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THE EFFECTS OF TRIM, HEEL AND DISPLACEMENT ON A "TEMPEST" CLASS YACHT

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SUMMARY

Measurements were made of the effects of trim, heel and displacement on the performance of a 1/6th scale model of a Tempest class yacht in a recirculating water channel. A comparison has previously been made between results obtained in the water channel and those measured on the same model in a towing tank. The results showed satisfactory agreement.

It was found that the optimum trim angle was close to the natural trim of the hull under test at low speeds but was greater at higher speeds.

The effect of an increase in displacement was found to decrease the downwind performance and also the windward performance at low wind speeds. Above wind speeds of 7 knots the increased displacement, if represented by an increase in crew weight, was shown to be an advantage.

A heel angle to leeward was shown to decrease performance but an unusual effect was found in that at low and medium speeds for windward and reaching performance there was an advantage in allowing the yacht to heel to windward.

NOMENCLATURE

C_H	side force coefficient $\dfrac{F_H}{\frac{1}{2}\rho V_S^2 S}$
C_R	resistance coefficient $\dfrac{F_R}{\frac{1}{2}\rho V_S^2 S}$
F_H	side force
F_{HA}	aerodynamic side force
F_R	resistance
F_{RA}	aerodynamic driving force
F_V	vertical force
F_{VA}	aerodynamic vertical force
S	lateral area of keel and rudder extended to the design water line.
V_A	apparent wind speed
V_M	model hull speed
V_{MG}	speed made good to windward
V_S	yacht's speed
V_T	true wind speed
β	apparent wind angle
γ	track angle
θ	heel angle
λ	leeway angle
ρ	water density
τ	trim angle

1. INTRODUCTION

The purpose of the sailing yacht in racing is to complete a given course in the fastest possible time in a wide variety of weather conditions. In ocean racing the designer can vary the size and shape of the yacht to try to produce the best compromise for a chosen set of conditions but in one-design racing, such as in the Olympic Games, all the boats are nominally identical and it is supposed that any difference in performance of a particular boat is due to the skill of the crew.

The number of variables involved in predicting the performance of a sailing yacht is large so that in the forseeable future the skill of the crew seems likely to remain a dominant factor. However, the present paper shows the results of tests on the hull of a one-design yacht, a Tempest, to quantify the effects of trim, displacement and heel on the performance of the yacht with the purpose of assisting the technically minded helmsman.

The Forces on a Yacht

The sailing yacht operates at the interface between the fluids air and water. The sails provide the propulsion and extract their energy from the air while the hull, which provides the load carrying capacity, develops forces in the water. Thus the general forces on a yacht are a combination of aerodynamic and hydrodynamic forces as shown in Fig. 1, which are in equilibrium under steady sailing conditions.

The vector velocities in the horizontal plane are illustrated in Fig. 2 from which it can be seen that a convenient way of expressing windward performance is in terms of the vector V_{MG} - the speed made good to windward.

If both the sail and hull forces are known then it is possible to predict the performance of the complete yacht. In cases such as the present tests where only factors governing the hull performance were

varied then a more convenient method is to use some generalised sail forces such as the Gimcrack coefficients (Refs. 1 and 2).

2. Experimental Facilities and Method

The tests were carried out in the recirculating water channel at the University of Liverpool using a one sixth scale model of the Tempest made in glass reinforced plastic. The hull lines are given in Fig. 3 and other particulars of both model and the full size yacht are given in Table 1.

Several series of tests were made over a range of speeds from approximately 0.6 to 2.5 m/s (2 ft/sec to 8.5 ft/sec) corresponding to speeds in the full size yacht of 2.8 to 12.2 knots. Measurements were made of the resistance and side force on the model over a range of leeway and trim angles for three heel angles (0°, 10°, -10°) at the design displacement and also at a heavier displacement in order to investigate the effects of trim, heel and displacement.

A detailed account of the design of the water channel has been given by Preston (Ref. 3) and further details of the use of the channel in the present tests is given in Ref. 4.

3. Presentation of Results

The model resistance was scaled to full size using the Schoenherr friction line after correcting the model resistance for the effect of turbulence stimulators. It should be noted that the Reynolds numbers were calculated using an effective length of the model from the forward perpendicular to the transom of 6.17m full scale. This effective length is rather longer than the datum water line of 5.87m but it can

be seen in Fig. 3 that at the stern the hull is at a very shallow angle to the water and it was found in practice that the flow remained in contact with the hull to the transom. This modification is in agreement with Ref. 5 reporting comparative tests on the same model in a towing tank.

In sailing to windward the boat is intended to be kept upright by the crew. The windward performance was therefore calculated using the Gimcrack sail coefficients following the procedure outlined in Ref. 2 and is presented in Fig. 7 in the form of optimum speed made good to windward (V_{MG}) against true wind speed (V_T). A similar calculation was made for the heavier displacement condition.

With the assumption that sailing downwind under spinnaker the boat does not make leeway the downwind performance was also calculated. Using the same values as Ref. 5, that is a sail resistance coefficient of 1.2 and an area of $32m^2$ ($344\ ft^2$), the downwind performance was calculated for the two displacements and is shown in Fig. 6.

4. DISCUSSION OF RESULTS

The general practice of using tests of models to predict the behaviour of a full size ship has been accepted for many years both for conventional ships (see for example Ref. 6) and for sailing yachts (Ref. 1) which have to be tested through a range of leeway angles in order to simulate the sailing condition. In view of the recent paper by Kirkman and Pedrick (Ref. 7) a more detailed discussion of the validity of the model tests is given in Ref. 4.

4.1 Predicted Performance - Full Scale

Trim

The curves of resistance coefficient for the yacht against trim angle for different speeds are shown in Fig. 4 from which the optimum

trim angle for each speed has been deduced and is shown in Fig. 5. Also shown is a dotted line representing the natural test trim of the yacht. It can be seen that at lower speeds the yacht naturally trimmed at the optimum angle but at higher speeds, above 6 to 7 knots a higher trim was needed. This can be achieved by movement of the crew towards the stern since for the Tempest the crew weight is significant, approximately 30% of the total, and is of course a normal procedure when sailing.

It should be noted that in the tests the model was towed from a point near the deck level. For a displacement yacht, where the crew is a small proportion of the total weight, the real sailing trim would be achieved in model tests either by towing at the centre of effort of the sail plan or by adding a correcting moment if towed at deck level. Since the purpose of the test was to determine the best trim angle the position of the towing point was not considered to be important but for comparative purposes it should be noted that the natural trim angle of the yacht under sailing conditions would be lower than the trim under test due to the bow down pitching moment applied by the sails.

Downwind Performance

The downwind performance of the yacht under spinnaker is shown in Fig. 6 for different wind speeds. The influence of the planing capabilities of the hull is clearly shown for wind speeds above 14 knots by a shallow inflexion in the curve compared with a steeply rising curve which would be obtained for a conventional displacement yacht and is illustrated by the dotted line.

The effect on the downwind performance of an increase in crew weight of 0.245 KN (25 kg or 55 lb) was also calculated and resulted in slightly slower boat speeds for the same wind speed but the dif-

ference (rather less than 1%) was too small to be shown on the graph. This does not however necessarily mean that the increase in weight is not significant in practice because the speeds downwind are similar to the speeds made good to windward and considerably lower than speeds on the off-wind legs of a course. Thus the time spent on a downwind leg is large and a small difference in speed could be expected to give a lead that would be a significant tactical advantage to the lighter boat on the following windward leg.

The results show therefore that an increase in displacement whether as a result of a heavier boat or heavier crew reduces the downwind performance.

Windward Performance

The windward performance for the upright condition is shown in Fig. 7 in the form of a curve of speed made good to windward V_{MG} against true wind speed V_T. The curve is straighter than would be found for a conventional displacement yacht, which would have a nearly parabolic shape as shown in Fig. 8 which is taken from Ref. 8. The different form of the curve can be attributed to the ability of the Tempest crew to keep the yacht upright, particularly with the trapeze, whereas the conventional yacht heels further as the wind speed increases so that the efficiency of the sail plan is reduced. The maximum righting moment of the crew has been estimated as 2.59 KNm and it can be expected that when this limit is reached, at a wind speed of 6½ knots, the performance will be reduced below that shown either because the yacht will have to be allowed to heel or the mainsail eased in order to reduce the heeling moment.

The windward performance was also calculated for the heavier displacement on the assumption that all the increase would be in

crew weight alone and would therefore give an additional righting moment. The curve obtained is also shown in Fig. 7 together with the new limiting value of the righting moment on the assumption that the increase in crew weight has the same moment arm - i.e. there is no change in height of the crew or other ability to sit out. It can immediately be seen that the increase in displacement produces a noticeable reduction in performance compared with the equivalent downwind case discussed previously. This result can be expected since an examination of the force equations involved shows that the windward performance is extremely sensitive to changes in resistance.

It can be expected that above the wind speed at which the limiting heeling moment is reached the boat's performance will be reduced by the increased drag of the eased mainsail and can be expected to follow curves similar to those indicated on Fig. 7. Thus above a wind speed of 7 knots the performance of the boat with heavier crew is better even though it too has reached the limiting righting moment condition. It should be noted that the limiting wind speed for the standard displacement boat is very low for average racing conditions, corresponding to the upper end of Force 2 on the Beaufort scale, and it can be seen therefore that only at wind speeds below 7 knots will the boat with the standard weight crew have an advantage - this is in general agreement with the author's experience in practice.

It can also be deduced from Fig. 7 that an increase in displacement without a corresponding alteration in righting moment (e.g. from an overweight boat) is a disadvantage since the performance would follow that indicated by the chain dotted line. However, an increase in righting moment by using a taller crew without a corresponding increase in displacement would result in an improved performance at

higher wind speeds.

Effects of Heel Angle

The measurements of the effect of heel angle were made at three speeds corresponding to 2.88, 5.75 and 8.63 knots on the full size yacht and taken as typical of the low, medium and high (planing) regions of Tempest performance. Results were obtained for 10° heel, both positive (to leeward) and negative (to windward), and are shown in the form of side force coefficient against leeway angle in Fig. 9 and side force coefficient against resistance coefficient in Fig. 10.

This form of presentation is used in preference to the normal windward performance curve for this case because it involves less assumptions and portrays more readily the changes in forces. In order to relate the results to actual changes in performance it should be remembered that when reaching or beating the sails produce a sideforce and a driving force. Thus the hull has to produce an equal and opposite side force and so moves at an angle of leeway. It can therefore be deduced that if a change in hull configuration, without a change in the sail forces, produces the same sideforce at the same or smaller leeway angle combined with a lower hull resistance then this will result in an improvement in performance. However, in the case of a reduction in sideforce combined with a reduction in resistance the situation is less obvious and a complete performance calculation must be made.

In the present case it can be seen from Fig. 9 that at the higher speed (8.63 knots) there is less side force produced at any leeway angle with a worse result for a negative (windward) heel angle. Similarly Fig. 10, which gives the resistance coefficient as a function of the side force coefficient (plotted as C_H^2), shows that the heeled hull has a greater resistance for a given side force value. Thus

the results from Figs. 9 and 10 show that at the high speed, corresponding to a planing condition on a reaching course, the boat's performance is reduced by allowing the hull to heel and it is therefore important to keep the hull upright.

At the lower speeds the effect of a positive (leeward) heel angle results in no significant change in sideforce while a negative (windward) heel angle produces a possible small reduction in sideforce. In Fig. 10, which shows the resistance as a function of sideforce coefficient at the same two speeds, it can be seen that the results for the positive heel angle are similar to that for the upright hull suggesting that from consideration of the hull alone there is no disadvantage to allowing the boat to heel at low and medium speeds. It should be noted however that there is a reduction in sail efficiency with increasing heel angle so that the overall performance would be reduced by the effects of heel.

At a negative angle of heel Fig. 10 shows that the resistance at a given sideforce is reduced compared to the upright hull. This result, combined with that shown in Fig. 9 of the same or slightly reduced side force indicates the possibility of an improvement in performance. The reduction in resistance may possibly be associated with a change in cross flow under the asymmetric heeled hull with a resulting reduction in induced drag of the keel and rudder although this point has yet to be investigated.

Since there did not appear to be any result available for sail forces at negative heel angles the overall windward performance was calculated on the assumption that a similar reduction in resistance was obtained at other speeds in the regime covered by the two speeds

tested (2.88 and 5.75 knots) for two different cases:

i) assuming that the sail forces at the negative heel angle would be the same as for the upright condition - considered to be an optimistic situation,

ii) assuming that the sail forces were represented by those for 10° positive (leeward) heel angle - considered to be a pessimistic situation since the windage effects of the hull at least would be likely to be less for a negative heel angle.

The two curves obtained are shown in Fig. 11 together with the standard curve for the hull in the upright condition and it can be seen that in both cases there is an improvement in performance with a larger improvement for the more optimistic assumption with regard to the sail forces. A similar improvement in performance can be expected for the reaching condition at boat speeds within the range for which this heel effect was observed (up to 5.75 knots).

In practical sailing the effect of heeling the boat to windward may result in some changes in handling since care would need to be taken that the gains made by the improvement in hull performance were not offset by, for example, additional drag of crew in the water following a change in wind speed. Equally at very low wind speeds there may be a reduction in sail forces resulting from a change in sail shape caused by the weight of the fabric at the negative heel angle.

In general the present tests have shown that a positive heel angle does not greatly affect the hydrodynamic forces, except at high speed, but the overall performance would be worse because of the reduction in sail forces. However, at low and medium speeds it

is shown to be an advantage to produce a negative heel angle although the exact improvement in performance cannot be determined without a better knowledge of the sail forces involved. At high speeds, in the planing region, the effects of heel (positive or negative) result in a reduction in performance.

5. CONCLUSIONS

Tests on the model of a Tempest yacht showed that the optimum trim angle was close to the test trim angle at low speeds but at higher speeds the optimum trim angle was greater than the test or natural trim and would therefore need to be achieved by a rearward movement of centre of gravity, a result which is in agreement with normal sailing practice.

The effect of an increase of displacement representing an increase in crew weight, was shown to be a disadvantage for downwind performance and also for windward performance at low true wind speeds. In the particular case studied, with an increase in crew weight of 0.245 KN(55 lb) it was shown that the increased righting moment provided by the additional weight would result in an improved windward performance in wind speeds above about 7 knots.

Measurements of the effects of heel angle at selected speeds showed that a positive (leeward) heel angle would result in reduced performance at all speeds. An unusual result was obtained with a negative (windward) heel angle of 10°, showing that a significant improvement in performance should be found for low and medium speeds when the hull is moving with leeway (i.e. on a beating or reaching course).

ACKNOWLEDGEMENT

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TABLE 1

Yacht and model details

Symbol	Description	Units	Yacht	Model
L_{OA}	length overall	m	6.70	1.117
L_{DWL}	length on design waterline	m	5.87	0.978
B_{DWL}	beam on design waterline	m	1.44	0.240
T	total draught	m	1.10	0.183
Δ	*total displacement	KN	5.690	
Δ_c	*design crew weight	KN	1.619	
S_W	total wetted area	m^2	5.90	
S_A	effective windward sail area	m^2	18.74	
S_{AD}	effective downwind sail area	m^2	31.97	

* It is understood that the average crew weight in competition is 1.668 KN and with an increase in boat weight the total would currently be 6.318 KN. The tests and predicted performance were made with the design weight so that some alteration is absolute values can be expected but the relative values obtained on the effects of increased crew weight will remain valid.

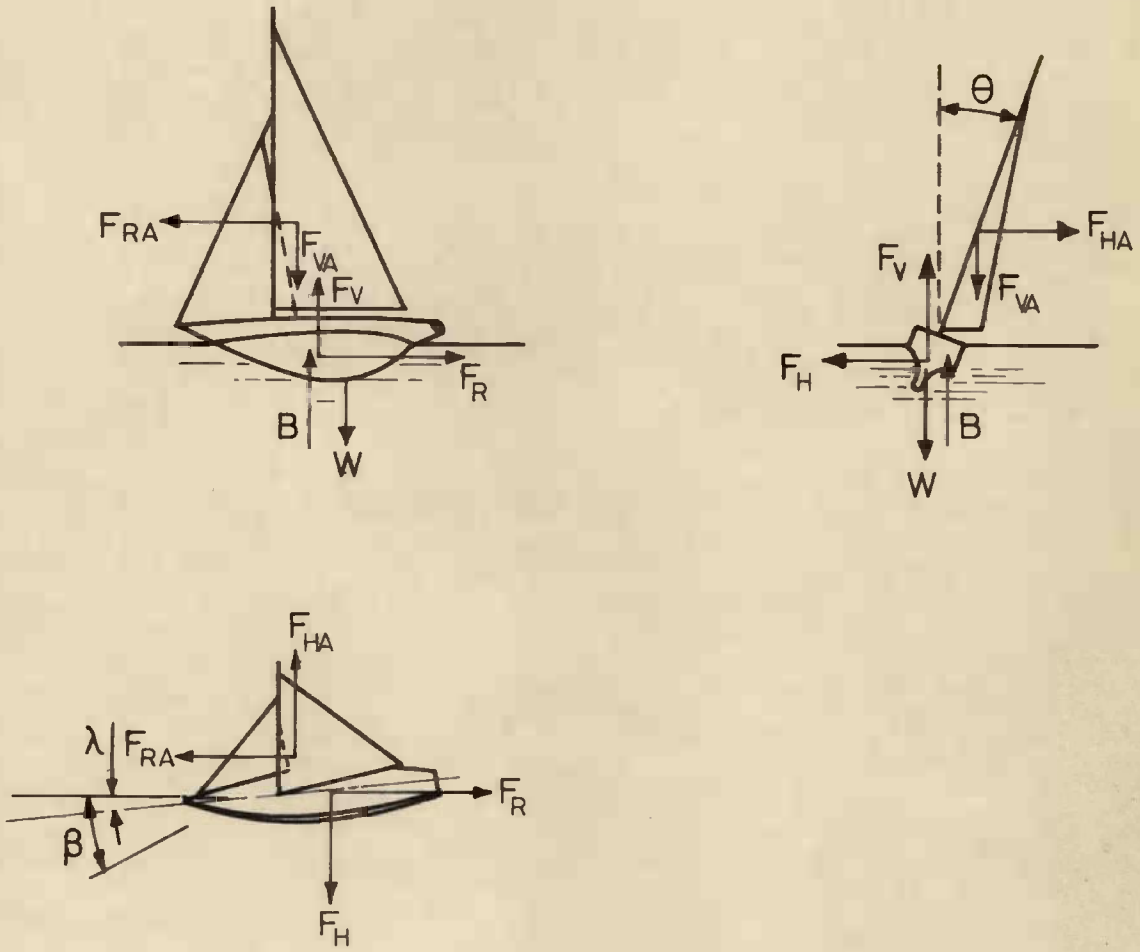

FIG.1. THE AERODYNAMIC AND HYDRODYNAMIC FORCES ON A SAILING YACHT.

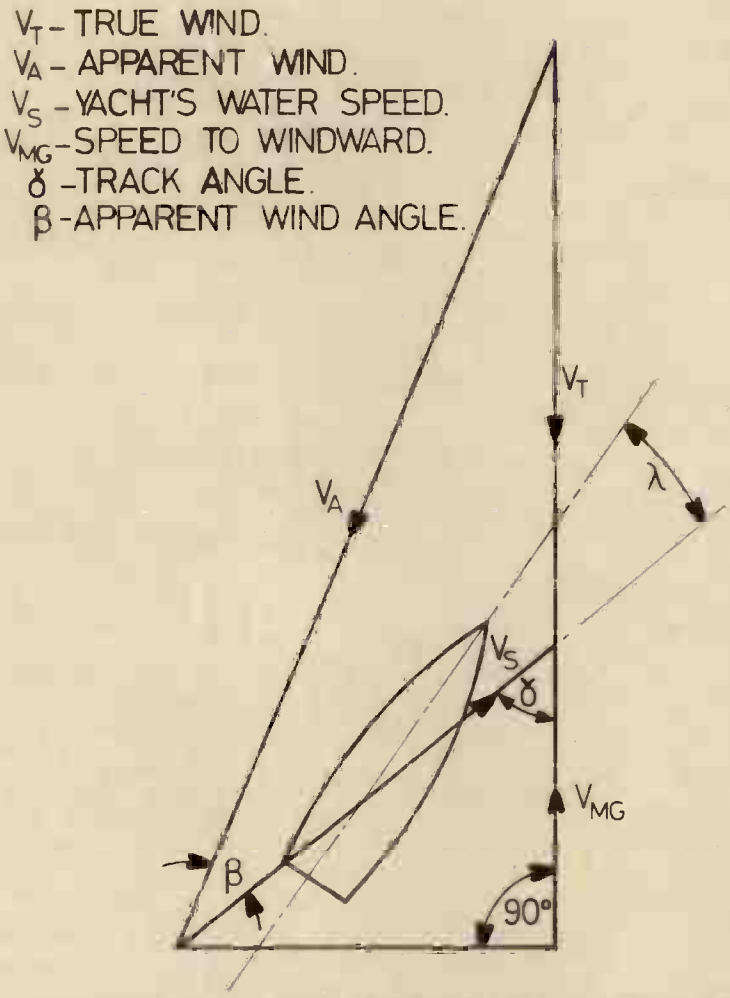

FIG. 2. THE HORIZONTAL VELOCITY VECTORS.

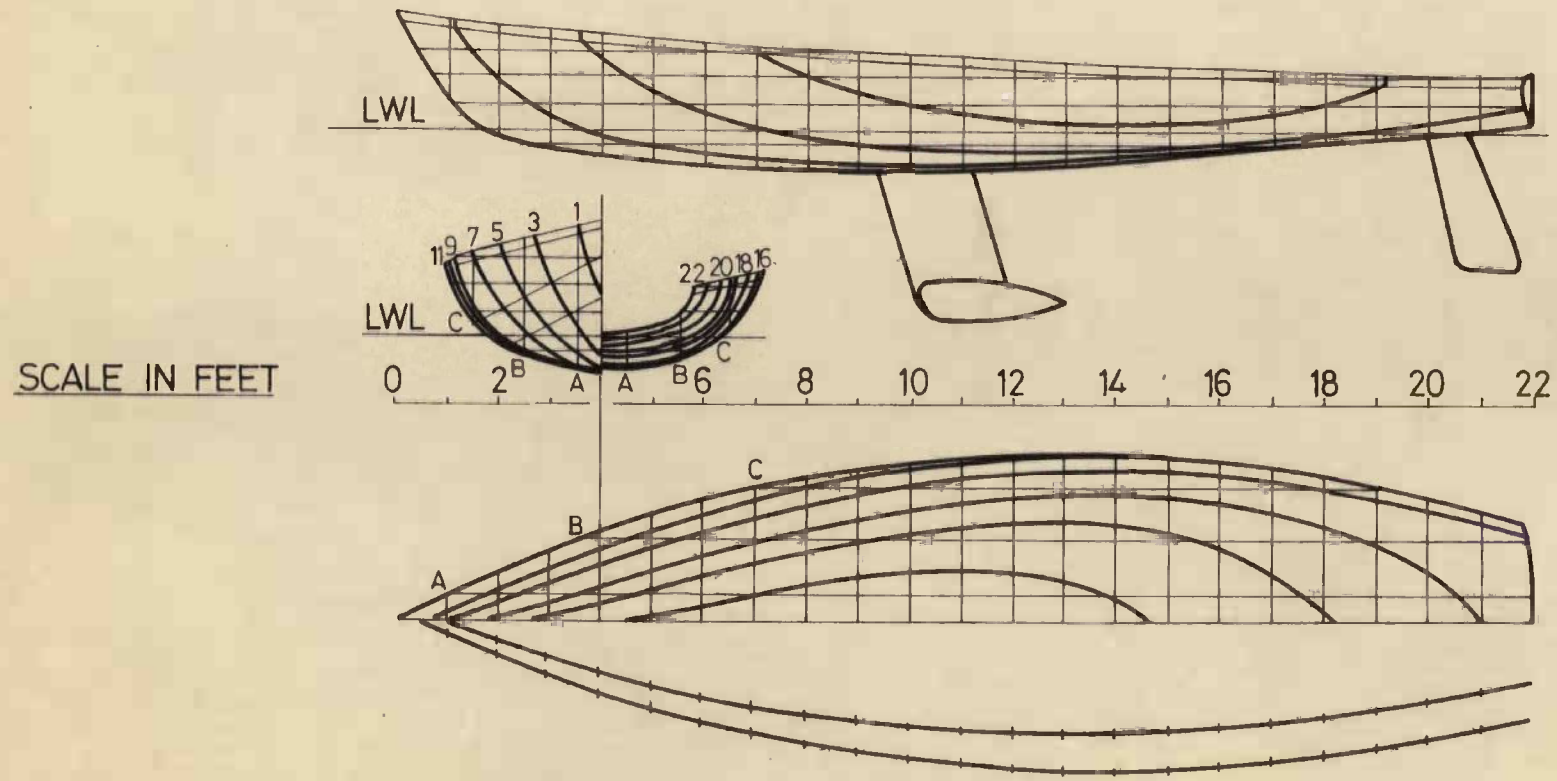

FIG.3. HULL LINES OF THE "TEMPEST."

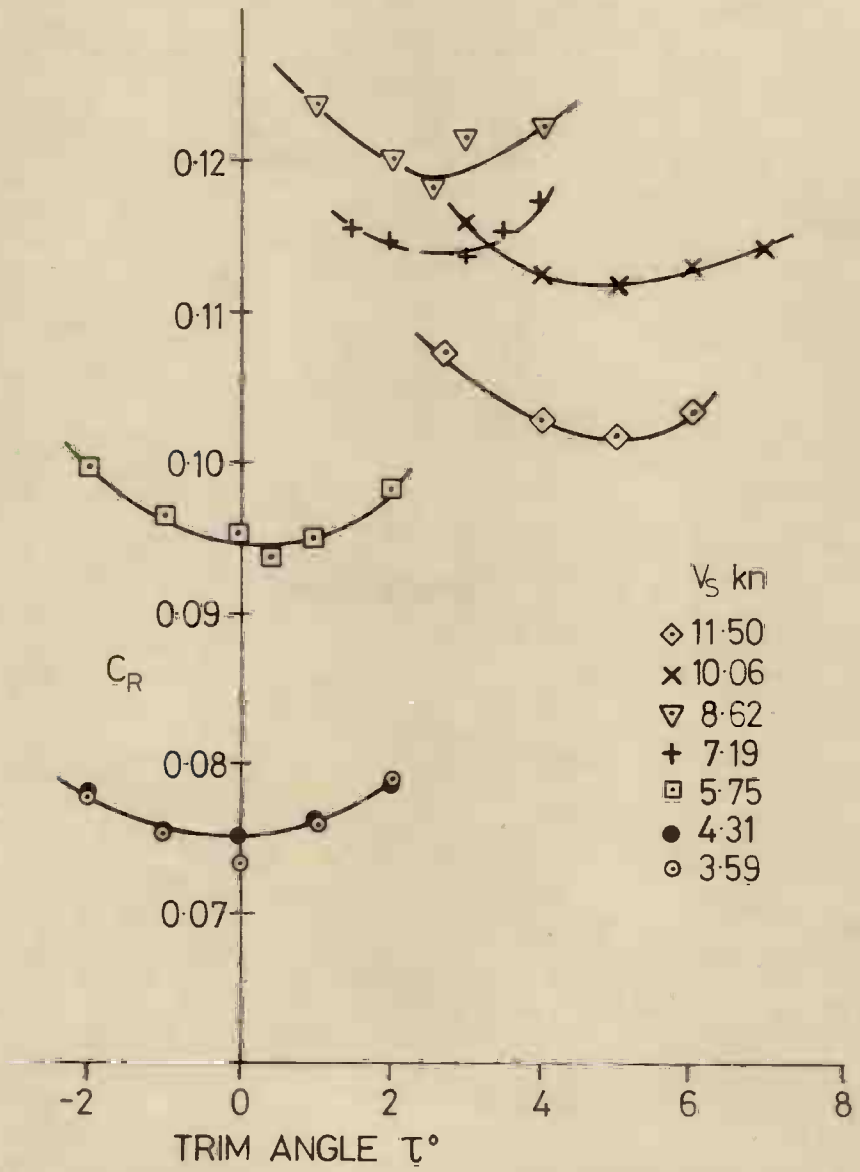

FIG. 4. THE VARIATION OF RESISTANCE COEFFICIENT WITH TRIM ANGLE FOR A RANGE OF SPEEDS.

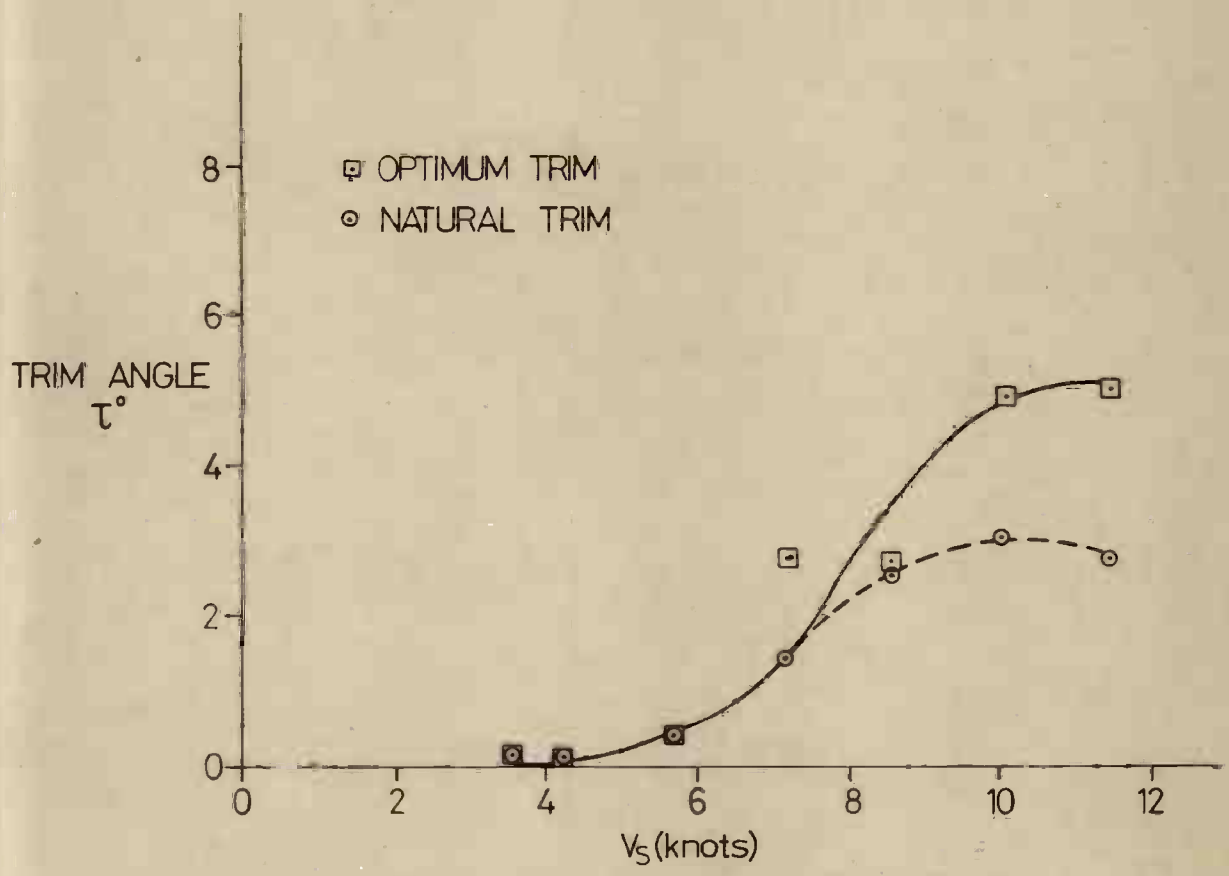

FIG. 5. THE VARIATION OF OPTIMUM TRIM ANGLE WITH SPEED.

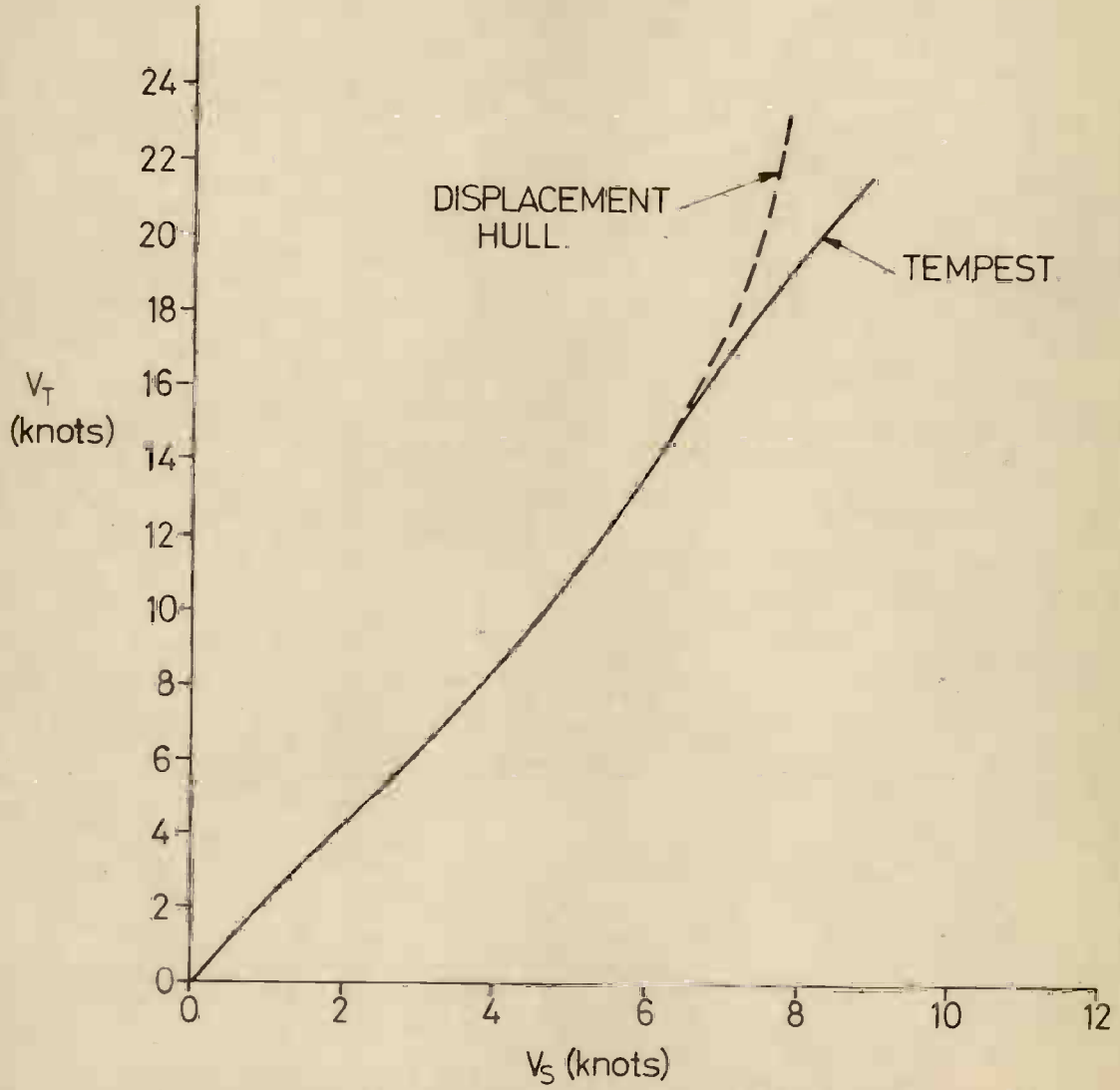

FIG.6. THE DOWNWIND PERFORMANCE AT THE DESIGN DISPLACEMENT.

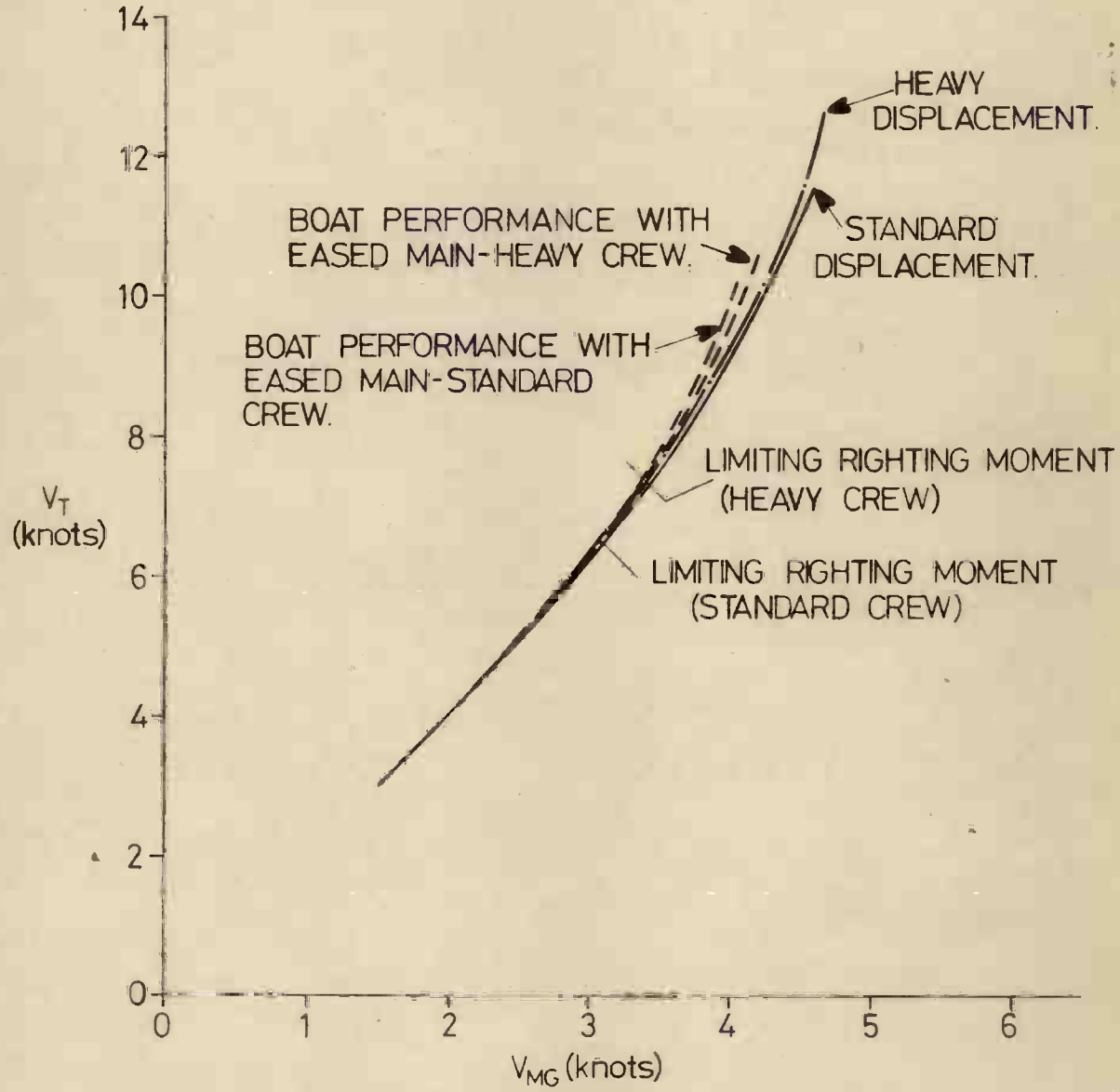

FIG.7. WINDWARD PERFORMANCE.

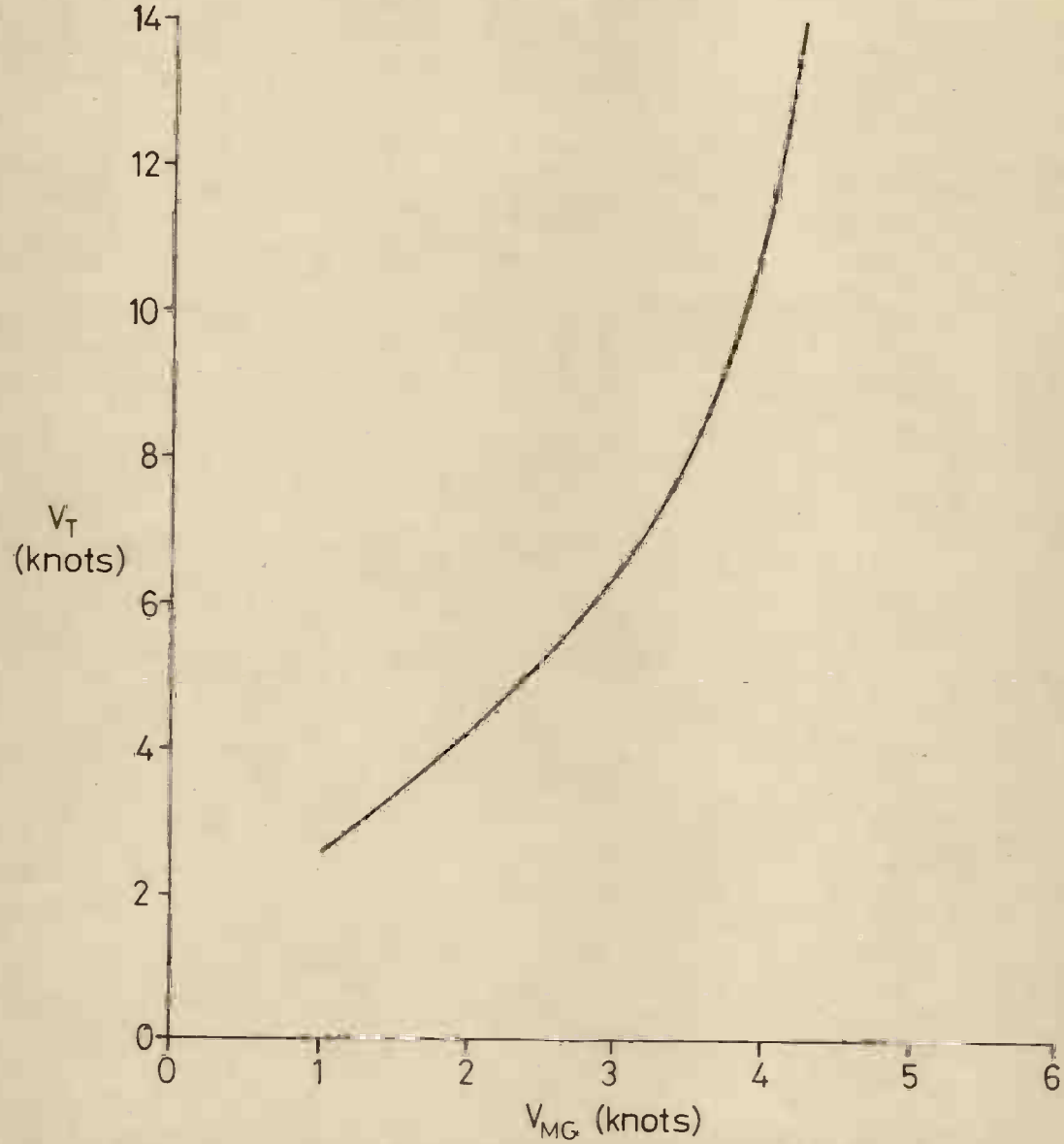

FIG. 8. WINDWARD PERFORMANCE OF A CONVENTIONAL DISPLACEMENT YACHT - 'YEOMAN V'.

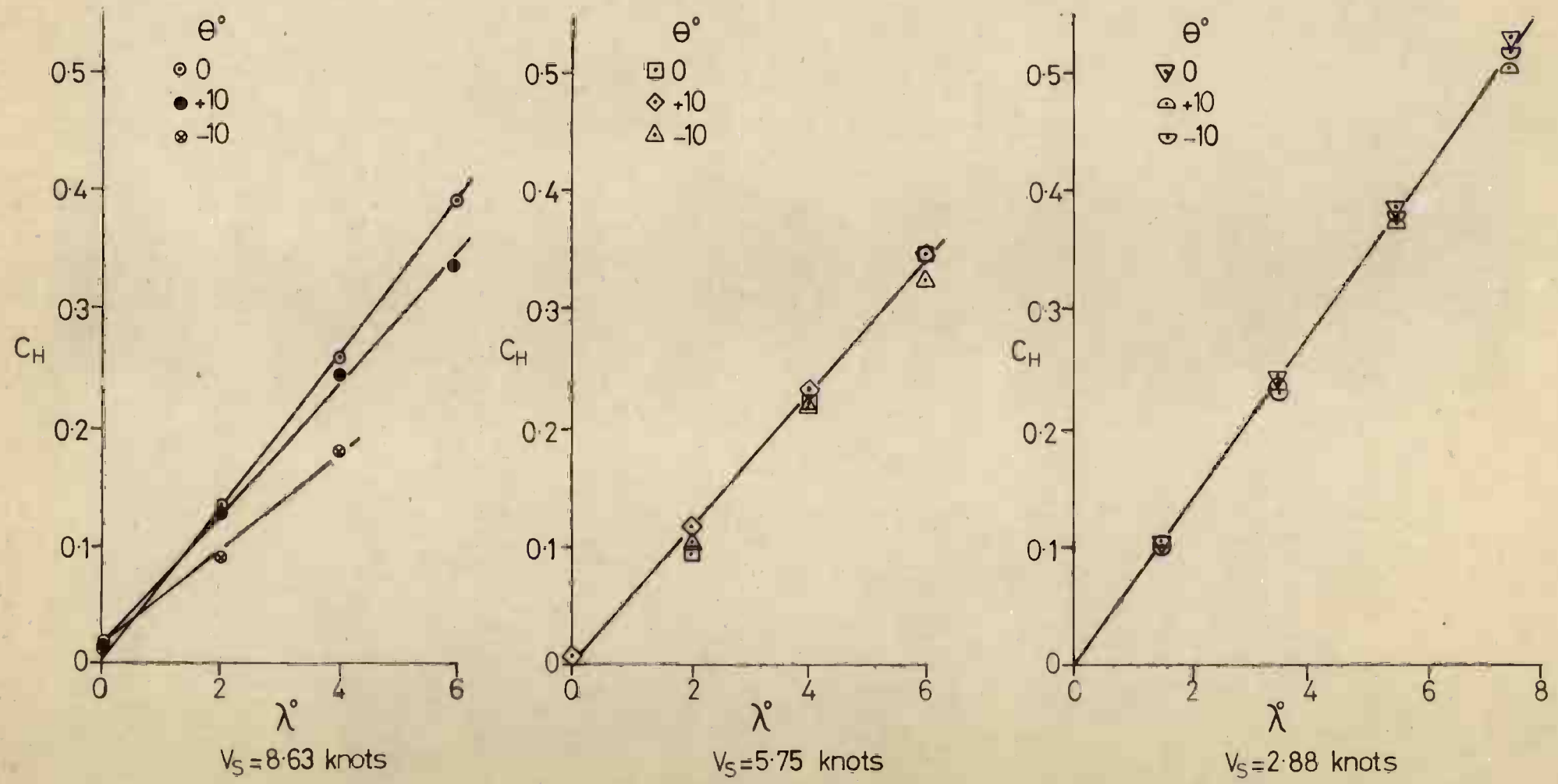

FIG.9. THE VARIATION OF SIDE FORCE COEFFICIENT WITH LEEWAY ANGLE AND HEEL ANGLE.

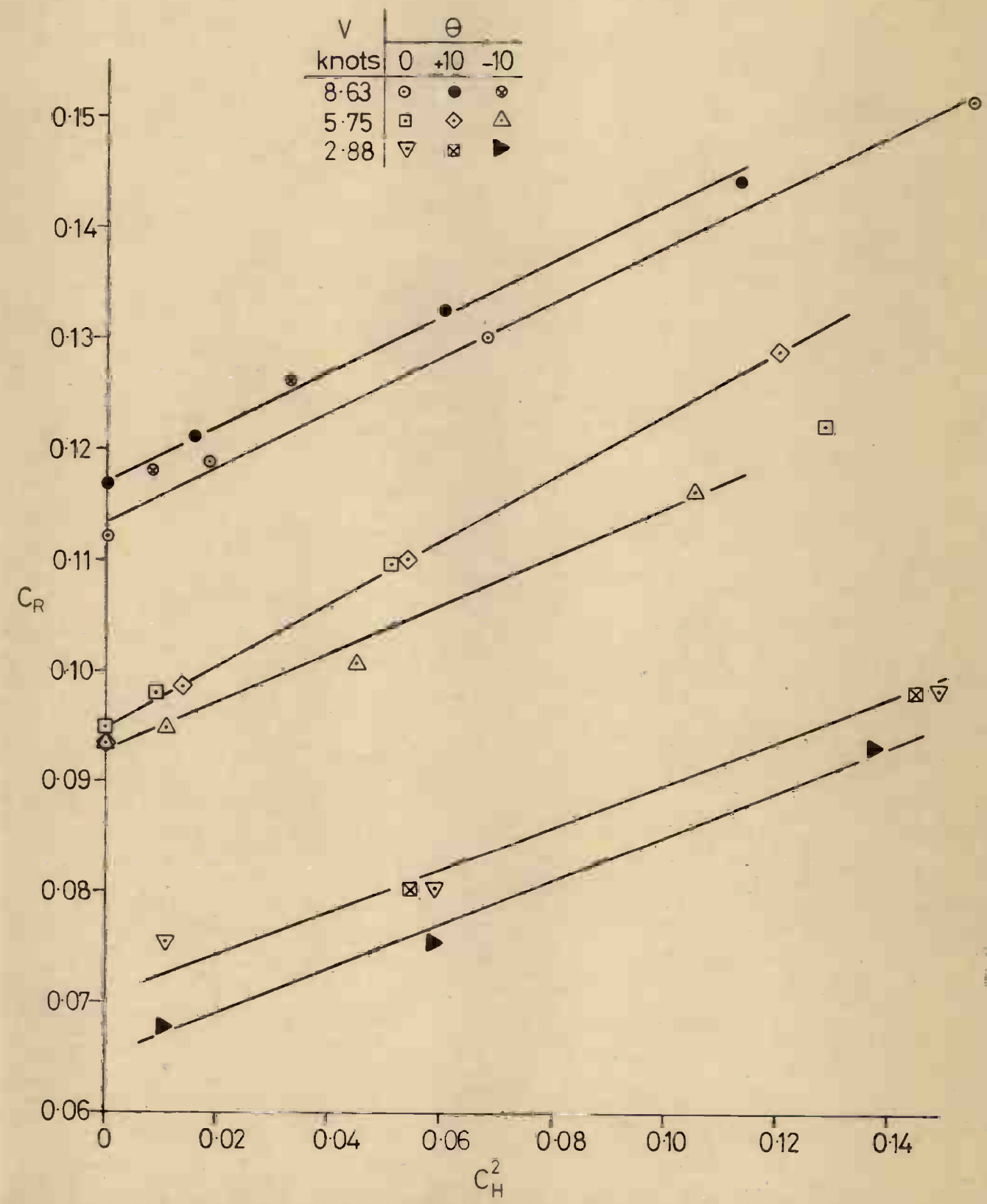

FIG.10. THE VARIATION OF RESISTANCE COEFFICIENT WITH SIDE FORCE COEFFICIENT FOR THREE HEEL ANGLES.

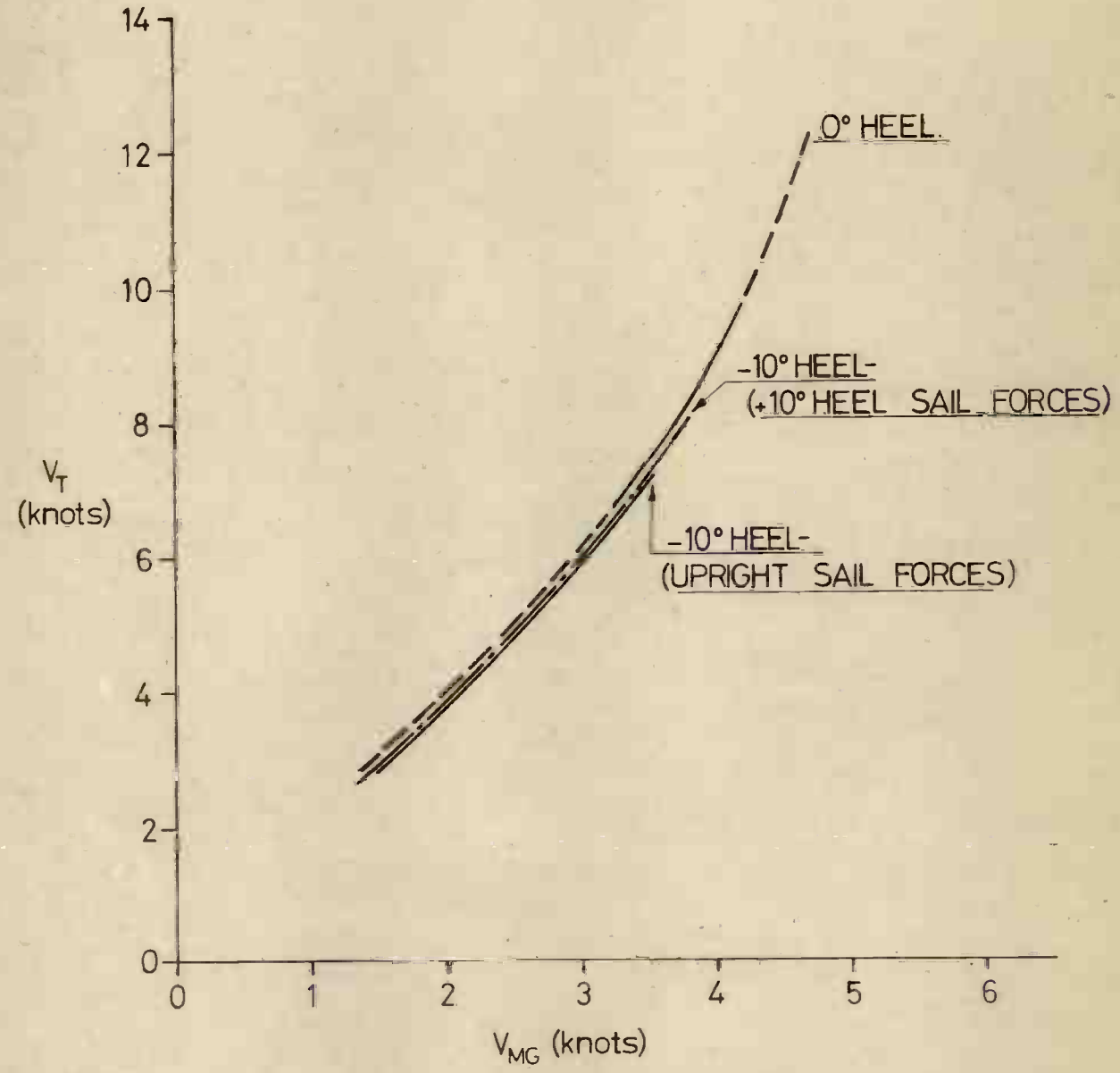

FIG.11. THE PREDICTED WINDWARD PERFORMANCE FOR A WINDWARD HEEL ANGLE.