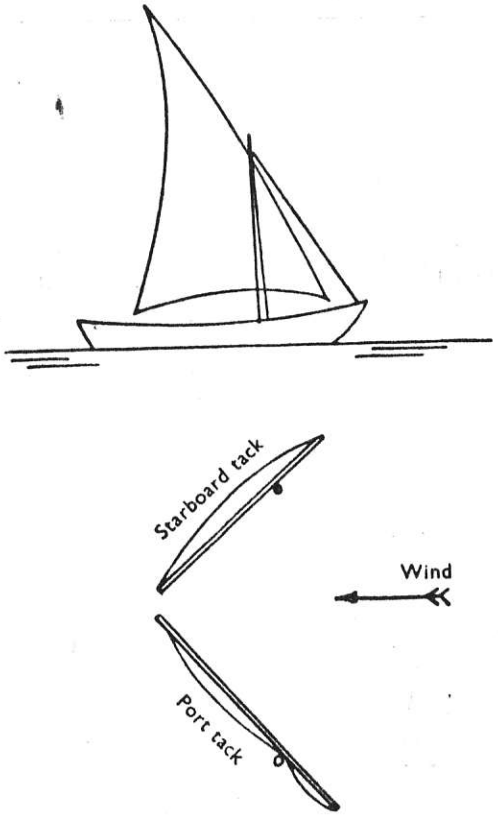


Fig. 6

One reason is perhaps the fairly widespread belief that the sailing ship could hold its own against the steamship by following routes where fair winds prevailed. Great strides had been made in working out the pattern of meteorological and oceanographic conditions on the main trade routes of the world. It was astonishing to what extent the trade winds and the ocean currents could be counted upon to produce quick passages if careful attention was paid to the routes followed. The steam tug had solved the problem of being held in port by adverse winds. As a consequence, the advantages of good windward ability probably did not stand out as clearly as they might have under other circumstances.

But a more telling reason is, surely, that the fore-and-aft rig was not yet able to demonstrate its inherently greater potentialities for windward work. Until the windage of spars and rigging could be drastically reduced, and until flatter and better-setting sails could be made, the lift/drag ratios of fore-and-aft rigs were little better than those of square rigs. These developments took time. Wire rigging had to be introduced, and many other improvements. The realization came only very slowly that really large gains were possible. The point seems to have been missed for some time that in a long view of the situation the various improvements that were being developed could be fully exploited only in the fore-and-aft rig, and not in the square rig.

PART II

Modern yachts are a far cry from square-rigged ships. Progressive changes in the rig produced progressive changes in the hull, until at last the overall configuration and the proportions have become radically different. In fig. 7, a large and a small racing yacht are compared at the same scale with a typical square-rigged merchant ship of about 1860. The very different proportions are evident, and stand out even more strongly when the principal dimensions are reduced or expanded to a common overall length to permit direct comparison—100 ft. in the lower tabulation adjacent to fig. 7.

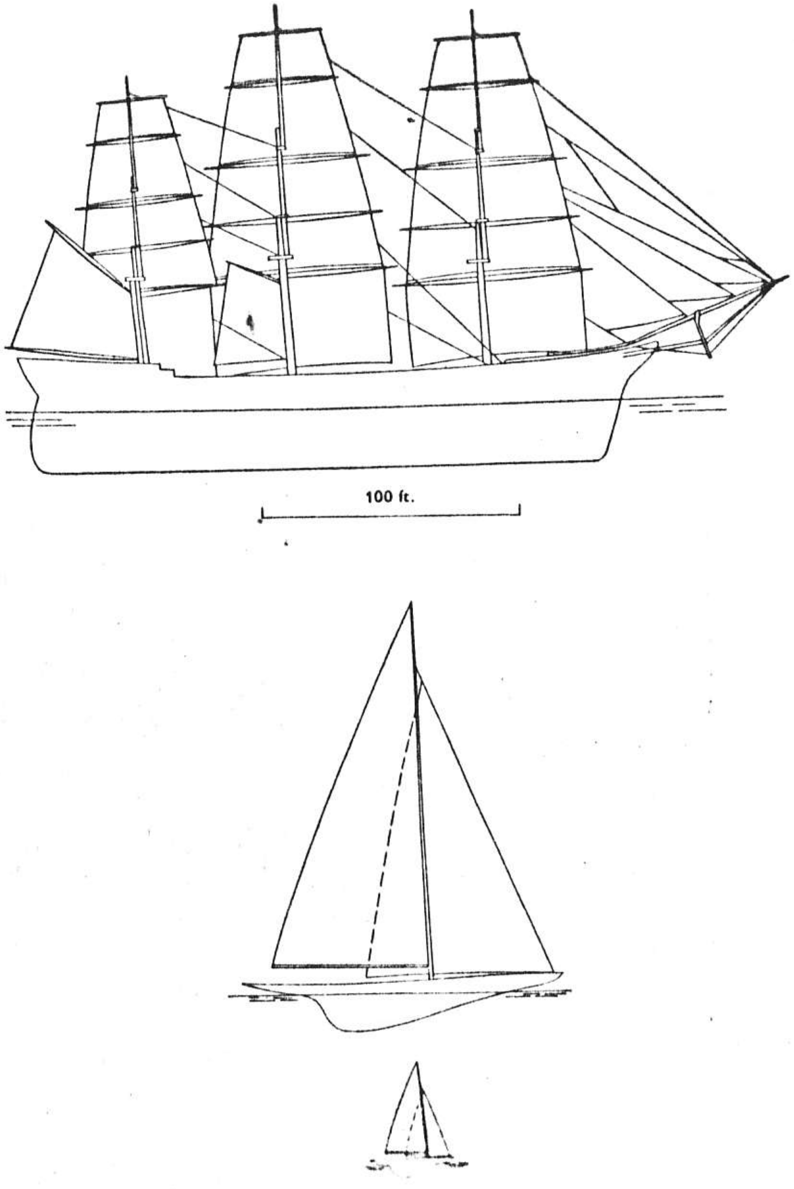


Fig. 7

The yachts are seen to have considerably less fullness of hull form. It has been implied earlier that they have reasonably full hull forms, in the sense that they have good space below decks and are good sea-boats. This is true. The fact is that the old ships had abnormally full hull forms according to modern notions. For many centuries full-bodied 'round ships' and fine-bodied 'long ships' existed side by side. The round ships became the cargo carriers and the long ships became the war galleys, largely propelled with oars. The square-rigged ships of the nineteenth century were the lineal descendants of the ancient round ships. But it will be seen in table 2 that they were already much less full than say Columbus's ships, and that at the end of their era, in the biggest sizes like *Preussen*, their fullness had dropped down much farther, to roughly that of modern bulk carriers like tankers. There is no great difference of fullness between *Preussen* and *Stormy Weather*. The racing yachts continue the gradual trend towards decreasing hull fullness that has evidently been going on for a long time.

The extended overhangs of the yacht hull, which date from about the 1880's, are in principle a very ingenious concept. Basically, they permit the displacement on a given overall length to be greatly

	Ship	J-boat	6-metre
Actual dimensions			
Length overall, LOA (ft.)	242	135	36
Load waterline length LWL (ft.)	221	87	23·5
Beam, B (ft.)	45	25	6·5
Draft, H (ft.)	23	15	5·4
Sail area, SA (ft.^{2}) (actual)	22500	10000	600
Wetted surface, S (ft.^{2})	15200	2200	192
Displacement, Δ (tons)	4100	166	4·1
SA/S	1·5	4·5	3·1
SA/Δ	5·5	60	146
Relative dimensions			
Length overall, LOA (ft.)	100	100	100
Load waterline length, LWL (ft.)	91	64·5	65·5
Beam, B (ft.)	18·6	18·5	18·1
Draft, H (ft.)	9·5	11·1	15·0
Sail area, SA (ft.^{2})	3850	5500	4600
Wetted surface, S (ft.^{2})	2600	1210	1480
Displacement, Δ (tons)	290	68	88
$\sqrt{SA}/\sqrt[3]{\nabla}$ (∇ is displacement in ft.^{3})	2·9	5·5	4·7

Fig. 7. Comparison of square-rigged ship with racing yachts.

Table 2. *Hull fullness*

Displacement on a nominal overall length of 100 ft.

	Tons
Square-rigged ships:	
(1492) Columbus	440
(1860) Ship (fig. 7)	290
(1900) *Preussen*	160
Modern power-driven ships:	
Large tankers	120–150
Fast liners, airplane carriers	50–70
Destroyers, cruisers	45–60
Modern sailing yachts:	
Stormy Weather	130
6-metre (fig. 7)	88
J-boat (fig. 7)	68
Canoes:	
16 ft. Canadian canoe (with two men and their gear)	50
Gökstad Viking ship (*c.* A.D. 900)	50

reduced without corresponding loss of the lateral stability needed to carry sail. In fig. 11, a 6-metre boat hull is compared with an hypothetical destroyer-type hull having the same overall length and displacement. It turns out that the two hulls have nearly the same wetted surface at rest. However, the much larger mid-section of the yacht and her very deep keel give her tremendously greater power to carry sail when on the wind. Also the immersed lateral plane area is more concentrated towards the mid-length. This provides a better aspect ratio, (draft)^2/area, which helps to reduce the induced resistance arising from the lateral water thrust that offsets the lateral component of the sail force.

The yacht rig, too, has a much better aspect ratio, (height)^2/(sail area), than the ship's square rig, and this helps to reduce the induced aerodynamic drag. The yacht rig incorporates two features which have come into general use only quite recently, within the past twenty-five years or so, but which from their names are obviously adaptations of earlier concepts. These are the jib-headed or 'Bermuda' mainsail, and the overlapping or 'Genoa' jib. The first does away with the gaff or upper supporting spar of the older quadrilateral mainsail. This saves weight aloft and reduces the skew of the mainsail so that there is less loss of angle of attack to the wind in its upper portions. The Genoa jib, with its large overlap, is thought by some to perform the function of a slot at the leading edge of an aerofoil, preventing breakdown of the flow over the lower portions of the mainsail due to the high angles of attack of these portions which persist because the skew cannot be wholly eliminated. This rather elaborate notion may be questioned, but the overlap of the Genoa jib does add sail area without requiring any change in the fore-triangle dimensions of the rig.

Last but not least the yachts have proportionately very much more sail area than the ship. They have ratios of sail area to wetted surface SA/S of over twice, and ratios of sail area to displacement SA/Δ of the order of ten to twenty times. The ratio SA/S, which governs only at very low speeds, is independent of the size of the craft. The ratio SA/Δ, which governs most of the time, varies inversely with the size on account of the square-cube relationship involved. Higher values of SA/Δ would therefore be expected in the yachts because of their smaller size. But the yachts also have nearly twice the non-dimensional ratios $\sqrt{SA}/\sqrt[3]{\nabla}$ which describe proportions.

The rock upon which the more successful systems for fixing racing handicaps among yachts have been built is that to first order, disregarding differences of design, changes in SA/Δ cause corresponding changes of average relative speed $V/\sqrt{L}$ which depend only on the characteristic shape of the resistance curve. Using the same principle, and starting with the $V/\sqrt{L}$ of 0·90 given for yachts in table 1, a $V/\sqrt{L}$ of about 0·50 emerges for the smaller SA/Δ of the ship. However rough, this result can be compared with the 'mean figure' of about 0·40 given for ships in table 1, and is enough to show how important it is to carry sail.

The larger non-dimensional ratios $\sqrt{SA}/\sqrt[3]{\nabla}$ in the yachts are possible because of the proportionately greater lateral stability. The smaller non-dimensional ratio in the ship is well enough explained by the structural difficulties encountered in very large rigs: structural problems have an unpleasant way of becoming less tractable as size increases.

What sort of performance in a technical sense is actually attained by modern racing yachts? A great many general statements have

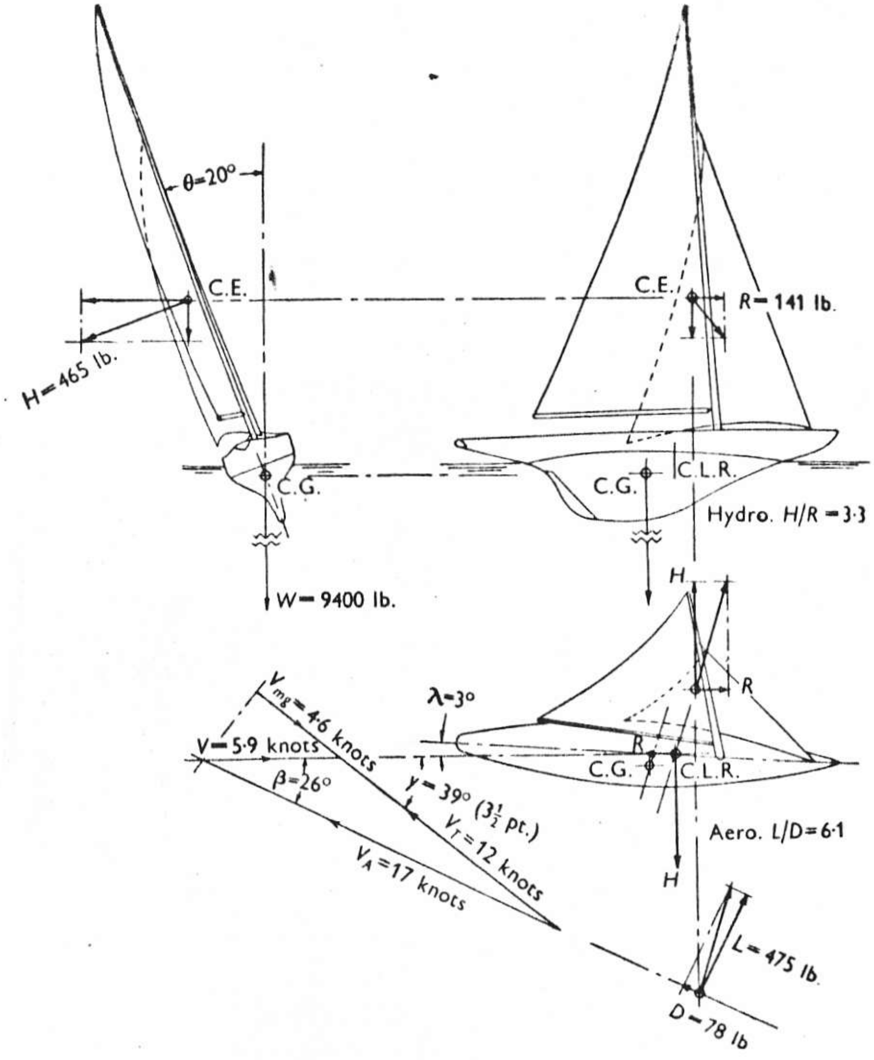


Fig. 8

been made regarding this question but there are not many systematic data. Altogether, the work done on the subject has not been very extensive.

Fig. 8 is taken from some studies of a successful 6-metre boat of fairly recent vintage. The boat is close-hauled in a 12-knot true wind.

The sailing performance, represented by the triangle comprising sailing speed V, true wind speed V_T, and apparent wind speed V_A, was determined in this instance from a respectable number of observations on the boat itself under sail. It will be seen that at a sailing angle γ of only 3½ points from the true wind the sailing speed is very nearly half the true wind speed (5·9/12) and corresponds to a relative speed $V/\sqrt{L}$ of very nearly unity ($5{\cdot}9/\sqrt{36}$). These are really rather remarkable figures. A 12-knot wind is only just over the line into force 4 on the Beaufort scale, where it is described as a 'moderate breeze'. Yet with only this much breeze the relative speed of the boat has already reached some 85% of the nominal maximum relative speed, taking the latter to be 1·15 as mentioned earlier. Furthermore, the notations on the Beaufort scale, dating from about 1806, give '5–6 knots full and by' for the speeds of square-rigged ships in a force-4 breeze. 'Full and by' would

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Particulars	
Length overall, *LOA* (ft.)	36·0
Load waterline length, *LWL* (ft.)	23·5
Beam, *B* (ft.)	6·5
Draft, *H* (ft.)	5·4
Displacement, *W* (lb.)	9400
Sail area (with Genoa jib), *SA* (ft.²)	600
Lateral area hull, *LA* (ft.²)	70
Right arm at 20° heel, *RA* (ft.)	0·96
Sailing performance	
Heel angle, θ (deg.)	20
Sailing speed, V (knots)	5·9
True wind, V_T (knots)	12
Apparent wind, V_A (knots)	17
Apparent wind angle, β (deg.)	26
Sailing angle, γ (deg.)	39 (3½ points)
Speed made good to windward, V_{mg} (knots)	4·6
Leeway, λ (deg.)	3

Rig	
Lift, *L* (lb.)	475
Drag, *D* (lb.)	78
Lift/drag ratio, *L/D*	6·1
Lift coefficient, C_L (non-dimensional)*	0·80
Hull	
Heeling force, *H* (lb.)	465
Resistance, *R* (lb.)	141
Heeling force/resistance, *H/R*	3·3
Heeling force coefficient, C_H (non-dimensional)*	0·07
Resistance/displacement, *R/W*	0·015

* Non-dimensional force coefficients are defined by

$$F = C_F A \tfrac{1}{2}\rho V^2$$

where, in consistent units, **F** is force, **A** is surface area, **ρ** is fluid density, **v** is speed.

Fig. 8. Analysis of 6-metre boat close-hauled in 12-knot wind.

Table 3. *Beaufort scale of wind speed*

Beaufort number	Seaman's description of wind	Mode of estimating for full-rigged ship	Mode of estimating for average sized sailing trawler	Specifications for use on land	Miles per hour (statute)	Equivalent in knots	Equivalent in m. per second	Equivalent pressure in millibars* (10^3 dynes per cm^2.)	Terms used in U.S. Weather Bureau forecasts
0	Calm	Full-rigged ship, all sails set, no headway	No headway	Calm; smoke rises vertically	Less than 1	Less than 1	Less than 0·3	Less than 0·005	
1	Light air	Just sufficient to give steerage way	Sufficient to give good steerage way to fishing smacks, with 'wind free'	Direction of wind shown by smoke drift, but not by wind vanes	1–3	1–3	0·3–1·5	0·005–0·03	Light
2	Light breeze (slight breeze)	Speed of 1 or 2 knots, 'full and by'	Fishing smacks with topsails and light canvas, 'full and by', make up to 2 knots	Wind felt on face; leaves rustle; ordinary vane moved by wind	4–7	4–6	1·6–3·3	0·03–0·1	
3	Gentle breeze	Speed of 3 or 4 knots, 'full and by'	Smacks begin to heel over slightly under topsails and light canvas make up to 3 knots, 'full and by'	Leaves and small twigs in constant motion; wind extends light flag	8–12	7–10	3·4–5·4	0·1–0·2	Gentle
4	Moderate breeze	Speed of 5 or 6 knots, 'full and by'	Good working breeze, smacks heel over considerably on a wind under all sail	Raises dust and loose paper; small branches are moved	13–18	11–16	5·5–8·0	0·2–0·5	Moderate
5	Fresh breeze	All plain sail, 'full and by'	Smacks shorten sail	Small trees in leaf begin to sway; crested wavelets form on inland waters	19–24	17–21	8·1–10·7	0·5–1·0	Fresh
6	Strong breeze	Ship 'full and by' can just carry topgallant sails	Smacks double-reef gaff mainsail	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty	25–31	22–27	10·8–13·8	1–1·5	Strong
7	Moderate gale (high wind)	Ship 'full and by' can just carry whole upper topsails	Smacks remain in harbour, and those at sea lie to	Whole trees in motion; inconvenience felt in walking against wind	32–38	28–33	13·9–17·1	1·5–2	
8	Fresh gale	Ship 'full and by' can just carry reefed upper topsails and whole foresail	Smacks take shelter if possible	Breaks twigs off trees; generally impedes progress	39–46	34–40	17·2–20·7	2–3	Gale
9	Strong gale	Ship 'full and by' can just carry lower topsails and reefed foresail	—	Slight structural damage occurs (chimney pots and slate removed)	47–54	41–47	20·8–24·4	3–4·5	
10	Whole gale (heavy gale)	Ship 'full and by' can only carry main lower topsail	—	Seldom experienced inland; trees uprooted; considerable structural damage occurs	55–63	48–55	24·5–28·3	4·5–6	Whole gale
11	Storm	Ship can only carry storm staysail or trysail	—	Very rarely experienced; accompanied by widespread damage	64–75	56–65	28·4–33·5	6–8	
12	Hurricane	No canvas can stand	—	—	Above 75	Above 65	33·6 or above	Above 8	Hurricane

* One millibar equals approximately 10 kilograms per square metre or 2 pounds per square foot.

probably mean something like 7 to 8 points from the wind for those ships. The evidence is, then, that a 6-metre boat could actually outsail a square-rigged ship, boat for boat, when going to weather in this moderate breeze.

The angle of heel was observed at the same time as the speeds and sailing angle. The heeling force *H*, which may be called the basic force magnitude, could then be estimated from the lateral stability characteristics of the boat, which were known. For simplicity, the heeling force was assumed to lie in a plane normal to the mast containing the estimated centre of effort C.E. of the sail plan.

To complete the resolution of forces it was evidently necessary to know only one more force magnitude, which could be either the resistance *R* of the hull in the direction opposite to its motion or the drag *D* of the rig in the direction of the apparent wind. It was clear that in principle the hydrodynamic characteristics of the hull or the aerodynamic characteristics of the rig might be determined by separate experiments, which would ordinarily be more conveniently carried out in model scale than in full scale. There was another alternative, that the characteristics be deduced from measurements on the boat itself of the force directions and magnitudes at all points of attachment between the hull and the rig. As a matter of fact, some work has now been done along all three of these lines, notably by Davidson, Warner and G. I. Taylor, respectively.* In the present instance, model experiments were employed to determine the hull resistance. The model was ballasted to have the desired heel angle, and the leeway was adjusted until the scaled-down heeling force was developed at the proper scaled-down sailing speed. The resistance was then measured and converted to full scale by the usual methods employed in model work.

It will be seen in fig. 8 that the heeling force *H* is about 5% of the displacement and that the resistance *R* is about $1\frac{1}{2}\%$ of the displacement. The lift/drag ratio L/D of the rig works out at 6·1, and the lift/drag ratio H/R of the hull at 3·3. What these figures really signify, and whether or not they indicate that a limit on performance has been closely approached within the framework of the principal dimensions and proportions, can be judged only by analysis and by

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* Further work has been undertaken within the past two years by the Yacht Research Council in Great Britain.

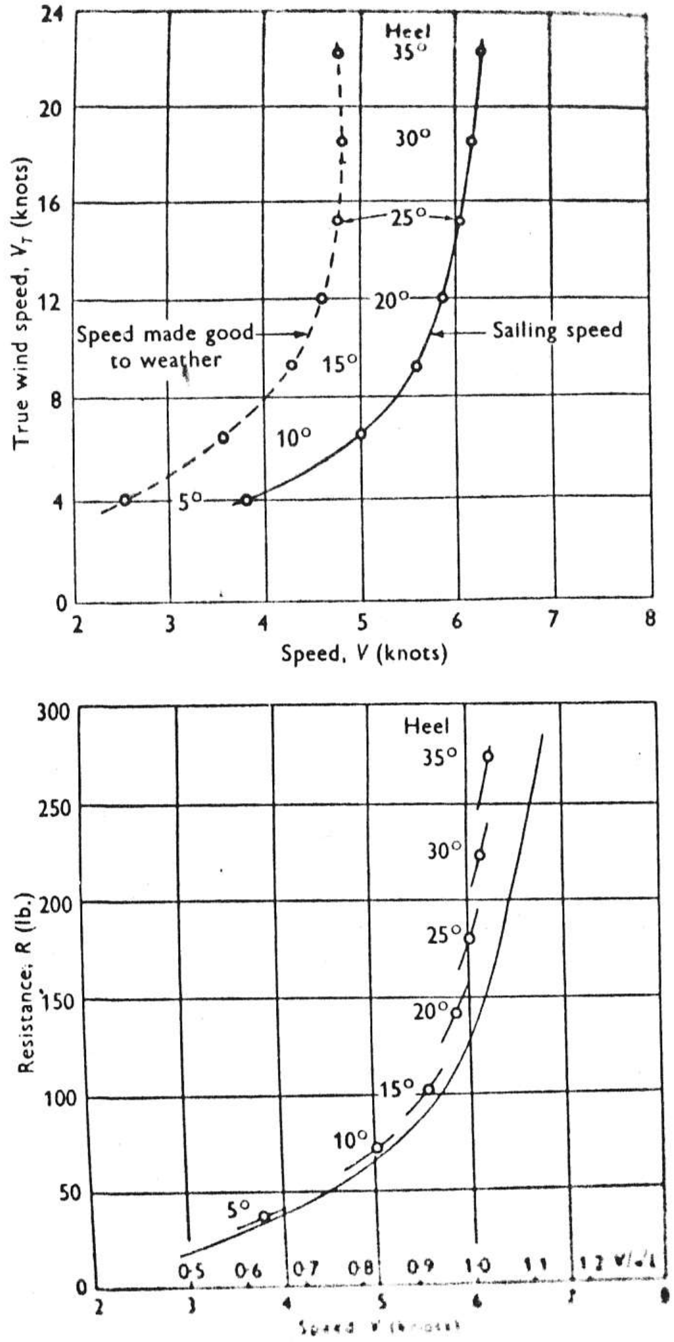

Fig. 9 Sailing performance on the wind and hull resistance of [illegible]

comparison with other aerodynamic and hydrodynamic experience. No great claim can be made for the absolute accuracy of the figures because of the narrow basis on which they rest. But that is only an additional reason for trying to extract as much as possible from them.

The studies from which the figures were taken actually covered a range of true wind speeds up to about 22 knots, embracing angles of heel (in 5° steps) up to 35°. Fig. 9 shows the sailing speeds and the hull resistances over these ranges and provides a greater breadth of view than does fig. 8 alone. The complete set of diagrams like fig. 8 reveals comparatively little variation with heel angle in either of the two lift/drag ratios, H/R and L/D. The sharp upturn of the speed curves therefore follows closely the sharp upturn of the resistance curves, being due mainly to the need for rapidly increasing wind strength to provide the necessary force to offset the rapidly increasing resistance. It will be seen that nearly the best speed has already been reached when the true wind has reached 12 knots and the heel angle 20°, as in fig. 8. It follows that radical improvements can scarcely be expected unless something drastic

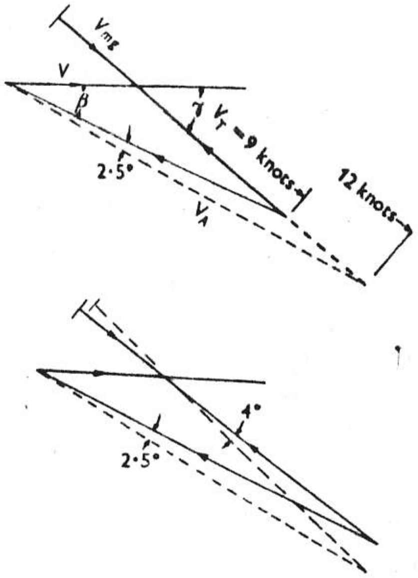

Fig. 10

can be done to reduce the resistances in the higher-speed regions of the curve.

But this does not exclude the possibility that substantial, if not radical, improvements might be made without major changes of design or dimensions. As matters stand today, boats like the 6-metres are built to strict measurement rules which govern their principal dimensions and proportions, and races between them are often lost or won on time margins of a few seconds. An improvement of say 5% in their performance on the wind would therefore be quite dramatic.

It is easy to show by manipulating the speed triangle, as in fig. 10, that a 5% improvement over the speed made good to windward in fig. 8 would result if, for example, (1) the same sailing speed V and sailing angle γ could be attained in 9 knots instead of 12 knots of true wind by increasing the sail force coefficient, or (2) the same sailing speed in the same true wind could be attained with 4° less sailing angle. The first would lower the speed curves in fig. 9 bodily, the second would push the curve of speeds made good to the right. The main point is that in either case the apparent wind angle β would have to be reduced by about 2·5°, and it can be verified that this would in turn require either an increase of about 36% in the lift/drag ratio L/D for the rig, or an increase of about 18% in the lift/drag ratio H/R for the hull: if H/R for the hull remained unchanged, L/D for the rig would have to increase from 6·1 to 8·3; if L/D for the rig remained unchanged, H/R for the hull would have to increase from 3·3 to 3·9. Viewed in the light of the past, improvements of this order of magnitude do not seem beyond reason. Improvements of much greater magnitude have obviously been made over the past hundred years. The jib-headed mainsail and the overlapping jib may well have effected improvements at least as large, though reliable figures are not easily determined. Nor are the present lift/drag ratios in themselves particularly high by aerodynamic standards. Conventional subsonic aeroplanes have lift/drag ratios of the order of 15–20.

To try to assess the possibilities more exactly it is useful to go a little further into detail, employing the usual methods of aerodynamic and hydrodynamic analysis. Taking fig. 8 as a starting point, the non-dimensional lift coefficient C_L of the rig is there

given as 0·80. This rather high coefficient implies a rather high angle of attack of the sails. A reliable estimate of the mean angle of attack is difficult to make because of the skew of the sails. However, a little judicious juggling of figures suggests that for the conditions of fig. 8 the mean angle of attack is probably in the neighbourhood of 8–9°. Some confirmation of this estimate is given by generalized aerodynamic data, which indicate that a similarly cambered aerofoil of the same geometric aspect ratio as the 6-metre rig, (height of mast)^2/(actual sail area) $= 3{\cdot}2$, would be expected to develop a lift coefficient of 0·80 at an angle of attack of about 8°. However, the aerofoil would then be expected to have a lift/drag ratio of around 10, which is more than half again as great as the 6·1 lift/drag ratio of the rig. Thus it would appear that there is still room for significant improvement of the yacht rig without altering the sail area or the aspect ratio. The problem, following the lead of the aeroplane, is to improve the set of the sails and to reduce the drag.

The hull is somewhat less simple to analyse. For although it may be regarded as an aerofoil in so far as it develops a hydrodynamic force to balance the sail force, the hull must also provide buoyancy to float the weight and have lateral stability to carry the sails. With these three things to do, the hull ought not to be criticized in too summary a fashion for turning up with a lift/drag ratio H/R of not much more than half the lift/drag ratio L/D of the rig (3·3 as against 6·1). The problem is to unravel the separate influences of its several duties.

Taking the hull as a simple weight carrier, the resistances in the upright position, without heel or leeway, may be compared directly with those of (say) a destroyer type of ship of the same overall length and displacement, as in fig. 11. When this is done, it is seen at once that a not inconsiderable price has been paid in the yacht form for the relatively greater beam and draft and the shorter waterline. At the 5·9-knot sailing speed of fig. 8, the upright resistance is some 80% greater. The long overhangs of the yacht form are evidently less effective than the immersed ends of the ship form in delaying the sharp upturn of the resistance curve at the high end of the speed range, where wave-making is large. The yacht form is also poorer in the low-speed region where wave-making is negligible, and this in spite of its having very nearly the same area of wetted surface.

Even at 3 knots its resistance is some 20% greater, presumably because the greater beam and blunter underbody lines increase the resistance per unit of wetted surface by accentuating eddy-making at the stern.

When lateral stability is taken into account, however, the higher resistances of the yacht form are found to be amply compensated for. The heeling force that the destroyer-type form could support at 20° heel angle could scarcely be more than 100 lb., assuming a centre of effort at the same height as for the yacht. This is only a bit more than 20% of the 465 lb. given in fig. 8 for the yacht. Thus the yacht form has a clear advantage from the point of view of the lift/drag ratio H/R of over $2\frac{1}{2}:1$, even when the resistance added by heel and leeway is disregarded. The figures are $H/R = 465/112 = 4{\cdot}2$ for the yacht form and $H/R = 100/62 = 1{\cdot}6$ for the destroyer-type form at 5·9 knots.

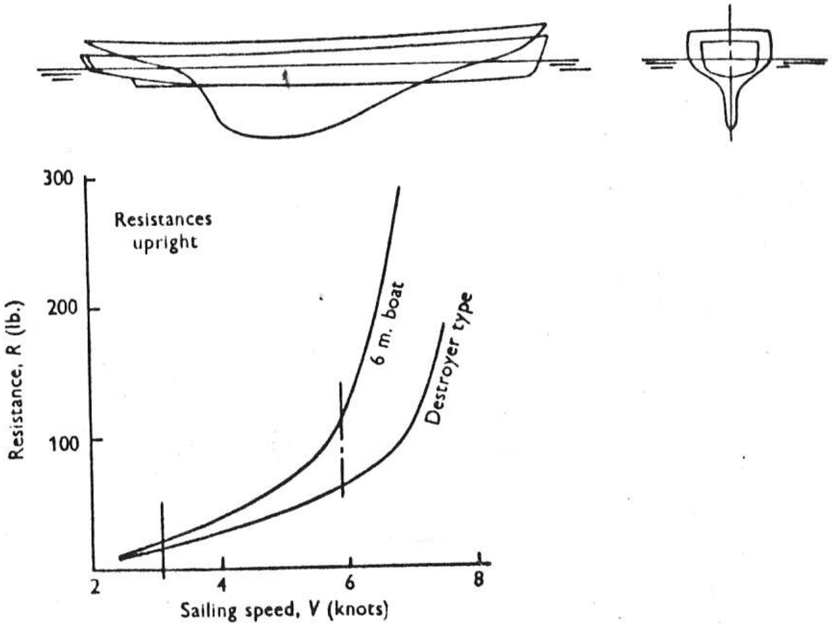

Fig. 11. Comparison of 6-metre and destroyer-type hulls of same length and displacement.

The resistance added by heel and leeway is 29 lb. for the yacht form at 5·9 knots, which corresponds to 26% and which reduces

the lift/drag ratio H/R from the above figure of 4·2 to the actual figure of 3·3. Fig. 12 indicates that only about 4 lb. of this added resistance is attributable to the heel angle alone. The remaining 25 lb. is attributable to the leeway, or more properly to the fact that a hydrodynamic lift is being developed by virtue of the leeway. The 25 lb. is therefore in principle an induced drag in the aerodynamic sense, which theory says should vary in the manner suggested by the experiments, namely, in proportion to the square of the amount of lift developed. There is some question regarding the constant of proportionality. Elementary aerofoil theory gives the expression $C_{Di} = C_L^2/\pi AR$, where C_{Di} is the non-dimensional coefficient of induced drag and AR the aspect ratio. Taking the aspect ratio of the yacht's underbody profile as $(\text{draft})^2/(\text{lateral area}) = 0{\cdot}41$, this expression yields 24 lb. for the induced drag, which

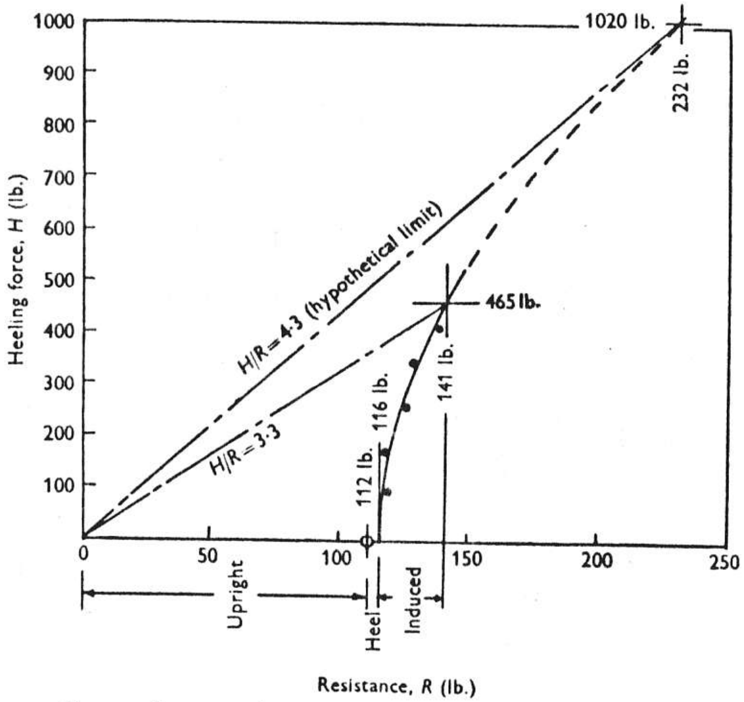

Fig. 12. Forces on 6-metre hull at 5·9 knots with 20° heel angle. From model experiments.

is in remarkable agreement with the experimental figure. A question arises, however, because on the one hand the elementary theory is really applicable only to aerofoils of much higher aspect ratio and sometimes underestimates the induced drag of aerofoils of low aspect ratio, while on the other hand, it can be argued that the yacht's lateral plane ought to be considered a half-aerofoil, so that with a mirror image above the water surface the aspect ratio would be doubled and the theoretical induced drag halved. There seems to be little chance of resolving the question completely. But the alternatives have compensating effects, and a complete answer is perhaps more of academic than of practical interest.

The answer is of less practical significance than the implication of fig. 12 that the lift is much too small to develop the maximum lift/drag ratio *H*/*R* of which the hull form is inherently capable. If the experimental value of the parabolic constant were to remain unchanged at higher lifts, more than twice the actual lift, around 1000 lb. or 11% of the displacement, would be needed to develop the maximum lift/drag ratio. A 6-metre boat already has nearly three-quarters of its total weight concentrated in lead ballast at the bottom of the keel, so that there is no chance of doubling the lateral stability and hence the lift. Even if this were possible, however, and even if the experimental constant held, the lift/drag ratio would still not exceed about 4·3. The real trouble lies of course with the high resistance that exists before the induced drag is added.

Another matter of some importance is that of 'balance'. This is the name usually given to the tendency or otherwise for a boat to sail a straight course with very little helm angle. Mechanically, the resultant hydrodynamic and aerodynamic forces have to lie in the same vertical plane when the course is straight. Generally speaking it is desirable in practical sailing, first to trim the sails to best advantage, thereby fixing the fore-and-aft position of the centre of effort C.E., and then to bring the centre of the lateral hull force C.L.R. to the required fore-and-aft position for balance by a very small adjustment of the helm. It is therefore important to know the effect of helm angle on the hull resistance. Model experiments on the 6-metre hull made for this purpose indicated that changing the helm from lee to weather by a few degrees was quite effective in moving the force centre aft. It also reduced the leeway. That is caused the resistance first to drop and then to rise. If the initial drop in resistance is attributable to the reduced leeway of the hull proper as distinct from the keel, which seems probable, the hull is evidently very sensitive to small changes of leeway. The subsequent rise in resistance does not necessarily confound this reasoning, for it can be explained on the ground that continuing increase of the weather helm eventually increases the resistance of the rudder or rudder-keel combination, but only after the leeway has been reduced so much that further reduction has a negligible effect on the hull proper.

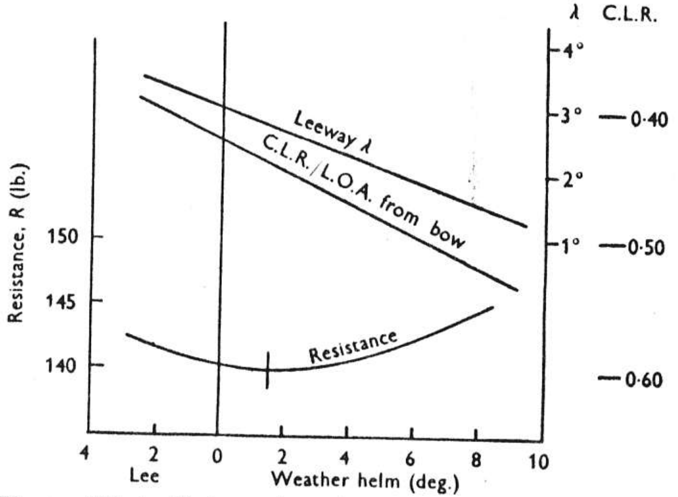

Fig. 13. Effects of helm angle on 6-metre hull at 5·9 knots with 20° heel angle. From model experiments.

The 6-metre boat itself sailed with practically no helm and was considered 'well balanced'. Thus she sailed at nearly the best point on the resistance curve of fig. 13, leaving no room for significant gain from a change in the fore-and-aft location of the rig with respect to the hull which would alter the centre of effort position C.E. The lateral force centre C.L.R. must then have been in the position given in fig. 13 for practically no helm, which is some 45% of the overall length from the bow. This is the same position as is shown in fig. 8, where it is seen to be well ahead of the geometric centre of area of the lateral plane. By working from this lateral force centre C.L.R., it can then be concluded that the centre of effort C.E. must also have been well ahead of the geometric centre of area of the sail plan, as shown in fig. 8. The position of the centre of effort thus deduced can be accounted for quite well by assuming the mean wind pressure on the jib to be twice that on the mainsail, an assumption which is consistent with a rough integration of some pressure measurements on sails made by Warner and with the known effectiveness of the Genoa jib.

It is well established that the centre of pressure of rectangular aerofoils is normally at about one-third of the chord from the leading edge, or well ahead of the geometric centre of area. There is good evidence too that the centre of lateral pressure of the generally rectangular underbody profiles of normal ship hulls lie at about one-third of the length from the bow, when the hulls are making leeway. This accounts for the long bowsprits of the earlier sailing ships, their object being to put the centre of effort of the rig far enough forward to effect proper balance. The generally triangular underbody profile of the yacht form is evidently successful in moving the lateral force centre aft by about 12 % of the overall length (0·45–0·33) and thus successful in largely avoiding the need for bowsprits, which are at best a nuisance.

The triangular underbody profile of the yacht form seems to have another advantage connected with balance. The deep forefoot of the earlier ships had a tendency to dig into the back of the wave ahead when the vessel was running before a heavy sea. This could be dangerous, as the lateral force centre could temporarily be moved a long way forward, which might lead to a loss of directional control by the rudder. In this event the vessel might broach to, slewing around broadside on and going over on her beam ends, jeopardizing the rig if not having more serious consequences. It may be that the real, if only partly understood, reason why the very blunt bows persisted for so long in the square-rigged ships is that they had less tendency to dig in and would therefore provide some safeguard against broaching to. Anyway, it is a fact that the blunt bows gave way to sharp bows only as sailing closer to the wind became possible and there was less need to run before the wind. The obvious disadvantages of the blunt bows in head seas must then have become apparent. The yacht hull with its cut-away forefoot is much less susceptible of broaching to.

Summing up, it is more difficult to gauge for the hull than for the rig how much room there is for improvement within the framework of fixed overall length, displacement and draft. The hull is more complicated to analyse. As matters stand the form of the yacht hull represents, for its purpose, a considerable technical advance over that of the ship hull. Any reduction of resistance without loss of lateral stability would, of course, be a net gain.

Broadly speaking, the combination of the principal dimensions and proportions embodied in the 6-metre boat is representative of a great many present-day racing, ocean racing, and cruising yachts It has evolved gradually over the years and has stood the test of time. It is rather encouraged by a number of the measurement rules that have been devised as a basis for establishing racing handicaps for these boats.

There tend to be quite consistent relationships between the three main variables, sail area, displacement and length, which are tolerably represented on a geometric basis by the expressions

$$\sqrt{SA}/\sqrt[3]{\nabla} = 4{\cdot}9\pm,$$

$$\sqrt[3]{\nabla} = 0{\cdot}13L + 0{\cdot}5 \text{ for racing boats,}$$

$$\sqrt[3]{\nabla} = 0{\cdot}16L + 0{\cdot}8 \text{ for cruising boats,}$$

where SA is the actual sail area, ∇ the immersed volume corresponding to the displacement, and L the overall length. The racing yachts in fig. 7 conform fairly well to these expressions. It will be seen that as the size of boat increases there is progressively less sail area and progressively less fullness of hull form in proportion to displacement. However, these two trends have compensating effects. Relative to displacement, the first reduces the heeling and driving force components developed by the rig in the same wind, while the second reduces the lateral stability and the resistance of the hull at the same relative speed $V/\sqrt{L}$. In consequence, there is to first order no very great change in either the heel angle or the relative sailing speed when close-hauled in the same wind as size is increased within the usual yacht range.

Nor is there very much change of speed in any one size on different points of sailing. This is shown by fig. 14. As the sailing angle is widened in the same true wind the apparent wind is rapidly reduced,

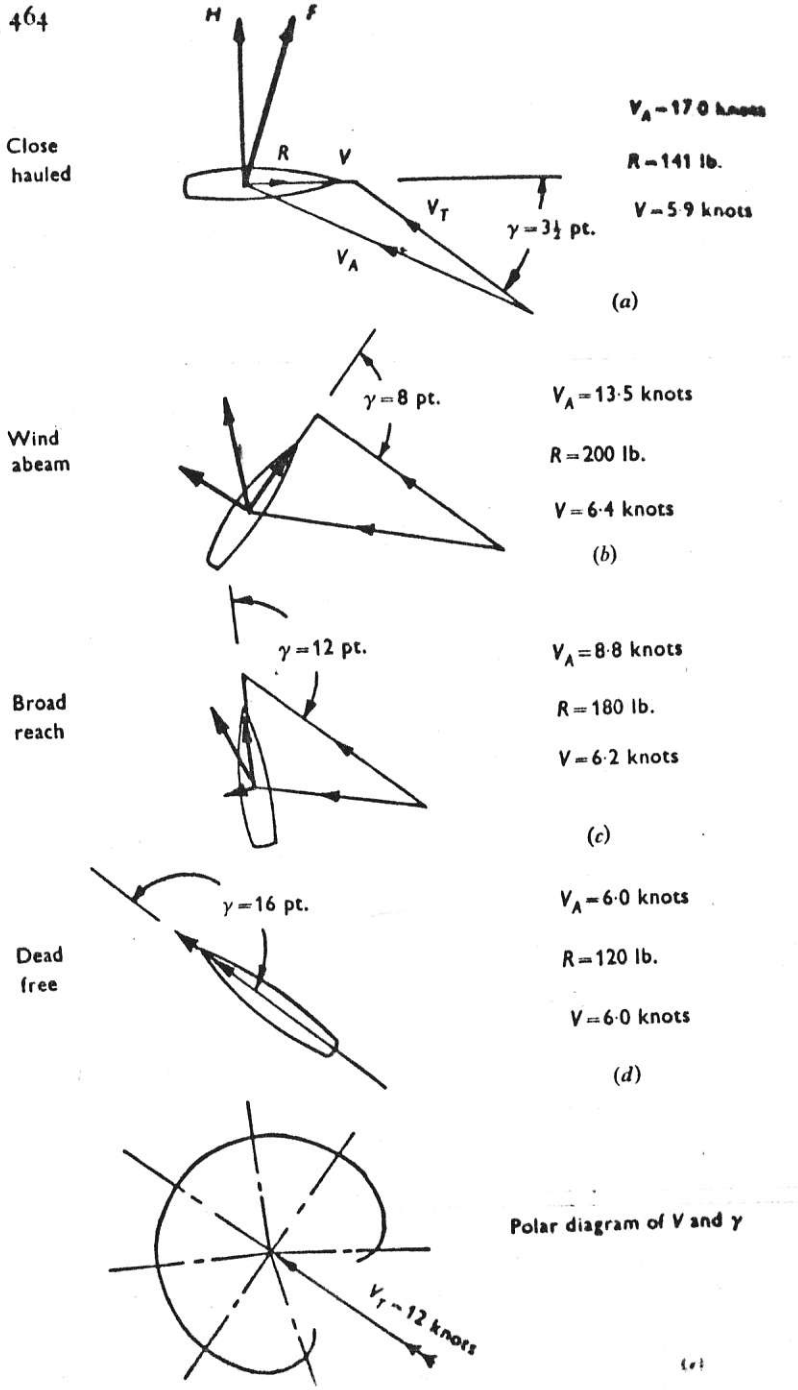

Fig. 14. Effect of sailing angle on 6-metre boat speeds in 12-knot wind

thus reducing the resultant sail force developed. But this reduction is at first much more than offset by the larger component of the sail force that becomes available for driving; later it is offset in some degree by the greater sail force coefficients that are developed as the sheets are freed and the sails become more bellied; finally, when the apparent wind gets far enough aft to allow a spinnaker to be set, it is largely offset by a substantial increase of actual sail area. Moreover, provided the wind is not much less than about 12 knots, variations of driving force produce much smaller variations of speed because the curve of hull resistances is so steep. For the 6-metre boat in 12 knots of true wind, the speed changes by less than 10% whatever the point of sailing. A 'polar' diagram of sailing speed plotted on sailing angle is in consequence nearly circular.

A distinguishing feature of the traditional combination of dimensions and proportions in the modern yacht is therefore the consistent relative speeds it produces, provided there is any reasonable breeze at all. The comparatively small improvement of speed in wind strengths greater than about 12 knots was seen in fig. 9. It is now seen that the influences of size and of the point of sailing are also comparatively small. The 'average' relative speed tends to hover around unity under all conditions.

PART III

High-speed sailing may be defined as the attaining of relative speeds materially greater than unity. It will be evident from what has gone before that the essential need is to circumvent the sharp upturn of the curve of hull resistances. One way to accomplish this is to reduce the hull fullness drastically, sacrificing space within the hull and a measure of the sea-keeping ability of the normal yacht. The problem is then to provide lateral stability in some way that does not require high displacement, so that sail area can be retained. Otherwise the net gain may be small.

Light-displacement craft are not new in principle. For many centuries there have been canoes, proas and the like in the South Pacific and other places with much lower displacement in proportion to their sail area and length. There are today large numbers of modern craft, for example, racing dinghies, of which the same thing is true. In all instances the combination of the three major variables, sail area, displacement and length, is radically different from the traditional combination found in the yacht.

The key to these light-displacement craft is that they are essentially small. They are small enough for the weight of their crew to come to a sizeable fraction of their total displacement. Under these circumstances, the lateral stability to carry a lot of sail can be provided by shifting the crew to the weather rail, to outriggers, or to 'trapezes' that hang from the masthead. A 6-metre is not a large boat. But with a crew of four at 150 lb. each, not counting the helmsman, the weight that can be shifted is less than 7% of the total displacement (600/9400), and the narrow beam of the hull prevents this weight being shifted very far to weather. A 6-metre is in fact about the smallest size of boat in which the traditional combination of the major variables has been maintained. In some of the still smaller craft that are popular these days the crew weight may reach as much as 50% or even more of the total displacement, and because in many instances the hulls are relatively wide the crew can get well out to weather even without outriggers.

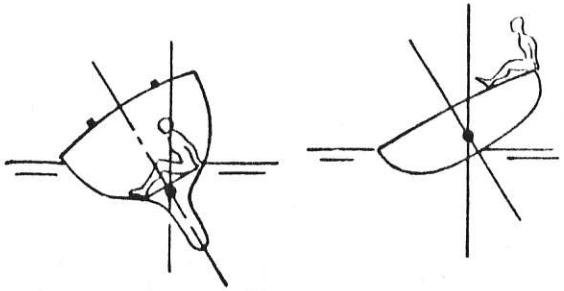

Fig. 15

There are all manner of gradations among light-displacement craft. To get a general view of their comparative performance, imagine as an example a craft which has the same sail area and length as the 6-metre boat in fig. 8, but which carries a movable crew of six instead of four and has a total displacement of only 2300 lb., or one-quarter of the 6-metre's displacement. The crew weight is then about 40% of the total displacement. In order to match the heeling force H of 465 lb. for the 6-metre boat at 20° heel angle the

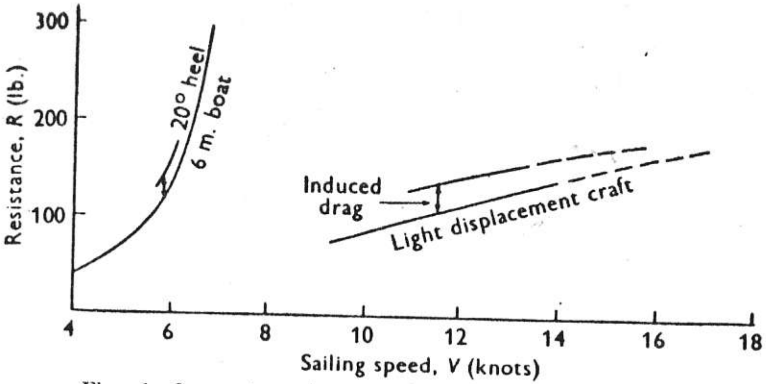

Fig. 16. Comparison of resistance of 6-metre boat of 9400 lb. light-displacement craft of 2300 lb.

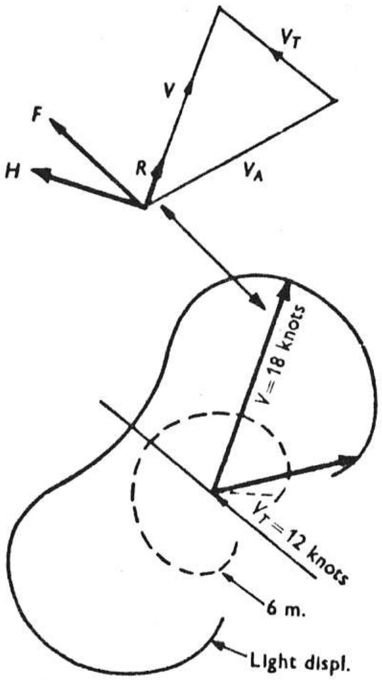

Fig. 17. Polar diagram in 12-knot wind for 6-metre boat and light-displacement craft.

crew would need to be disposed some 5 ft. to windward of the boat centre line, which would of course be quite feasible. The hull form could be of the 'ship' type rather than the 'yacht' type because of the very lenient requirement for lateral stability, and fig. 11 indicates that this change would by itself save considerably on resistance, even if there were no reduction of displacement. The reduction of displacement would effect a further large saving. A resistance curve can be estimated from available data for ship forms, as in fig. 16, and an allowance made for induced drag. With a suitable centreboard the induced drag would probably be less than the induced drag of the 6-metre boat hull and could scarcely be more. The polar diagram in fig. 17, developed from this resistance information, for 12 knots of true wind, shows a maximum speed of nearly 18 knots when the wind is a point or more abaft the beam. This is three times the roughly 6-knots maximum speed of the 6-metre boat in the same wind, and corresponds to $\frac{3}{2}$ instead of $\frac{1}{2}$ the wind speed. The craft is in effect close-reaching instead of broad-reaching on this point of sailing because the apparent wind is drawn far ahead by the high sailing speed, and the full heeling force of 465 lb. is being exerted. For all higher points of sailing the diagram assumes that wind would be spilled by easing the sheets or sail shortened in order to prevent the heeling force exceeding 465 lb. In summary, comparing with the 6-metre boat:

the sail area and length are the same;
the hull fullness, as in table 2, has been reduced from 88 to 22;
the geometric ratio $\sqrt{SA}/\sqrt[3]{\nabla}$ has been increased from 4·7 to 7·4;
the heeling force ratio H/W has been increased from 0·05 to 0·20;

and at maximum sailing speed in a 12-knot true wind,

the relative speed $V/\sqrt{L}$ has been increased from 1 to 3;
the speed ratio V/V_T has been increased from $\frac{1}{2}$ to $\frac{3}{2}$;
the resistance ratio R/W has been increased from 0·02 to 0·08.

There is nothing wildly extreme about this craft. Its weight without crew is rather on the low side, and it would be rather large compared to most of the light-displacement craft being built today—though not larger than, for instance, the famous Chesapeake Bay canoes, which used to carry crews of eight or ten and from all accounts furnished really exciting sport. On the whole, the craft is reasonably representative. What has happened is that, by relieving the hull of the requirement of inherently high lateral stability and reducing the displacement, the sharp upturn of the resistance curve has been circumvented and the speed allowed to rise, without any improvement whatever in either of the two lift/drag ratios L/D or H/R.

The remarkable flattening of the resistance curve is due mainly to the very great reduction of wave-making by virtue of the small displacement. In combination with wide beam the hull may be lifted somewhat at high speeds, so that it tends to plane or skim over the surface of the water, instead of ploughing through. Co-ordinated data for ship hull forms indicate that the hull fullness as defined in table 2 has to be reduced to well below 70 or so before any material benefit can be had from the flattening of the resistance curve. Thus the reduction of hull fullness from 290 to 88 between the square-rigged ship and the 6-metre boat in table 2 is relatively ineffective, whereas the further reduction to 22 in the craft under consideration is extremely effective. A hull fullness of around 70 can be said to define roughly the distinction between heavy-displacement and light-displacement craft.

The tendency to plane at high speeds raises the question of whether a hull form with V sections like a fast motor-boat might not be preferable to a hull form with rounded sections like a ship. Actually, for relative speeds of the order of 3, there is little to choose between the two kinds of form, provided of course that both are well designed. It is only when relative speeds of at least 4 are reached that V sections begin to show a clear advantage.

An interesting consequence of the attainment of relative speeds materially greater than unity—and therefore a characteristic of light-displacement craft in general—is a peculiar ability to coast down the fronts of following or quartering seas. This can add to the speed and is great fun. The physical relationship between the speed and the length of natural gravity waves in deep water corresponds to a relative wave speed of

$$V_w/\sqrt{\lambda} = 1{\cdot}34,$$

where V_w is the wave speed in knots and λ is the wavelength in feet. Thus a craft that can sail at a relative speed $V/\sqrt{L}$ of at least 1·34 can keep up with natural waves that are at least as long as her own length. Waves only a little longer than this are often big enough to lift the craft bodily and carry her along continuously on a wave front. The normal yacht, with its maximum relative speed of the order of 1·15, just misses in this respect. The natural waves that she can keep up with are only about $\frac{2}{3}$ of her own length, like the waves she herself is making, and these are too short to have much effect. She may be carried along intermittently to some extent, as was *Stormy Weather* on the occasion that has been mentioned earlier when an average relative speed of about 1·20 was logged for some 48 hours in big following seas. But this seems to be about the limit for normal yachts.

The bellying outward of the polar diagram of sailing speed against sailing angle, when the wind is brought more or less abeam, seen in fig. 17, is characteristic of all high-speed sailing craft, and has to be accepted. It is the direct result of increasing the speed ratio V/V_T. On the wind, the sailing angle has to be widened to prevent the apparent wind drawing so far ahead that the sails will not fill. Off the wind, the craft runs away from the wind and reduces the apparent wind strength; in fact, the speed achieved dead to leeward can usually be improved by 'tacking downwind', thereby developing more apparent wind. Only with the wind more or less abeam is greatly increased speed possible.

It would be idle to attempt to argue the relative merits of the 6-metre boat against those of the particular light-displacement craft that has been considered here. It is simply a matter of how much one chooses to emphasize maximum speed for its own sake and how much one cares to sacrifice in the way of sea-keeping and so on, in order to get it. Nor is there, after all, any need to argue the case. There are all sorts of craft intermediate between these two, embodying the full range of compromise between speed and the other desirable attributes. One can take one's choice. The point for present purposes is really this: that the maximum speed estimated for this light-displacement craft appears to be close to the best speed that has actually been attained in 12 knots of wind by any sailing craft up to the present time—which leads naturally to the question of how much more speed is possible.

Here the discussion becomes speculative, for nobody knows the answer to that question. However, the requirements for higher maximum speeds are fairly clear, and by reasoning from them it is not too difficult to persuade oneself that a speed of say 40 knots in a 12-knot true wind ought to be feasible, and even higher speeds

not beyond the realms of possibility. At 40 knots in a 12-knot wind the ratio V/V_T is evidently nearly $3\frac{1}{2}$, as compared with $1\frac{1}{2}$ for the light-displacement craft that has been discussed. To make this jump, rather different tactics need to be employed.

The basic requirement is to increase the ratio H/R, which was not done in going from the 6-metre boat to the light-displacement craft. The reason for its necessity if much higher speeds are to be attained can be seen in fig. 18. This diagram gives a broad picture of the purely geometric relationships which fix the maximum possible ratio V/V_T that can be reached with various combinations of the two lift/drag ratios H/R and L/D. The most favourable sailing angle γ is assumed, with the true wind V_T normal to the apparent wind V_A. When $H/R=2{\cdot}5$, as for both the 6-metre boat and the light-displacement craft, the chart shows that the maximum possible V/V_T is less than 2 if L/D remains at 6, and would be just short of $2\frac{1}{2}$ even if L/D could be increased by a factor of say 3, raising it to 18 or to about the L/D of a modern subsonic aeroplane. On the other hand, if H/R could be increased by a factor of 3,

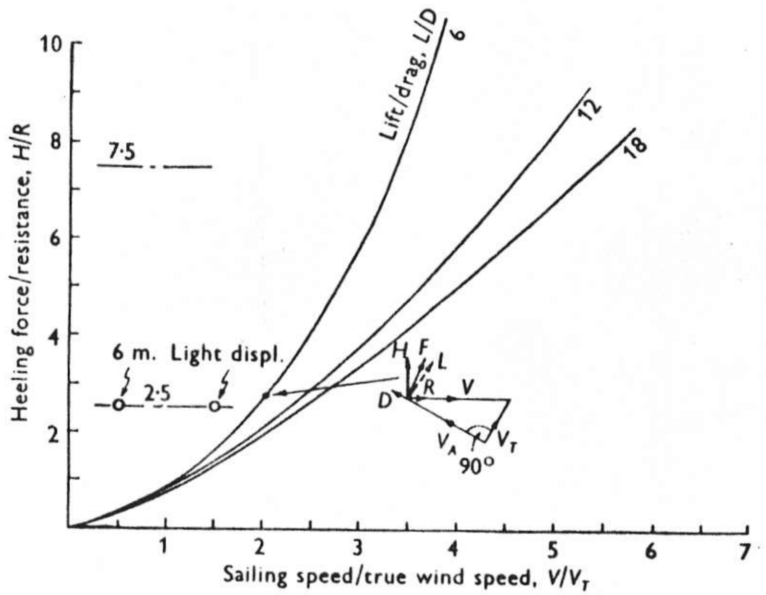

Fig. 18. Limits on V/V_T in terms of H/R and L/D, fixed by geometry.

raising it from 2·5 to 7·5, the maximum V/V_r could go up to just short of $3\frac{1}{2}$ with no improvement at all in L/D, while any improvement in L/D would have an immediate effect.

There is a big difference between improving L/D and improving H/R. The first requires basic aerodynamic developments, whereas the second is in many ways simply a matter of design. Writing for H/R its equivalent

$$\frac{H}{R}=\frac{H/W}{R/W},$$

it becomes clear that a high value of H/R requires either a high value of H/W or a low value of R/W. The resistance characteristics of any type of hull can be expressed in the form

$$R/W=f(V/\sqrt[6]{W}),$$

where f is a function and $V/\sqrt[6]{W}$ expresses the idea of relative speeds in the same way as $V/\sqrt{L}$, but provides an even more fundamental basis for comparing different hull forms because displacement is a more fundamental characteristic than length. Fig. 19 compares

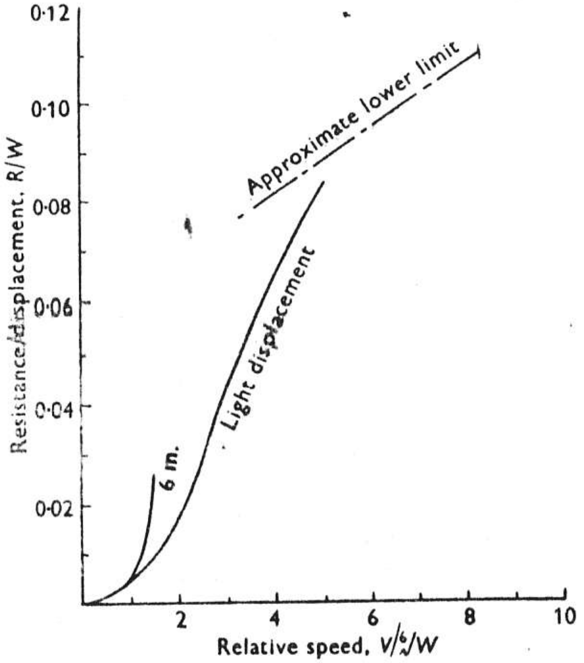

Fig. 19. Specific resistance against relative speed.

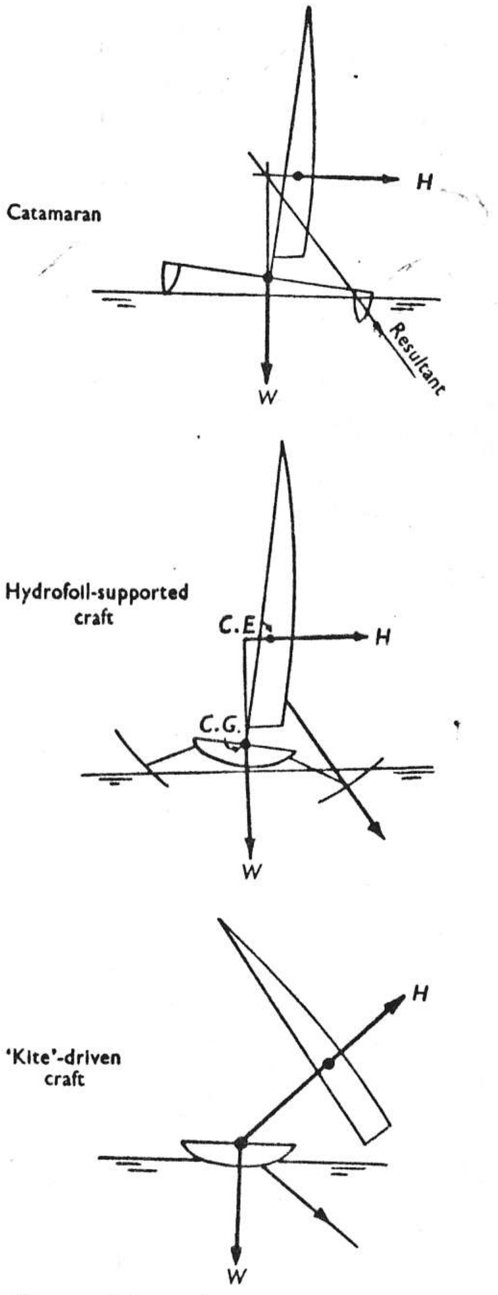

Fig. 20. Schemes for getting high H/W.

the 6-metre hull and the light-displacement hull on this basis, and shows also a dashed line to mark roughly the lower limit of the ratios R/W that can be obtained by any presently known means in the region of higher ratios of $V/\sqrt[6]{W}$. The fact is that in this region of high relative speeds there is not yet available any type of hull form or other means of providing water support for which ratios of R/W of less than something like 1/10 can be counted on. It follows therefore that if H/R is to be increased to something like 7·5, it is necessary that H/W be increased to something like 0·75.

There are in principle various ways of doing this, apart from shifting the crew an impossible distance to weather. Catamarans, comprising two long narrow hulls abreast of each other (fig. 20), with a connecting framework, have existed for a long time. Some of them are said to have sailed at well over 20 knots. Here the object is to keep the line of action of the resultant of H and W between the two hulls, thus providing very high lateral stability—at least until the weather hull is lifted clear of the water. Obviously there is no reason why H/W cannot reach 0·75 or even more. The same principle is employed in iceboats, with their widely separated main runners.

Other schemes have been put forward in recent years, and some of them have been experimented with. There is the possibility, which Barkla has mentioned, of supporting a craft on hydrofoils formed to circular arcs, centred at the height of the rig's centre of effort so that the resultant of H and W falls normal to them. There is the scheme of substituting some sort of rigid aerofoil for the usual fabric sails, so oriented with respect to the hull that the line of action of the resultant sail force passes through the centre of gravity C.G. Both of these schemes eliminate the heeling moment, thereby vastly simplifying the problem of increasing H/W. And there are many other ideas—most of them, incidentally, involving somewhat formidable structural problems.

Who can say what maximum speed will some day be attained in sheltered waters by following one or another of the various leads?

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