The development of the winged keel for twelve-metre yachts

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In this paper the authors present a numerical and experimental analysis of the winged keel originally developed for the International twelve-metre class yacht *Australia II* that won the America's Cup in 1983. After briefly explaining why this keel was evolved in 1981, some basic considerations are presented relating keel performance to various design parameters. The results of numerical flow analyses and wind-tunnel measurements on a model of a winged keel are then presented and compared. The differences between the performance with and without winglets fitted to the keel are discussed. The fitting of winglets appreciably enhances the performance of a low-aspect-ratio lifting surface such as the keel of a twelve-metre yacht.

1. Introduction

G. I. Taylor found much enjoyment from yachting, especially in his earlier years. In 1926 he sailed his yacht *Frolic* across the North Sea to Norway and after visiting many places up and down the coast finally left her at Kristiansund for the winter. In the summer of 1927 he rejoined *Frolic* and cruised in her across the Arctic Circle and then back to Scotland. An account of this adventure can be found in Taylor (1927) and indeed resulted in the award of the Royal Cruising Club Challenge Cup. G. I. was particularly pleased at receiving this.

The evolution of the winged keel fitted to the International twelve-metre yacht *Australia II* and the part it played in helping to win the America's Cup in 1983 is just the kind of story that would have intrigued G. I., and for this reason is outlined here in his honour.

A suitable beginning is the analysis of the influence of major design factors on International twelve-metre-yacht performance by one of the authors, Van Oossanen (1979). There it was concluded that, 'for true wind speeds not exceeding 15 knots, the optimum twelve-metre size seems to be smaller than present-day designs'. It was further concluded that, '... it is incorrect not to maximize the allowable sail area'. Before proceeding further it should be explained that the rule governing the measurement of International twelve-metre yachts requires a balance between measured length, displacement and sail area. (Other requirements in the rule place a limitation on the shape of the midship section and on maximum draft which results in a very low-aspect-ratio keel). So if measured length and displacement are reduced to produce a smaller yacht as suggested, then the sail area can be maximized.

The problem that arises from this adjustment involves lack of stability to balance
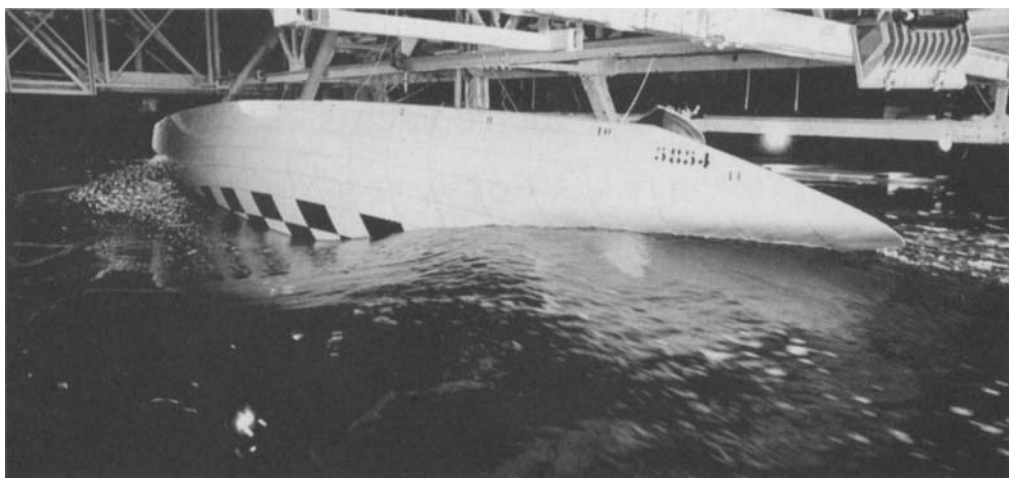
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FIGURE 1. Model of *Australia II* at 20° heel and 4° leeway and speed equivalent to 8 knots full scale, showing depressed water surface above windward side of keel.

the increased heeling moment from the larger sail area. This occurs for the following reasons. The overall length varies little between small and large twelve-metre yachts. Since the unit weight of the hull structure is constant (to meet the rules) it follows that there can be small differences in hull weights. The same applies to the mast, spar, rigging, sails and crew weights. Therefore, to make a lighter twelve-metre yacht of smaller length it is necessary to reduce the amount of ballast, which necessarily causes a reduction in stability. The designer trying to follow the suggested path towards a smaller, lighter yacht may find he is in a vicious circle.

The races for the America's Cup between *Freedom* and *Australia I* in 1980 had revealed that 'Australia I' lacked upwind ability, which again pointed to the need to improve the design of the keel. In 1981, the designer, Ben Lexcen, asked the Maritime Research Institute Netherlands (MARIN) at Wageningen to help with the evaluation of radical departures from traditional designs, and it was suggested to him that some initial computer modelling might be a quicker and cheaper method than model testing, for the purpose of evaluating different possible keel configurations.

The National Aerospace Laboratory of the Netherlands (NLR) was subcontracted for this finite-element modelling which could calculate side-force and induced-drag properties and they suggested that it might be worthwhile to include the free surface in the modelling process, as this acts as a pressure-relief surface. Prior to this suggestion most analyses of yacht keels had considered the free surface to be horizontal or the Froude number to be zero. As can be seen in the photograph given in figure 1 this is hardly true for an International twelve-metre yacht. The additional variables to be investigated were keel sweep angle and taper ratio, where sweep angle is the angle between the vertical and the quarter-chord line and taper ratio is the ratio of the chord length at the tip of the keel divided by the chord length at the root. The results of the subsequent numerical and experimental work by NLR and MARIN led to the development of the winged keel, which is presently being adopted for all twelve-metre yachts; see van Oossanen (1985).
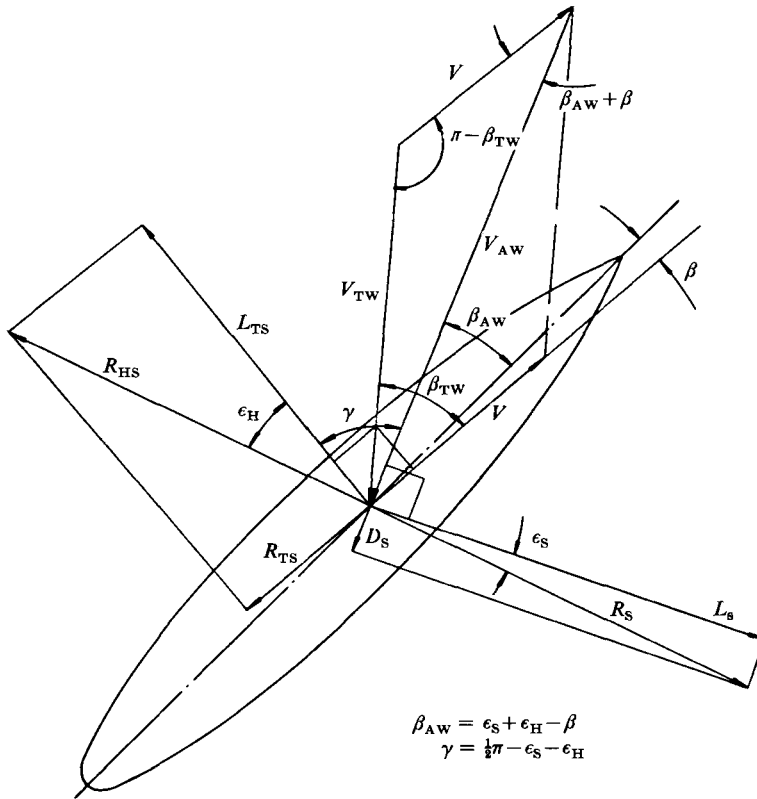
FIGURE 2. Definition of forces and angles used in mathematical relations for a yacht sailing to windward with velocity V and leeway angle β.

R_{HS}, R_S = resultant hydrodynamic and aerodynamic forces,
L_{TS}, R_{TS} = total hydrodynamic side and resistance forces,
L_S, D_S = total aerodynamic lift and drag forces,
β_{TW}, β_{AW} = true and apparent angles,
V_{TW}, V_{AW} = true and apparent wind velocities,
ϵ_H, ϵ_S = hydrodynamic and aerodynamic drag angles.

2. Basic considerations

When beating to windward the resulting force of the wind on the sails has a component at right angles to the yacht's heading. This transverse force can be up to about five times greater than the forward thrust component; see figure 2. In any steady sailing condition, equilibrium exists between aerodynamic and hydrodynamic forces on the yacht. Hence the transverse component of the wind force is in equilibrium with the transverse component of the hydrodynamic force (referred to as side force) on the hull (often referred to as the canoe body), keel and rudder.

The only way for a yacht to develop side force is to adopt an angle of incidence or leeway angle β relative to the track of the yacht through the water. Unlike the wings of an aircraft, the keel of a yacht does not have camber, requiring that the total side force be generated by leeway only.†

In sailing-yacht design it is necessary to minimize the amount of leeway required to generate the desired side force. This is because the hydrodynamic resistance of the

† A yacht must usually perform equally well on port and starboard tack, while an aircraft does not have to perform equally well when flying upside-down.
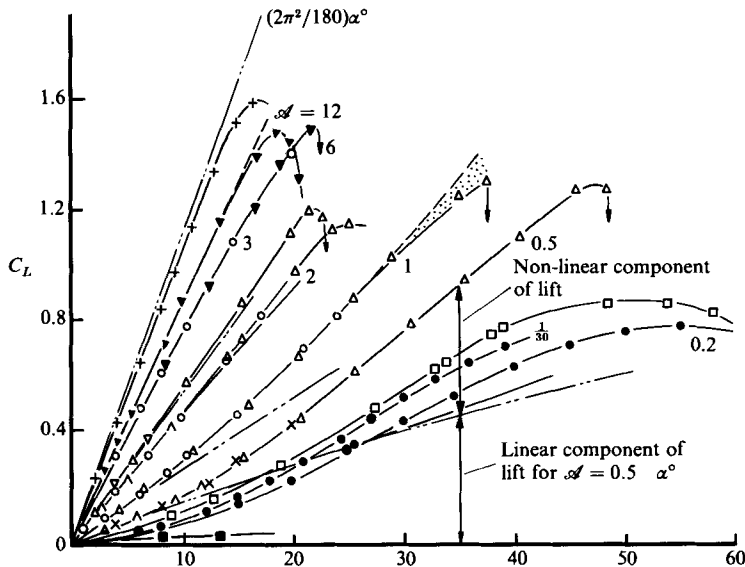
FIGURE 3. Dependence of lift-curve slope on aspect ratio and angle of incidence (from Hoerner & Borst, 1975). + NACA, $t/c = 12\%$ in two-dimensional tunnel; ▼ NACA tapered $\mathscr{A} = 6$ and 12; ● NACA and ARC, 0012, $\mathscr{A} = 6$; △ NACA, Clark Y, various aspect ratios; ○ AVA, sharp-edged rectangular wings; ▽ BRUNSWICK, $\mathscr{A} = 3$; ∧ ARC, rectangular, $\mathscr{A} = 0.5$ and 2; × SCHOLZ, rectangular, $\mathscr{A} = 0.5$; □ NACA, rectangular plate; ■ Winter strip with $\mathscr{A} = \frac{1}{30}$.

hull increases with increasing leeway angle. The most important single problem in racing yacht design can be formulated as how to design an underwater configuration that generates a certain side force for minimum resistance or, how to maximize the side-force-resistance, or lift–drag ratio. The better solution of this problem in *Australia II* than on any other twelve-metre-class yacht constituted an important reason for this yacht's success.

The ability of a yacht to generate a high side force for a small increase in resistance (relative to the resistance at zero side force) depends mainly on the design of the keel and the rudder. If keel and rudder are capable of generating a high side force at small leeway angles, in the order of a few degrees, the associated increase in resistance will be mainly composed of induced resistance. If large leeway angles are required to generate the required side force (from 5° to 10° for example) the flow around the aft part of the canoe body will separate, and the resistance associated with leeway increases markedly. The flow on the windward side is particularly prone to separate at such values of the leeway angle.

The single most important design parameter in the design of keels and rudders is the aspect ratio. The geometric aspect ratio is defined as the ratio of the square of the span or height of the keel or rudder, divided by its lateral area. To fully understand the role of the aspect ratio it is necessary to comprehend the nature of the so-called lift-curve slope and of the induced resistance.

The side force or lift produced by a keel or rudder, for small leeway angles, can be considered to be a linear function of the leeway angle for a constant speed and given geometry. The slope of the lift or side-force curve, as a function of leeway angle, can therefore also be considered as a constant for a constant speed and given geometry. The leeway-angle or angle-of-incidence range for which this is the case depends primarily on the aspect ratio. This follows from figure 3, taken from Hoerner
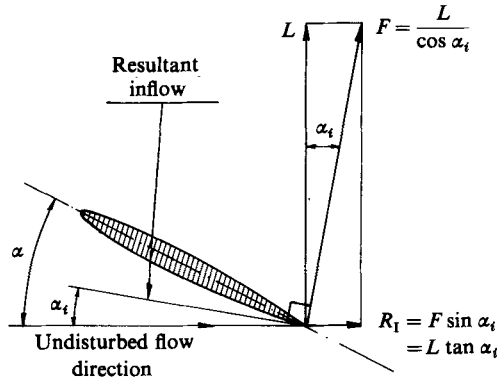
FIGURE 4. Induced drag – a component of the lift force.

& Borst (1975), which shows the value of the lift coefficient C_L as a function of angle of incidence as measured on wings of various aspect ratios $\mathscr{A}$.

It follows from figure 3 that for a particular value of the aspect ratio the lift-curve slope is constant, for all practical purposes, up to angles of incidence of about 5° for an aspect ratio of about 0.5, and to about 10° for an aspect ratio of 6 and higher. Since the maximum leeway angle on a racing yacht very rarely exceeds about 6°, the assumption of a constant lift-curve slope in keel-design analysis is therefore valid for values of the aspect ratio in excess of about 0.5.

Neglecting effects of heel and sweep angle and the type of section used, the lift-curve slope for geometric aspect ratio values less than about 1 is approximately equal to $\frac{1}{2}\pi\mathscr{A}$, and the side force or lift L produced by a rudder or keel becomes

$$ L \approx \tfrac{1}{2}\rho V^2 (\tfrac{1}{2}\pi\mathscr{A}) \, \beta A_L \quad \text{(for } \mathscr{A} \leqslant 2), $$

in which ρ is the density of water, V the velocity of the yacht, $\mathscr{A}$ the effective aspect ratio of keel or rudder (usually assumed to be double the geometric aspect ratio), β the leeway angle, and A_L the lateral area of the keel or rudder.

This equation is not entirely correct since the additional side force induced by the keel (or rudder) on the canoe body and by the canoe body on the keel (or rudder) has been neglected.† Hence, the total lift or side force generated on a keel or rudder is generally not written in this way. For the purpose of amplifying the importance of aspect ratio in the design of keels and rudders, however, the formula is satisfactory.

Lift on a body is generated by deflecting the flow over an angle downward (or sideways) from its undisturbed direction. This is experienced as an upwash in front and a downwash behind the body. The resultant force on the body acts approximately at right angles to the resultant flow velocity at the body. The useful component of this resultant force is the lift or side force, at right angles to the undisturbed flow direction; see figure 4.

For lift L, the resultant force then becomes $F = L/\cos\alpha_i$, where α_i is the downwash angle at the body.‡ A study of figure 4 reveals that a force component exists acting against the direction of the undisturbed flow $R_I = F \sin\alpha_i$ or $R_I = L \tan\alpha_i$. This force component is experienced as a resistance. It is termed the induced drag D_I because it is associated with the deflected or induced flow around the body.

† For a full development of this subject and associated formulas see van Oossanen (1981).

‡ The downwash angle at the body is half the angle through which the flow is deflected far downstream.
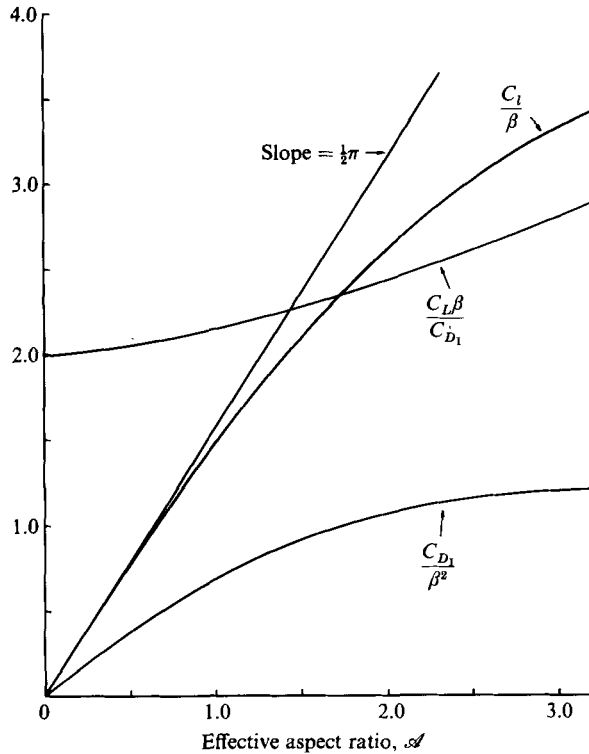
FIGURE 5. Lift and induced drag coefficients and lift-induced drag ratio as a function of aspect ratio; β is leeway angle.

It can be shown (see Hoerner 1965) that $\alpha_i \approx C_L/\pi\mathcal{A}$, $C_L = L/\frac{1}{2}\rho V^2 A_{\mathrm{L}}$. Hence,

$$D_{\mathrm{I}} \approx L \tan\alpha_i \quad (= L\alpha_i \text{ for small } \alpha_i \text{ angles})$$

$$= \frac{LC_L}{\pi\mathcal{A}},$$

or
$$D_{\mathrm{I}} = \frac{\frac{1}{2}\rho V^2 A_{\mathrm{L}} C_L^2}{\pi\mathcal{A}}.$$

From this formula it follows that as the aspect ratio increases, the induced resistance decreases.

To obtain some quantitative idea about the relative importance of the influence of aspect ratio on side force and induced drag, figure 5 has been prepared giving values for the lift divided by $\frac{1}{2}\rho V^2 A_{\mathrm{L}}\beta$ and the induced resistance divided by $\frac{1}{2}\rho V^2 A_{\mathrm{L}}\beta^2$. This figure shows that for given β the ratio $C_L/C_{D_{\mathrm{I}}}$ increases by about 12 % as the aspect ratio increases from 0 to 1. More importantly, however, for a given C_L, the ratio $C_L/C_{D_{\mathrm{I}}}$ is directly proportional to the aspect ratio and this is what matters.

From these considerations it follows that it is extremely important to maximize aspect ratio. Usually, however, the aspect ratio of the keel is limited by restrictions to the maximum draught. For six- and twelve-metre-class yachts the geometric aspect ratio of the traditional highly swept keel varies from about 0.30 to 0.40, depending on the hull form adopted. This is an extremely low value, leading to an appreciable induced-resistance component.
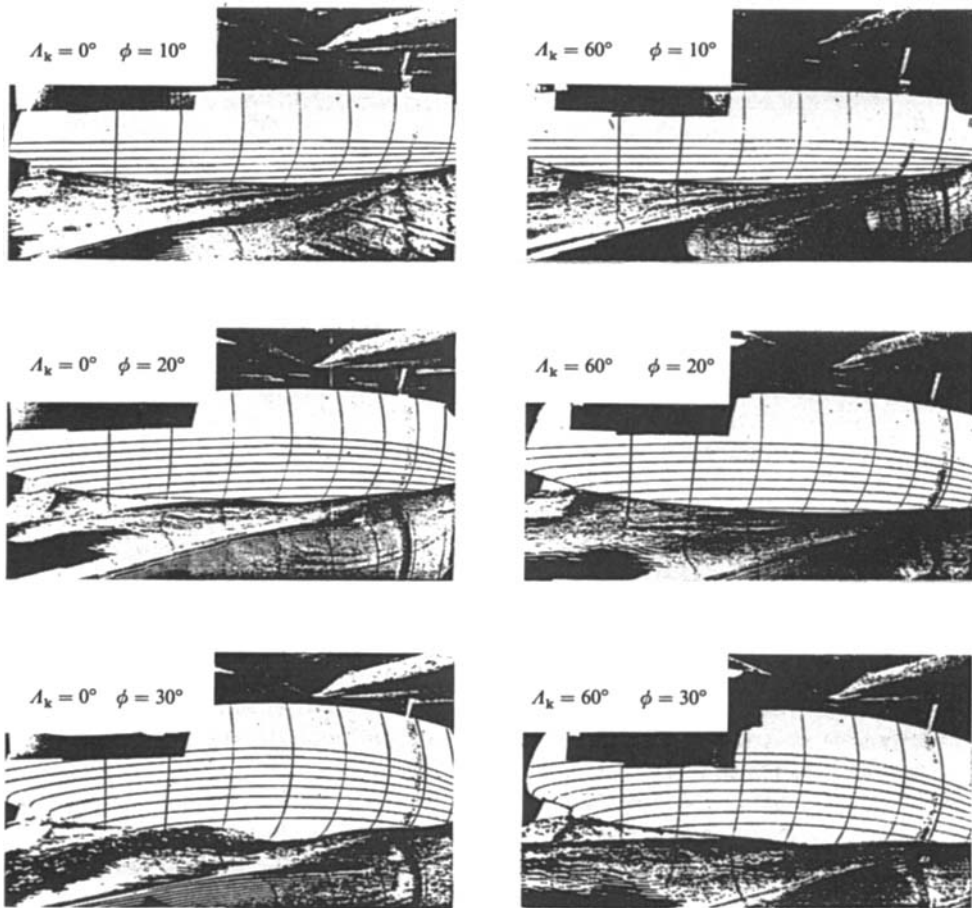
FIGURE 6. Photographs of the wave pattern under heel and leeway for a sweep-back angle $\Lambda_{\rm k} = 0°$ and 60° (from Beukelman & Keuning 1975). $\Lambda_{\rm k}$ = keel sweep angle, ϕ = heel angle of model.

3. Use of inverse taper

The radical keel design adopted for *Australia II* has proved that, contrary to the belief of many, not all has yet been written or said about the optimum planform of a keel (or rudder), particularly with regard to the taper ratio and the sweep angle. Until recently most books and papers on the subject suggested that a trapezium-type planform with a considerable sweep-back angle, depending on the aspect ratio, and a taper ratio of between 0.3 and 0.4, constituted the optimum configuration. This belief is mainly based on aerodynamic theory used for the design of aircraft configurations, with the exception of the criteria used to determine the 'optimum' sweep angle. According to aerodynamic theory, the zero-sweep-angle case is to be preferred, for moderate to large values of the aspect ratio, since lift decreases with increasing sweep angle according to $\cos \Lambda$, where Λ is the sweep angle. However, the results of tests with yacht models fitted with systematically varied keel geometries repeatedly showed that as aspect ratio decreased the optimum sweep angle increased. Studies of the reasons for this result revealed that under heel the keel produces a pronounced wave, increasing the wave resistance. This effect is found to decrease with increasing sweep angle. The photographs in figure 6, taken from a study carried out by Beukelman & Keuning (1975), amplifies this point.
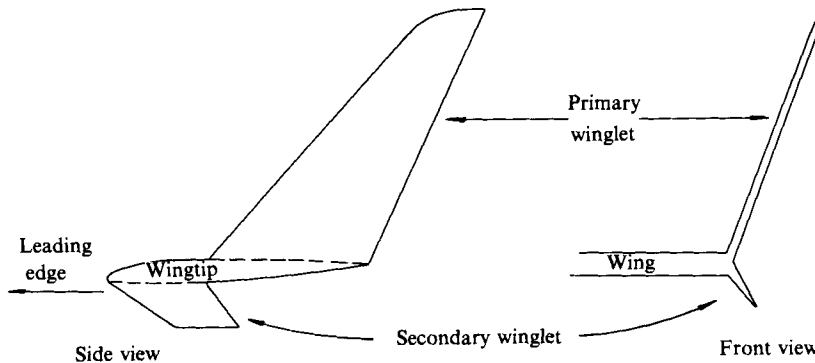
FIGURE 7. Winglets as used by R. T. Whitcomb (NASA) in 1976 in research on aircraft wings.

The reason for the results mentioned above was only fully comprehended in 1981 when analysing the results of computer calculations carried out to study the merits of different radical keel configurations for *Australia II*. It was found that as the centre of side force on the keel was situated further away from the water surface, i.e. further towards the bottom of the keel, the influence of the keel on the wave profile along the hull and, hence, on the wave resistance, decreased.

Then it was realized why large sweep angles, particularly on shallow, long, low-aspect-ratio keels were more beneficial. From aerodynamics it is known that as the sweep angle increases, the centre of lift moves towards the tip of a wing. Hence it follows that as keels become more shallow, it is important to try to place the main load on the keel towards the tip of the keel, as far away from the water surface as possible. Sweep-back does just that.

Notwithstanding the fact that minimum induced resistance is obtained for taper ratios between 0.15 and 0.35, depending on sweep angle, the keel of *Australia II* was given a taper ratio of over 1.5 to minimize the effect of keel loading on wave resistance. This was found to be much more effective than sweep-back in lowering the centre of side force on the keel. To maximize side force, so as to be able to minimize the lateral area of the keel (thereby reducing wetted surface and increasing the aspect ratio), the quarter-chord line of the keel was given zero sweep. Model test results showed that the 'upside-down' keel (as it was then referred to) designed for *Australia II*, even without the subsequently fitted winglets, was significantly superior (in terms of performance differences between twelve-metre yachts) to the traditional keel as used on *Australia I* for the America's Cup races in 1980, see van Oossanen (1985).

4. Use of winglets

Once it was ascertained that application of the 'upside-down'-keel concept for *Australia II* was advantageous, it was only a small step to look for means and ways of decreasing the relatively greater induced resistance, the one aspect of keels with a large taper ratio that needs further refinement. Almost immediately attention was focused on winglets. The winglets concept was developed and patented by Whitcomb of NASA in 1974 (see Whitcomb 1976). Winglets are not to be confused with end plates or fences which can only perform the simple function of preventing flow from the high to the low-pressure side at the wing tip. Unlike winglets, end plates do not develop significant lift.

Winglets are small wings that are carefully positioned so as to become an integral part or extension of the actual wing, see figure 7. They effectively increase the span of the wing and the fact that they are positioned almost at right angles to the plane of the wing does not matter in this respect, as long as the winglet is able to generate substantial lift. The wing with winglet performs approximately as if its span is increased by an amount equal to the span of the winglet. Accordingly, the lift of the wing becomes significantly greater, particularly near the tip, and the induced resistance is decreased.

As the lift-curve slope decreases more rapidly with decreasing aspect ratio, the application of winglets becomes more effective. For a geometric aspect ratio of 0.4, for example, the application of winglets with a span equal to half the span of the keel will result in a geometric aspect ratio of 0.6 and the side force produced on the keel with winglets will be approximately 1.5 times the side force of the keel without winglets at equal leeway angles.

In practice this is not quite true because the lower part of the keel, where the winglets have been fitted, will yield little or no side force. The net gain in side-force production will in this case nevertheless be in the vicinity of 35 %. Even though an important decrease occurs in the induced resistance, the total resistance of the keel configuration will slightly increase or remain about the same because of the added wetted surface of the winglets. Systematic performance calculations and tests are therefore required to fine tune the size of the winglets to obtain optimum performance. So far increases in overall performance in terms of the side force–resistance ratio, have yielded values of about 25–30 %.

Since a keel must perform equally well on port and starboard tack, winglets must be fitted to both sides. If the design of the keel is subjected to a maximum draught restriction, care must be taken to position the winglets such that, in the upright condition, they do not violate the maximum draught rule.†

In order to load the winglets so that they become an extension of the keel, it is necessary to set them at a certain angle down from the horizontal. This angle is termed the dihedral angle, and its value varies from about 7.5° (on some aircraft wings) to about 20° (on *Australia II*). This dihedral angle controls the angle of attack of the flow. If this angle is zero or too small (in which case the winglets would become simple end plates), every value of the leeway angle would yield essentially the same loading, very unlike the behaviour of the keel.‡ Small dihedral angles are required

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† During the America's Cup races in 1983, the New York Yacht Club protested that under heel the winglets on *Australia II* violated the maximum-draught requirement of 0.16 LWL + 0.5 m and that, therefore, she rated about 12.5 m. This possible development was studied in great detail in 1981 and it was decided not to apply to the International Yacht Racing Union (IYRU) for a (then) secret rule interpretation on this subject. The rule would have to be extended considerably to incorporate draught restrictions under heel. It would be necessary to specify the heel angles (or range thereof) at which the draught is maximized (traditional twelve-metre yachts would also violate such a rule extension at small angles of heel because of the specific square-tip keel and trim-tab geometries commonly adopted), and a whole set of requirements would have to be developed to describe heeled flotation tests, to check rating measurements. In 1982 a secret rule interpretation on winglets was made by the IYRU on request of the British *Victory* syndicate, approving the winglets concept, which was ratified by the annual IYRU meeting in November 1983.

‡ After the New York Yacht Club withdrew its protest against the winglets on *Australia II*, in August 1983, the *Liberty* syndicate experimented with small, delta-type wings on the keel of *Freedom*, the excellent US defender of the 1980 America's Cup. These wings had zero dihedral angle and were, in fact, simple end plates. These were removed a day later because it was found that no performance improvement could be detected.

when the angle-of-attack range is significant (such as on rudders), and large dihedral angles are required when the opposite is true, in the case of a keel, when leeway angles are only a few degrees.

To ensure that the winglets are a 'natural' extension of the keel they need to have a root-chord length of about 30–50 % of the length of the keel at the tip. A smaller length, particularly at the keel–winglet intersection, would result in inadequate winglet influence on the flow over the keel, causing the flow to be much more three-dimensional.

A further important design consideration is the longitudinal orientation of the winglets. It is important for the keel configuration not to generate lift while broad-reaching and running under spinnaker, when the leeway angle is virtually zero. Model tests are usually required to accurately determine this zero-lift setting of the winglets. An experimental technique often adopted is to set the winglets on the keel on a torsion shaft, at the quarter-chord or maximum-thickness location. Measurement of the lift, drag and moment in the shaft at different angles of attack of the winglets, in the upright condition at zero leeway angle, at various speeds, yields the required information for determining the zero-lift and minimum-resistance attitude of the winglets.

Twist is necessary because the required angle of incidence for minimum drag varies along the span. On the basis of the results of many winglet orientation tests, it can be deduced that the orientation of the flow at the winglets at zero leeway angle is almost wholly determined by the design parameters of the canoe body and the keel position. Generally the mean chord line of the winglets has to be orientated with a negative angle of attack to achieve the zero-lift condition.

When the winglets are designed to have zero lift at zero leeway angle, the windward winglet, when sailing to windward, will be subjected to a lift force directed upwards, at right angles to the winglet. In that case the windward winglet will generally not have a significant transverse component. The force on the leeward winglet is directed obliquely downward, also at right angles to the winglet. This force has a sizeable transverse component, enhancing the side force on the keel. Even though these forces are generally relatively small they nevertheless help the winglets to 'pay their way'. It should be observed that in all cases the force on the leeward winglet, in enhancing the side force on the keel, increases the overturning couple constituted by the transverse force in the sails and the hydrodynamic side force. In the design of the keel for *Australia II*, the additional side force associated with the leeward winglet was substantial enough to enable the lateral area of the vertical part of the keel to be reduced by 20 %.

Measurements of the forces on the winglets generally reveal that 'on the wind' the effective angle of incidence of the flow is considerably greater than that when running at zero leeway. The leeward winglet, when originally aligned so as not to yield any lift when running or broad-reaching, experiences an angle of incidence in excess of about 6° when the dihedral angle is of the order of 20° for about 4° leeway angle and 25° heel angle. In some cases the angle of incidence on the leeward winglet is great enough to cause the lift vector to have a net horizontal component acting in the direction of motion (see figure 8) great enough to offset the viscous drag of the winglet and hence produce a net thrust.
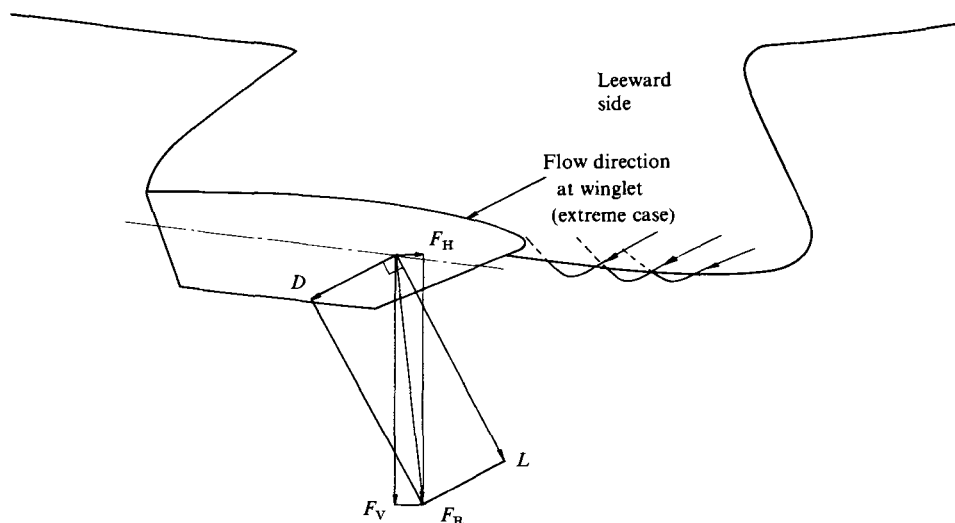
FIGURE 8. When the angle of incidence of the flow relative to the chord line of the winglets is greater than about 6° a net horizontal force generally acts on the winglets in the direction of motion, constituting a thrust force.

5. Further wind-tunnel studies

In order to gain a clearer idea of how well the computer modelling predicts the pressure distributions, to look at the trailing vortex patterns and to examine the keel without winglets, some further studies were undertaken in the wind tunnel at the University of Melbourne. A one-sixth-scale model of the keel and canoe body was built of wood. Pressure tappings were positioned on the keel at the -5 ft waterplane, the $-6\frac{1}{4}$ ft waterplane and the $-7\frac{1}{2}$ ft waterplane. The winglets were pressure tapped at the $1\frac{1}{2}$ ft buttock line. Two positions of heel were examined, upright and 20°, while the leeway angle was varied from 0 to 4°. A ground plate was mounted on the -3 ft waterplane. The model was positioned in the slotted-wall working section of the wind tunnel which measures $1.675 \text{ m} \times 1.295 \text{ m}$. The ground plate was positioned parallel to and 200 mm above the floor, see figure 9. All tests were conducted at 25 m/s, which gave a Reynolds number based on the longest pressure-tapped chord (0.719 m) of the keel of 1.17×10^6. Typical full-scale Reynolds numbers, based on chord length, are of the order of 1.5×10^7. More complete details may be found in the report by Joubert, Wang & Clayton (1986), including a drawing of the keel. Since the actual *Australia II* keel geometry could not be used for this study, Joubert and co-workers estimated the required geometric particulars from available photographs.

The flow pattern was studied by means of tufts and the vortices were measured using a spinning vortometer as suggested by Hopkins & Sorensen (1956). A further series of tests were organized with the winglets removed and the tip of the keel smoothed to a half-rounded cross-section.

The computer calculations were carried out with the NLR panel program by MARIN, in which the flow about the hull is simulated by means of source–sink and vortex distributions. The surface of the hull, keel and rudder and of a specific area of the free surface around the yacht is divided into small quadrilateral panels. For some of the calculations as many as 2000 panels are used. Each panel is given a pre-determined source strength. On those parts of the yacht developing lift a system of bound and free vortices is superimposed. The free vortices are shed at the trailing
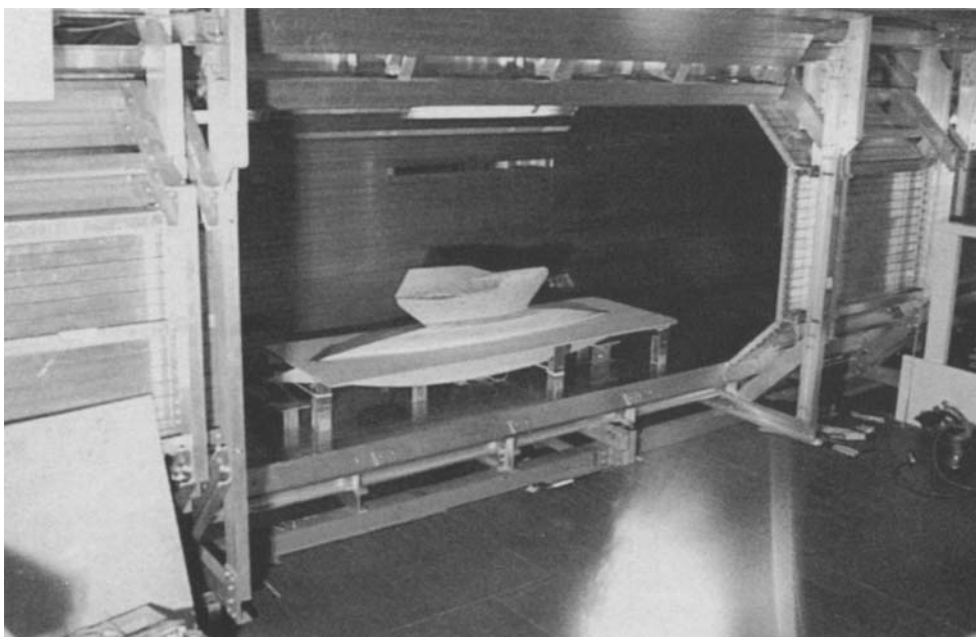
FIGURE 9. Model of winged keel of *Australia II* in wind tunnel at 20° heel and 4° leeway, also showing ground plane.

edges of the keel, the body of the hull and the rudder along pre-determined paths. The bound vortices are positioned on the centreplane of the keel, hull and rudder. The non-dimensional distribution of vortex strength along a vortex line is also pre-determined, leaving only the total circulation as an unknown for any longitudinal strip of panels.

Whereas in 1981 NLR expanded their panel method (see Labrujere, Loeve & Slooff 1970) to take into account the free surface in only a crude way, in 1982–83 they were sponsored to expand their panel method to fully take into account the free surface. The resulting program, called 'hydropanel' is now in use at MARIN.

6. Results and discussion

The experimental results for the keel have been interpolated to correspond with the positions for the numerical results. The agreement between the predicted and measured pressure distributions is quite good, especially considering the inviscid nature of the numerical method. On the windward side the pressure rises for most of the chord, which is hardly conducive to laminar flow; see figure 10. On the lee side the point of minimum pressure occurs at about the 40 % chord position, so significant lengths of laminar flow are likely to occur on this portion of the keel when speeds are low (below about 6 knots) and the keel is constructed with great accuracy.

For the winglets the agreement between the experiment and the prediction is again good except at the first point closest to the leading edge. The pressure differences across the winglets are such that they both add to the heeling moment of the yacht. The leeward winglet in fact contributes substantially towards the side force; see figure 11.

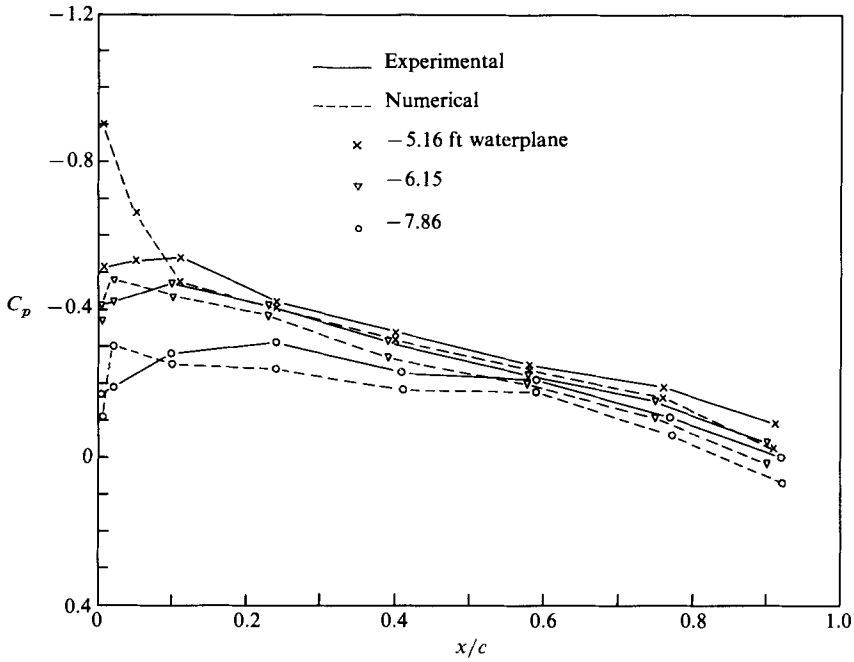At 0° leeway and 0° heel, which corresponds to the yacht running before the wind,

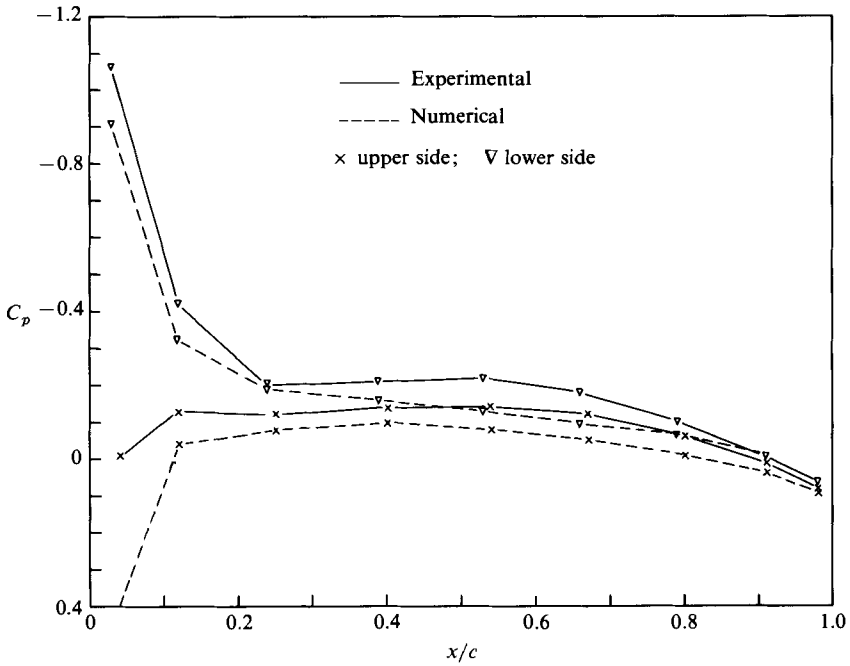FIGURE 10. Pressure distribution along the keel for 20° heel and 4° leeway, windward side.

FIGURE 11. Pressure distributions on the winglets for 20° heel and 4° leeway, leeward side.
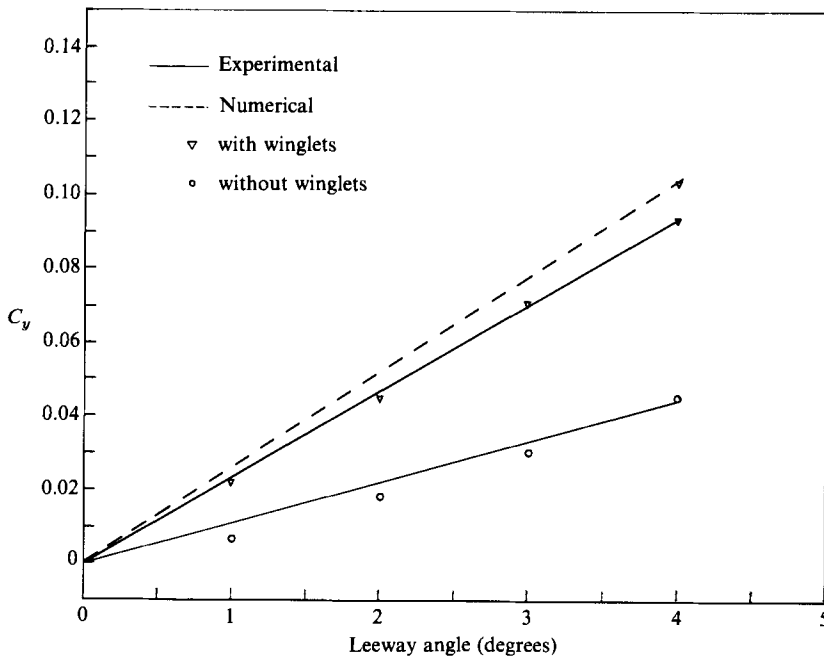
FIGURE 12. Side-force coefficient C_y for keel versus leeway angle at 20° heel.

the winglets both produce a small downward force essentially from the first 10 % of the chord. Laminar flow might be expected on the keel, again below about 6 knots and when the keel is constructed accurately, up to the line of minimum pressure at about 25 % of the chord, which would aid the downwind speed.

The effect of removing the winglets is to reduce the pressure difference across the keel mainly in the region of the $-7\frac{1}{2}$ ft waterplane and from 20 % to 60 % of the chord.

The side force on the vertical part of the keel, with and without winglets, has been found by integrating the pressure distributions and is shown in figure 12.

The lift-curve slope is considerably reduced when the winglets are removed. Also shown is one point from the numerical analysis which exceeds the measured value by 10 %. Re-examination of the pressure differences across the keel (figure 13) shows that the numerical method gives bigger differences from the measured values at the waterplane near the canoe body rather than near the winglets.

The main vortices were located at the tips of the winglets. For 20° heel and 4° leeway, that on the leeward side produced a non-dimensional circulation of 0.0055 compared with that on the windward side of 0.0012. This result is expected, since the more vertically oriented leeward winglet is more heavily loaded.

For the winged keel, the vortex and surface flow patterns as detected by tufts are sketched in figures 14 and 15. In figure 14, which depicts the flow for zero heel and zero leeway, weak vortices occur at the tips of the winglets while three very weak horseshoe vortices spring from the leading-edge roots of the winglets and at the joint of the keel to the canoe body. At 20° heel and 4° leeway, a weaker additional vortex appears along the base of the keel between the winglets (see figure 15). The strong vortices at the wing tips are the dominant feature while, remarkably, the streamlines remain almost parallel and undistorted.
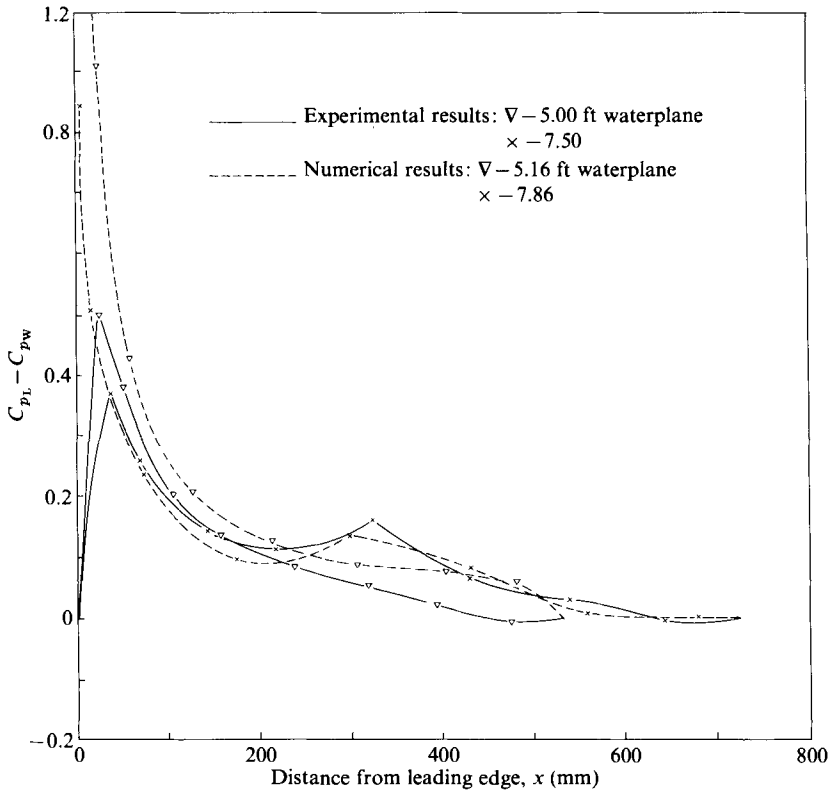
FIGURE 13. The difference between the pressure coefficients on the leeward and windward sides of the keel for two waterline positions, at 20° heel and 4° leeway.
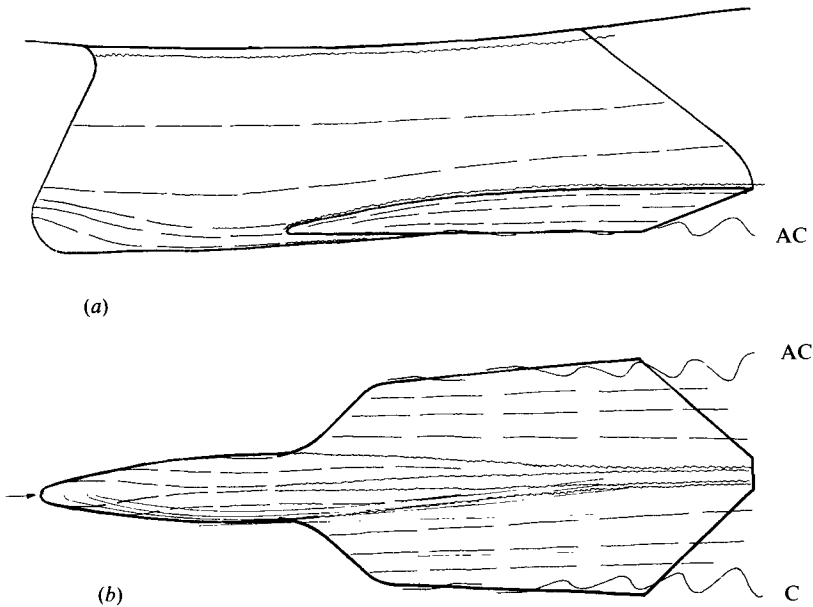

(a)

(b)

FIGURE 14. Sketch of flow pattern and vortices for 0° heel and 0° leeway; (a) side view, (b) bottom view. A broken line indicates a streamline, a continuous wavy line indicates a vortex of strength represented by the amplitude of the wave, and C and AC denote clockwise and anticlockwise sense of the vortex relative to an observer looking upstream.
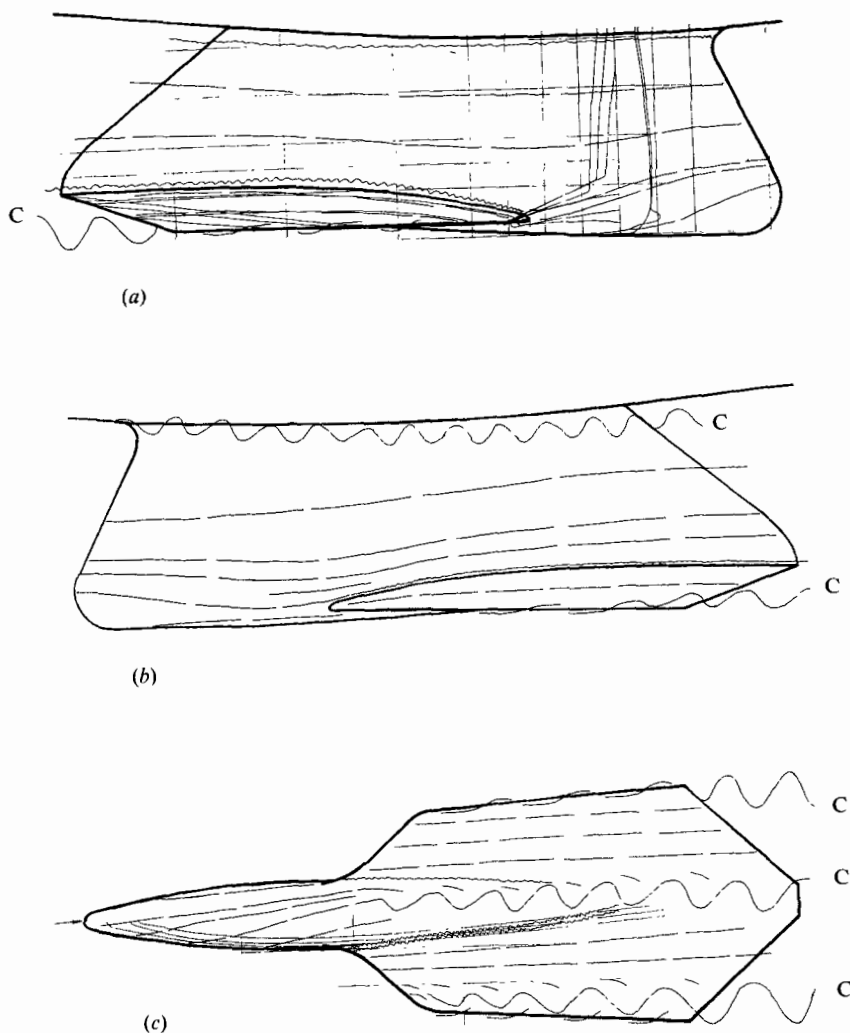
FIGURE 15. Sketch of flow pattern and vortices for 20° heel and 4° leeway; (a) leeward side, (b) windward side, (c) bottom view. Key as for figure 14.

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