

## The Design of a Sailing Hydrofoil—FORCE 8

by D. R. Pattison, C.Eng., RCNC\* (Member)

*Read in London at a meeting of the Royal Institution of Naval Architects on April 20, 1983, Professor J. F. C. Conn, D.Sc. (Honorary Vice-President) in the Chair.*

**SUMMARY:** This paper describes the design and development of the sailing hydrofoil FORCE 8 as a challenger for the world sailing speed record. It has been shown that fully submerged foil systems give excellent seakeeping and control in small fast powered craft, and FORCE 8 was designed to show these advantages in a sailing craft. Stable height keeping is achieved by using mechanical feedback from the surface as in the Hydrofin system invented by the late Christopher Hook. The craft is powered by an unusual rigid wingsail, which automatically angles itself to the apparent wind, controlled by a tab. FORCE 8 now sails reliably at speeds over 20 knots and developments are planned to raise her speed to 30 knots.

### 1. INTRODUCTION

Just over ten years ago John Player, in association with the Royal Yachting Association, published the rules for a new type of competitive sailing—the sailing speed record. The record rules, Ref. 1, are alarmingly brief and the main restrictions are that any record shall be measured over a course of at least five hundred metres; the yacht shall accelerate from rest, and shall be propelled only by the natural action of the wind on the sails, spars and hull, and water (not ice) on the hull; and that at least one person shall be on board throughout, using only manual power, with no power storage, to control the craft. As well as an overall record, records could be established in various IYRU sail area divisions, and a handsome prize of £2,000 was offered. FORCE 8 was designed to win this prize, but has not yet succeeded. She has, however, been described in an Australian magazine as looking 'like a cross between a Spitfire aircraft and an insect'.

### 2. PERFORMANCE REQUIREMENTS

For any rational design study some performance requirements had to be stated, and for a racing machine these had to depend on an assessment of the capabilities of the opposition. At the time it seemed that 30 knots was not going to be any sort of a barrier, although today only Tim Coleman with his magnificent CROSSBOWS has managed to beat this speed. The author had just read Bernard Smith's cruel (and unjust) condemnation of naval architects in his book 'The Forty-Knot Sailboat', Ref. 2, and so, inevitably the design speed was taken as 40 knots. The corresponding wind speed was 20 knots.

The craft was to be built at home without outside sponsorship and the overall size of the components was limited to about the size of a domestic garage.

### 3. BASIC CONCEPT

As soon as the sailing speed record attempts began it became clear that there were three important aspects that were limiting the speeds being achieved:

Efficiency — many boats could never achieve high speeds in a reasonable wind speed because of high drag from the hull or sails.

Strength — many boats that proved to be efficient in lighter winds, collapsed under the high loads caused by sailing at speed.

Control — boats that seemed both strong enough and efficient enough to reach very high speeds in a perfectly steady wind and flat sea, could not be controlled at speed in real conditions. The International Tornado class racing catamaran is typical here, never having been timed faster than 20 knots.

#### 3.1 Hull or Foils

The use of planing or displacement hulls was considered only briefly. Planing craft were too inefficient and were thought to have poor control in waves, and a displacement boat must be very big and expensive to give high efficiency and good seakeeping.

Surface piercing hydrofoils were being explored by Grogono and Hansford, Ref. 3, and were suffering from control problems in the relatively rough seas in which these small craft have to operate.

Since it had been shown that fully submerged hydrofoils gave the best seakeeping and control in small powered craft, it was decided to try to show these advantages in a sailing craft. The penalty of increased mechanical complexity was accepted.

#### 3.2 Crew

For a small boat the crew weight is a high proportion of the total and, for efficiency, the craft was designed as a single hander.

#### 3.3 Sail

Various different sail types were studied, Fig. 1, initially for the 10 m<sup>2</sup> sail area division. The main requirements were for efficiency in high winds (the relative wind strength is force 8 at design speed) and for low sheet loads, so that one man could handle the sail when very highly loaded, as well as controlling the boat.

There seemed no way of reducing the sheeting loads for a conventional soft sail, Fig. 1a and b, and there were also doubts concerning the control of sail shape in very high winds, particularly at lower lift coefficients. A substantial wing mast with a smaller sail, Fig. 1c, seemed to give some improvement but again the problems of cutting sails for unusually high winds seemed very great, especially as this rig

\*Constructor, Ship Department, Ministry of Defence

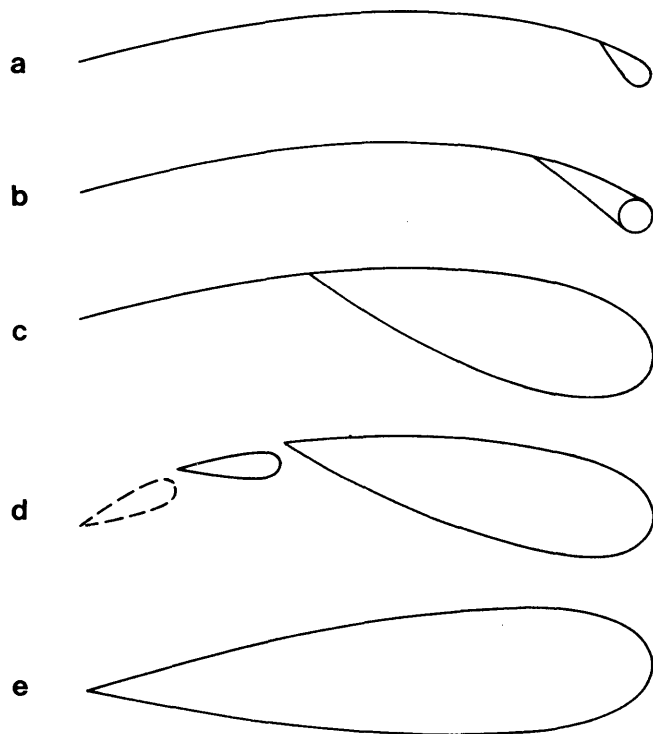


Fig. 1. Possible Sail Types

is known to be very sensitive to a kink near the mast arising from a poor sail shape.

In view of the mechanical complexity of the rest of the boat, it seemed foolhardy to build a very complex solid wingsail, Fig. 1d, such as those used by the C class catamarans MISS NYLEX or the PATIENT LADY series. It was finally decided to use a rigid symmetrical wing sail, and to overcome the problem of the low maximum lift coefficient that can be achieved with this unusual arrangement by increasing the sail area by 30%. It was thought that with this arrangement substantial reductions in mainsheet loads could be achieved by suitable positioning of the shrouds. It was also felt that this very simple sail would perform efficiently and predictably in the strongest winds.

### 3.4 Arrangement of Buoyancy and Controls

Although some improvement in performance could be expected from adopting a 'one way' craft, such as CROSSBOW I, which could only sail on the starboard tack, it was felt that the benefits would be more than offset by the constant need for a tender to get back to the other side of the harbour, and by the much reduced practice time that would result.

It soon became clear that the controls for foils, rudder and sail were too complex to allow the helmsman to move about the boat as ballast. These considerations led to a trimaran arrangement, with the helmsman sitting in the centre hull. The controls were arranged as in an aircraft, with a central control column for the foils and foot pedals for steering. The sail controls are also brought to the cockpit and there is a speedometer driven by a pitot tube in the nose of the rudder.

Side floats are not needed above about 5 knots, as the foils will supply ample righting moment, so only small floats are needed merely to give adequate stability when stopped.

### 3.5 Principal Dimensions

There were no type-ship data for a craft such as the one just described, so analytical methods were used to find how

performance varied with changes to the principal dimensions. A computer program was written to model the foil-borne performance of the craft.

The program fixes the true wind speed and direction and then varies the boat speed at one knot intervals. For each case:

- (i) The sail lift and drag are calculated and converted into thrust and sideforce.
- (ii) The forces on each of the three lifting foils and sideforce on the struts are calculated, together with the bending moment in the crossbeam.
- (iii) The drag of foils, struts and surface sensors and the windage of the hull, rigging, and crew are calculated.
- (iv) The total drag is compared with the sail thrust to see if the craft is still accelerating.

The lift and drag of the sail and lifting foils were estimated using the section data and methods of Ref. 4. The drag of the struts, wavemaking and flapping drag of lifting foils, the drag of the planing surface sensors, and windage were found using Ref. 5.

This computer program was also used to investigate the effect on performance of the foil configuration—airplane or canard. The canard was marginally faster than the airplane configuration but had several disadvantages:

- (a) all three foils would have to be controlled rather than just two for the airplane configuration;
- (b) the hullborne handling seemed far less predictable. The airplane configuration results in an ideal arrangement of lateral area, with twin 'centreplates' under the centre of pressure of the sail and a large rudder aft;
- (c) the arrangement seemed far less suitable for a fixed helmsman's position. Unless the helmsman was placed in front of the sail it seemed difficult to get sufficient buoyancy right aft.

The breakdown of drag for the original design study is shown in Fig. 2, the points on the curves showing increments in sail lift coefficient. The induced drag of the lifting foils varies with the load supported so that total drag at a given speed varies with the true wind speed and direction.

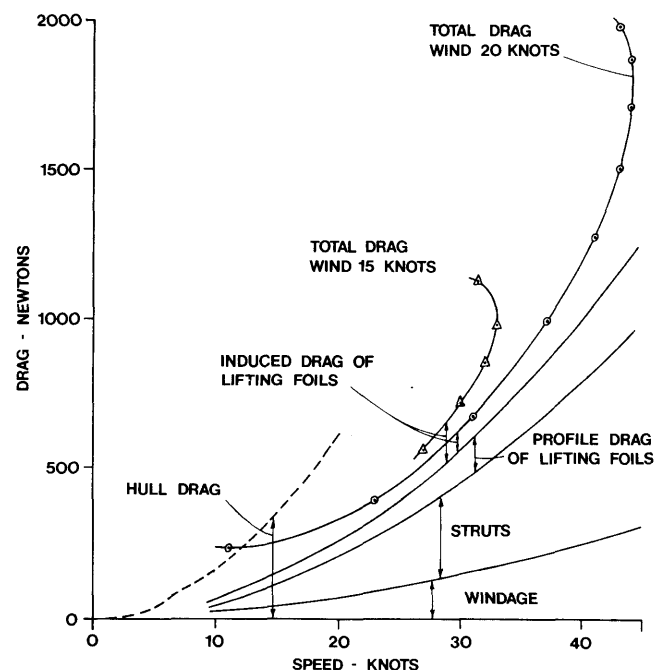


Fig. 2. Components of Drag in Beam Winds

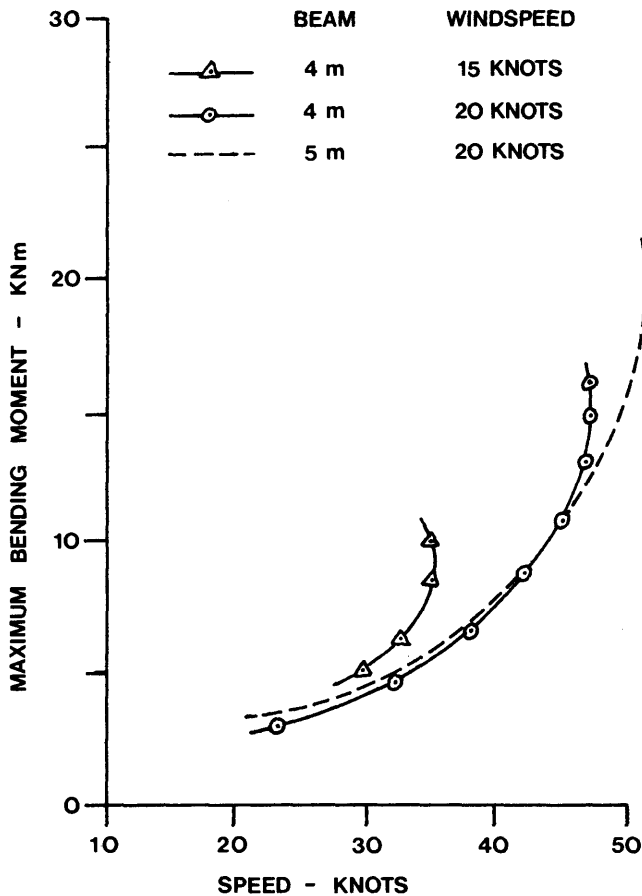


Fig. 3. Structural Loading of Crossbeam

At speeds above about 25 knots both the windward foil and the tail foil are pulling down, rather than lifting. This suggests the danger of a very rapid and probably unavoidable capsize if one of these foils should broach the surface. If this risk is accepted, however, the speeds obtainable are much increased, as the righting moment available is no longer fixed by the craft weight and beam, but eventually increases as the square of the boat speed. This also leads to the result that top speed increases in proportion to wind speed (slightly better because of the reducing proportion of drag attributable to craft weight), assuming that strength and control are sufficient.

The parameters which most affected top speed were the size of the foils, the beam of the craft and the height of the sail. Unexpectedly, craft weight is of secondary importance. The selection of foil size is discussed in the next section, but, for a given set of foils, the craft beam and sail height directly control the induced drag of the craft, both air and water. The induced drag of the foils is proportional to the sum of the squares of the foil loads, which reduces as the beam increases, and the induced drag of the sail reduces as its aspect ratio increases. This correctly suggests a spidery craft with enormous beam and sail height for high fluid dynamic efficiency. There is, however, a price to pay in structural terms, as the bending moments in the mast and crossbeam will increase at attainable boat speeds, Fig. 3.

The design that has resulted is shown in Figs. 4 and 5 and Table I. This design was capable of well over 40 knots in 20 knots of wind, by the theory in use in about 1974, but, when the boat flew well enough to test the theory the boat was slower! With some difficulty the theory has been adjusted to agree and the top speed in 20 knots of wind is now estimated to be about 35 knots.

#### 4. DETAILED DESIGN

##### 4.1 Foil Control System

Deeply submerged foils have no built-in height keeping stability, as have surface piercing foil systems. It seems most unlikely that direct manual control of the foil angles

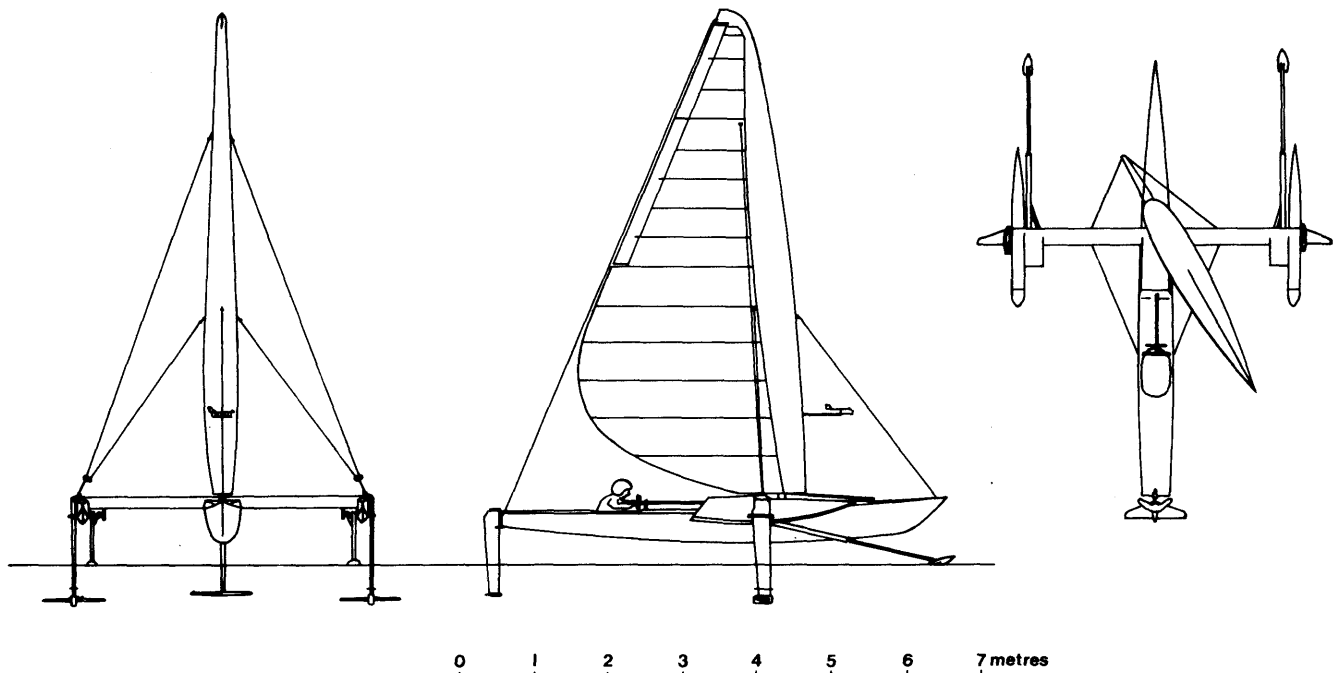


Fig. 4. General Arrangement of FORCE 8



Fig. 5. FORCE 8 at speed

could achieve the necessary 'flight envelope' of  $\pm 30$  cm in height, at speed and in realistic wind and sea conditions. To achieve stable flight some feedback from the water surface is required.

The system that was chosen is the Hook Hydrofin system, invented by the late Christopher Hook and used successfully in various powered craft, Ref. 6, and less successfully in the sailing craft MISS BOSHAM.

TABLE I. Principal Dimensions and Weight Breakdown

Length overall	6.14 m
Length between foils	3.66 m
Beam overall	4.80 m
Waterline beam foilborne	4.05 m
Draught hullborne	0.96 m
Draught foilborne	0.5 m
Sail projected area	13.0 m <sup>2</sup>
Mast height	6.50 m
Forward foil area (each)	0.108 m <sup>2</sup>
Aft foil area	0.12 m <sup>2</sup>
Strut area foilborne (each)	0.10 m <sup>2</sup>
Rudder area foilborne	0.07 m <sup>2</sup>
All up weight (including crew)	220 kg
Hull and floats	42 kg
Foils, struts and rudder	27 kg
Crossbeam	35 kg
Wingsail and rigging	38 kg

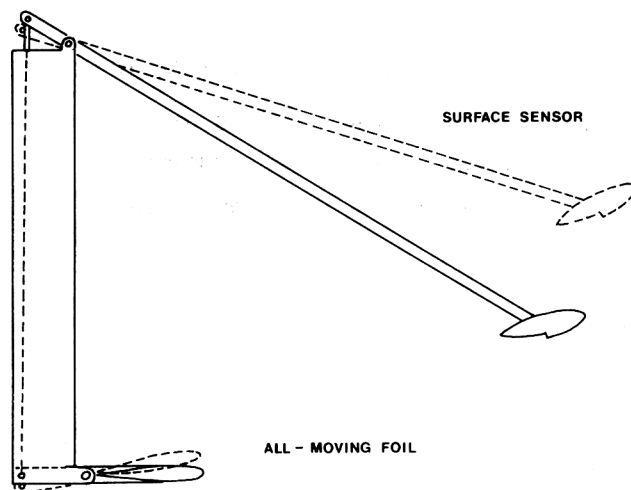


Fig. 6. Hook Hydrofin System

The Hydrofin system uses mechanical feedback from a planing surface sensor to control the angle of attack of the main lifting foils. The basic stabilising operation of the system is shown in Fig. 6.

The details of Hook's control arrangement are not suitable for a foil that must pull down as well as lift, and the final control arrangement for FORCE 8 is shown in Fig. 7. This system is fitted to both port and starboard main foils and provides stabilisation both in height and in roll. Added to the feedback from the surface sensor is an input from the helmsman's control column. This is used to adjust the steady flying height and roll angle of the craft, and to prevent the foils stalling due to high angle of attack when the craft is hullborne:

- (i) Below takeoff speed the two foils can be angled in opposition to generate a large righting moment to keep the craft level, but with little net foil lift. In this condition, with neither of the side floats in the water, the craft is a foil stabilised monohull, and this is the normal hullborne state at speeds above four to five knots.
- (ii) Takeoff is also controlled by the helmsman, and in marginal winds the inertia of the boat can be used to assist: if the boat can be driven above takeoff speed while still hullborne, the foils are rapidly put to rise. In this way takeoff may be achieved where a more gradual technique would fail due to the combined drag of hull and foils.
- (iii) There is also a requirement for the helmsman to assist in height keeping in certain situations as explained below.

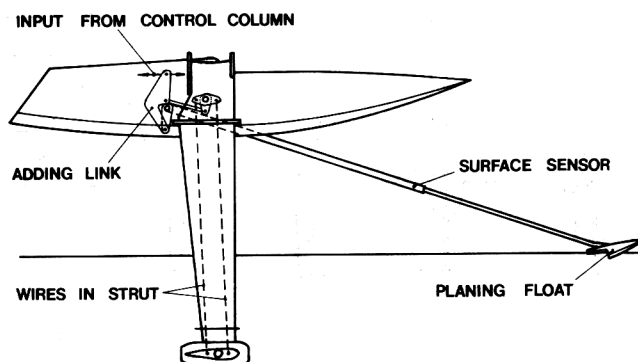


Fig. 7. FORCE 8 Foil Control System

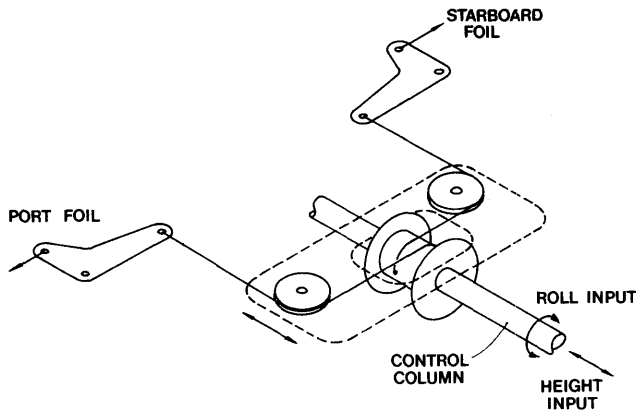


Fig. 8. Central Control Box

The helmsman's controls for the foils are similar to an aircraft control column, with a wheel that rotates to give roll input and slides fore and aft to change the flying height. The controls are unusual as they act as positional rather than rate controls, because of the feedback from the surface sensors. The central control box which converts movements of the wheel into cable inputs to the foils is shown in Fig. 8. For simplicity only half the cables (pulling the foils to rise) are shown.

#### 4.1.1 Analysis of Control System

Little information was available in the literature to suggest whether a particular geometry of foils and feedback linkage would be stable and controllable, and it was decided to use linearised equations of motion summarised in Appendix I to analyse the motion of the craft.

The results for the rolling equations showed that the transient behaviour was ideal, stable and non oscillatory.

The results for the height keeping equations, however, showed that while the transient motion was stable, it was oscillatory and had a low damping ratio. An example of the root locus plots produced at an early stage for a surface sensor of length 2 m, is shown in Fig. 9. Practical values of the system gain  $K_2$  are less than about 1.0. Examination of the frequency response to a wave input showed that at high frequencies the magnification ratio was very low, but that close to the natural frequency of about 10 secs, the height excursions could be double the wave height. This prompted a brief search for criteria of 'man controllability'—would this equation be more or less difficult to drive than a bicycle? There was at that time no suitable answer available, although the importance of the way the input and output are presented to the helmsman was stressed.

#### 4.1.2 The Control System at Sea

Experience has shown that the roll control of FORCE 8 is very good, as predicted theoretically. Height keeping is certainly stable as predicted, and some flights have shown perfect height control with the control column fixed, but continuing problems with the mechanics of the foil control system have made it very difficult to judge if the predicted low frequency oscillations are present.

### 4.2 Foil and Strut Hydrodynamics

The overall configuration of the lifting foils and struts is shown in Fig. 10, with the distances between the foils compressed for clarity. Early in the design the horizontal foil on the rudder was to be adjustable by the helmsman to regulate fore and aft trim, similar in effect to an aircraft trim tab. Later calculations showed that pitch variations are very small at speeds above about 15 knots, even between maximum lift on the sail, where the boat is accelerating, and

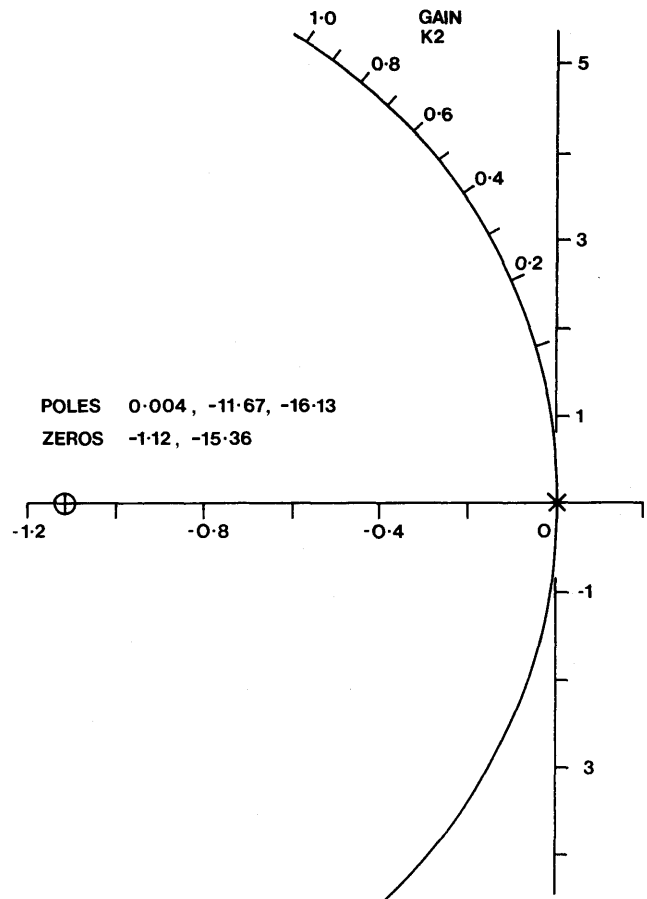


Fig. 9. Detail of Root-Locus Plot for Height-Keeping

no sail lift. The stern foil is now fixed with an angle of attack of  $-2^\circ$ .

The use of auxiliary foils to assist takeoff and thereby reduce the size of the mainfoils was considered, but they would have to be mounted so close to the running waterline that spray drag in waves could be considerable. The use of dihedral or possibly anhedral on the mainfoils was also investigated. Dihedral reduces the side load on the struts and therefore a thinner strut might be used. A small amount of anhedral

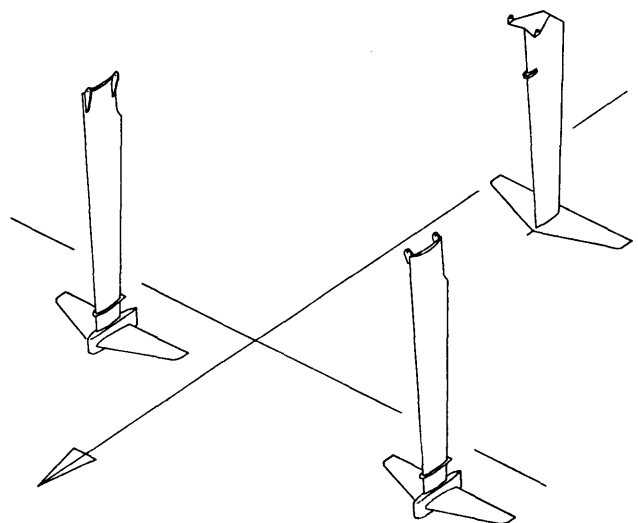


Fig. 10. Arrangement of Foils

reduces the strut length for a given foil tip submergence and is used on powered hydrofoils, e.g. TUCUMCARI for this reason. Eventually, vertical struts and horizontal foils were picked.

One good feature of the layout is the lack of any interference between forward and after foils. The wake, and particularly the trailing vortices, shed by the forward foils are well clear of the tail. This must help to produce a boat with predictable handling characteristics.

#### 4.2.1 Main Foil Design

The design of the lifting foils was critical to the success of the craft (and indeed poor foils led to several years of unsatisfactory performance). In the latest design, these foils absorb about a third of the power generated by the sail and so efficient hydrodynamic design is essential. The foils are very highly loaded at speed—the leeward foil produces about 0.4 tonne of lift at 40 knots. The foils are also an essential link in the control system and must respond continuously when under load.

- (i) **Section Shape:** The section shape chosen for the foil has a major influence on the control torque required and on the hydrodynamic efficiency, including the effects of cavitation. A cambered section has a non zero moment coefficient (or in other words the centre of lift varies with angle of attack). The amount of camber needed to give a small improvement in efficiency and improve cavitation performance produces a very large increase in the theoretical control torque required. For this reason only symmetrical sections have been used, and this also simplifies production, as separate moulds are not required for the two blades of each foil.

The first set of foils were designed for 40 knots, where cavitation is an important consideration, and the shape chosen was the elliptic/parabolic propeller blade section shown in Fig. 11. This was also expected to have a low drag due to extensive laminar flow. The second foils had a compromise section between cavitation and efficiency—NACA 0012-64. By the third set of

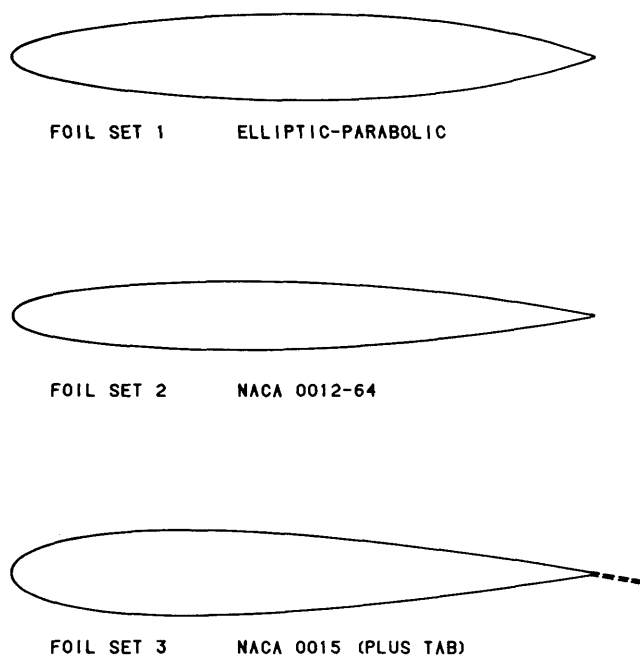


Fig. 11. Section Shapes of Lifting Foils

foils an improved criterion for efficiency had been arrived at:

$$\text{Efficiency Criterion} = \frac{C_{L_{\max}}(\text{Takeoff})}{C_{D_{\min}}(\text{Top Speed})} \quad (1)$$

The numerator is explained as the foil area is fixed by the requirement for takeoff at about 8 knots so that foil area is inversely proportional to the maximum lift coefficient at this Reynolds Number. At this stage 20 knots was more of a barrier than 40 knots and cavitation was not a consideration in choosing the section shape. The best section shapes by this criterion are the traditional low speed aerofoils and NACA 0015 was picked.

- (ii) **Planform:** The major parameters of the planform are area, aspect ratio, taper and the sweep angle. It was suggested by Hook that a high sweep angle helps to shed ventilation from the foil tips, although this was not confirmed in model tests carried out in a circulating water channel—Ref. 8. There is some evidence, Ref. 9, that positive sweep increases the maximum lift coefficient for a wing, and the sweep of the leading edge certainly helps to shed weed. For elliptic spanwise loading and minimum induced drag, Ref. 7 shows that increased sweep angle leads to reduced taper ratio (tip chord/root chord) and this also leads to thick root sections to enclose the stock.

For the reasons above a taper ratio of  $1/3$  and sweep to make the trailing edge normal to the flow were chosen. The choice of foil area and aspect ratio was tackled with the aid of a design chart, Fig. 12. The curves of constant foil area give an indication of takeoff speed. The curves of constant stress show the outer fibre stress in the leeward foil at 40 knots for a solid stock with diameter 90% of the root thickness. The curves of drag show the total drag for both main foils at 40 knots, allowing for the different lift on the foils and using the simple prediction method of Ref. 4.

The three sets of foils that have been used are marked on the design chart. Set 1 had a planform area of only  $0.06 \text{ m}^2$  (due to an error in calculating the area needed for takeoff). Set 2 had double the area with about 30% drag penalty, and, with this set, takeoff and brief stable flight were achieved. This set also showed the instability discussed below and a third set of foils was designed with slightly smaller area, to take advantage of the improved  $CL_{\max}$  of NACA 0015 at takeoff, and to give less drag at top speed.

- (iii) **Centre of Pressure:** With the second set of foils, the craft suffered from a foil jamming problem where, after a period of stable flight, the highly loaded leeward foil

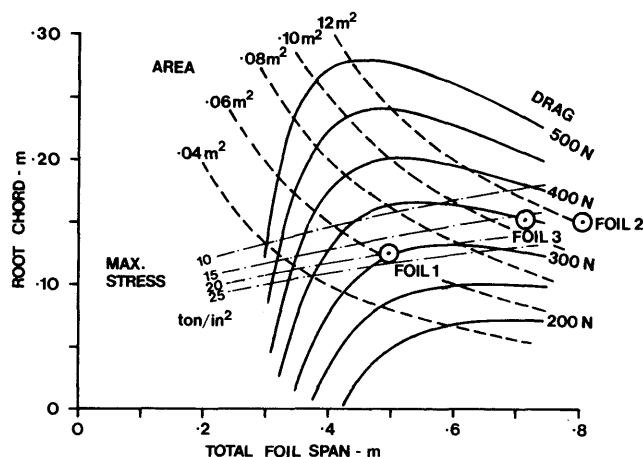


Fig. 12. Design Chart for Forward Foils

would jam at a high angle of attack, so that the foils would fly to the surface and ventilate. The foil would then lose most of its lift and the craft would 'crash' into the water. The problem was at least partly due to the complex foil control system providing too little torque, but there was also evidence during the experiments reported in Ref. 8 that the foils were hydrodynamically unstable, with the centre of pressure forward of the stock axis. Extensive calculations were carried out using the methods of Refs. 4, 10 and 11 but the reason for such a severe instability could not be found. There was some evidence in Ref. 10 that low aspect ratio foils with section shapes similar to NACA 0012-64 had the aerodynamic centre unusually far forward. This was another reason for choosing the heavily researched NACA 0015 section for the latest foils. The 'crashing' behaviour was reduced with the final set of foils, but not cured. A complete cure was achieved by increasing the torque supplied to the foil stocks by a factor of three. The small trim tabs were also added to the foils to be used as a last resort to provide added bow down moment at high speed, but these have proved unnecessary. The final foil design is described in Fig. 13 and Table II.

#### 4.2.2 Tail Foil

The tail foil must stabilise the craft in pitch but the size of this foil also governs the pitching caused by the pitchpole movement of the sail. The pitch stability of the craft with all foils fixed was checked by calculating the Margin of Stability:

$$G_v = 1 - \frac{(M' + Z'_q)M'_q}{Z'_w M'_q} \quad (2)$$

A value of 1.01 for the original foil system (tail foil identical to lifting foils) was quite satisfactory. The second requirement is most important as the craft is vulnerable to pitchpoling, particularly at takeoff in strong winds, when a gust with the wind aft can produce a large pitchpole moment and the pitch stiffness of the craft is least. At takeoff speed in a 20 knot wind with the first tail foil, the bow down pitch angle caused by sail thrust is about 12°. This was discovered in the first sail and as a result the boat was modified by moving the helmsman 1.4 m aft and doubling the size of the tail foil, using the moulds for set 2 lifting foils.

This tail foil (set 2) has been retained in the present design, and, as high angles of attack are not anticipated, the NACA 0012-64 laminar flow section is suitable.

#### 4.2.3 Struts and Pods

The struts support the foils, but also generate the sideforce to resist leeway, and since they must run at an angle of attack, ventilation was expected to be a serious problem. The size of the struts is governed, at the bottom, by the space needed for the control wires, and at the top by strength requirements, Fig. 7. The length of the struts was chosen to give 0.46 m (1.5 ft) immersion of the foil axis and 0.30 m hull clearance at the design flying waterline. The rudder is slightly shorter than the main struts but otherwise identical.

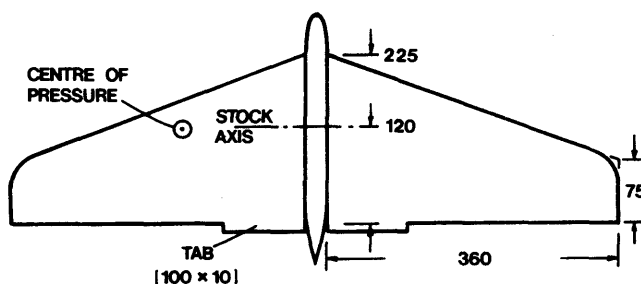


Fig. 13. Final Design of Main Lifting Foils Dimensions in mm

TABLE II. Properties of Main Lifting Foils (Without Tabs)

Section shape	NACA 0015
Planform area	0.108 m <sup>2</sup>
Aspect ratio, effective	4.80
Taper ratio	0.333
Sweep of quarter chord line	17.35°
Tip shape	sharp
$\left(\frac{\partial C_L}{\partial \alpha}\right)_{\alpha=0}^*$	0.066
(crossflow drag assumed 0.5)	
Centre of pressure from root*	153 mm
Centre of pressure from trailing edge* at $\alpha = 4^\circ$	118 mm

Data marked \* calculated using Ref. 10

The struts are of bi-ogive section for simplicity of manufacture from rolled plates, with the thickness to chord ratio varying from 15% at the bottom of the float to 10% at the pod. The radii at the leading and trailing edges are very low to reduce spray generation and drag (leading edge radius 0.5 mm, trailing edge less). The struts appear to be extremely resistant to ventilation at speeds up to 22 knots, and anti-ventilation fences have been progressively removed. One full chord fence remains about 100 mm above the pod, as shown in Fig. 10, but the sharp upper edges of the pod also act as a barrier to ventilation. The rudder has neither fences nor pod and occasionally ventilation is felt as a sudden kick on the rudder pedal at speeds above 20 knots; one or two fences should be added.

#### 4.3 Hull Design

##### 4.3.1 Main Hull

The main hull supports the weight of the craft up to the takeoff speed of 8-10 knots. The hull has to be long enough to provide a suitable foil base and spread of rigging for the mast, and large enough to allow the helmsman to sit inside to reduce windage. A high longitudinal waterplane inertia is also desirable to reduce pitch changes under sail. A waterline length of 5.5 m was chosen and the size of the helmsman's bottom dictated a minimum waterline beam amidships of about 0.4 m. At takeoff the boat is right on the 'main hump' of the resistance curve with a  $V/\sqrt{L}$  of about 2, and the hull design is similar to a slender destroyer type (length to waterline beam ratio is nearly 14) with rounded sections for ease of construction in foam sandwich. The body plan is shown in Fig. 14.

The hull is also a major strength member, resisting vertical bending due to the mast and rigging loads plus the weight of the crew, and considerable torsion from the rudder.

The long crossbeam can also introduce considerable racking forces into the hull, particularly if there should be a collision with one float. The hull depth has been kept high, particularly forward, to improve the strength properties. Three watertight bulkheads are built in, one directly under the mast and one each forward and aft of the cockpit to improve rigidity and provide three watertight compartments. This hull design has proved to be quite satisfactory and the only change that would be made is to add more flare above the waterline forward to reduce bow down pitching in strong winds.

##### 4.3.2 Side Floats

The floats are needed to give stability when the craft is stopped and at low speed when the foil lift is small. They were designed to have a total buoyancy of about 65 kg, enough

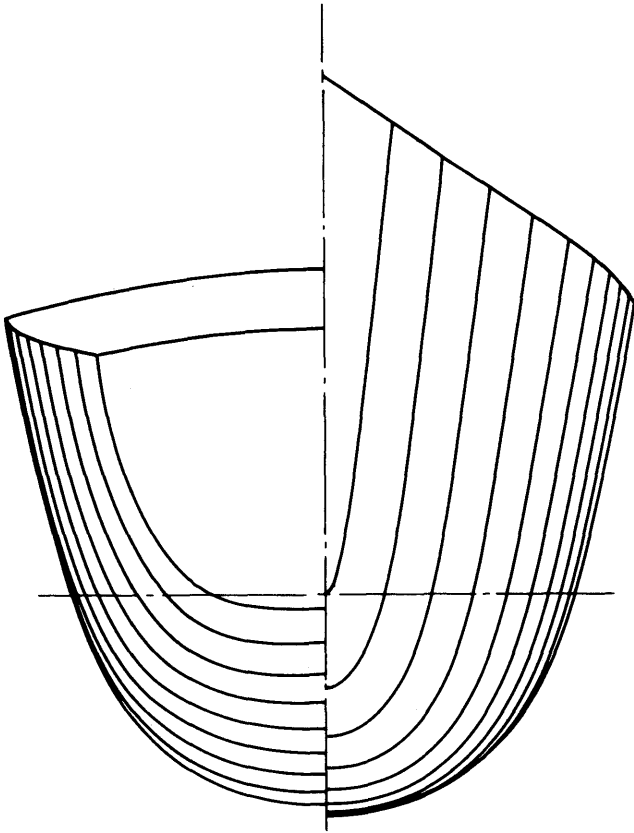


Fig. 14. Body Plan of Main Hull

for the crew to sit on the cross beam to raise or lower a foil. In practice this has not proved possible, as the wingsail takes charge as soon as the crew leaves the cockpit. The bottoms of the floats are raised about 50 mm above the design waterline, and the floats are designed to reduce impact loads when a wave top is hit at high speed, with a deeply veed bottom and long, narrow and sharply pointed shape, Fig. 4. These tiny floats have proved quite sufficient for low speed manoeuvring once control of the wingsail was mastered, but the shape is probably finer than necessary as wave impacts on the crossbeam have been quite severe, and larger floats would 'hide' more of the crossbeam. Each float is divided into two watertight compartments but the larger aft compartment, which contains the foil linkage, tends to leak through the various control openings.

#### 4.4 Wingsail Design

As discussed earlier, the basic concept of the sail was a rigid, symmetrical wingsail of about 13 m<sup>2</sup> area, which would generate moderate lift coefficients efficiently and reliably in relative winds up to 45 knots. Low mainsheet loads were to be achieved by positioning the shroud attachments just forward of the quarter chord point of the wing.

##### 4.4.1 Rigging

For simplicity the rigging was first just two shrouds plus a forestay. A simple three dimensional model showed that if the shrouds were tight enough to prevent the mast falling forward, they must be too tight for adequate sail rotation. This was because of the thickness of the wing where the shrouds were attached (about 0.3 m). Matters could be improved a little by moving the mast step forward, or the lower end of the shrouds aft, but the first affected the sailing balance of the boat and the second took the shrouds from the aluminium crossbeam and attached them to the flimsy foam sandwich floats.

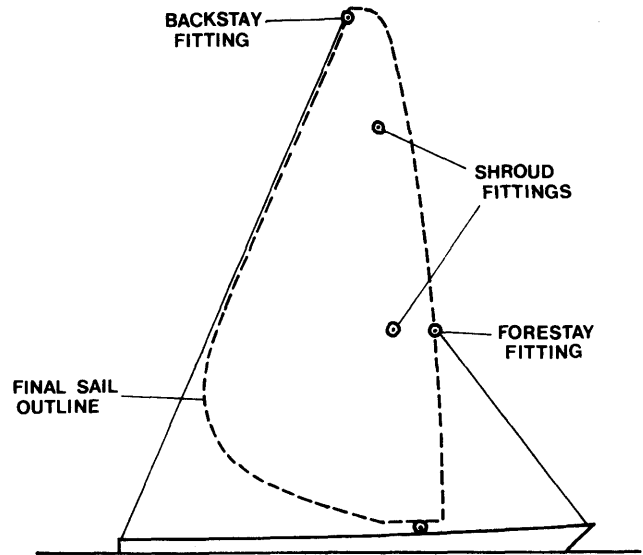


Fig. 15. The Effect of Rigging on the Sail Planform

It proved impossible to find a satisfactory compromise in this way and a backstay was reluctantly added. The geometry of the main structural members, the hull and crossbeam, is ideally suited to this arrangement of rigging, but the effect on the sail was fundamental and bad. For the sail to rotate, all of the rigging attachment points had to be kept reasonably in line, and this led to a pronounced taper on the sail, Fig. 15, (a second pair of shrouds was added later to reduce the bending moment on the sail).

##### 4.4.2 Analytical Sail Design

There was very little past practice on which to base the design of such an unusual sail, but a rigid wing is amenable to simple aerodynamic analysis, particularly if the lift coefficient is not too high. Milgram, Ref. 12, presents a lifting line analysis for yacht sails, allowing for the gap between the bottom of the sail and the sea and for the variation of wind velocity with height.

When combined with the forward speed of the craft, this variation causes a twist in the relative wind direction and makes the sail analysis very similar to propeller analysis. Using a power law to represent a typical velocity distribution in the boundary layer:

$$\frac{V}{V_{5m}} = \left(\frac{h}{5m}\right)^{0.1} \quad (3)$$

the wind twist is shown in Fig. 16.

The condition for minimum induced drag for the lifting line is shown in Ref. 12 to be a constant induced angle over the span. Milgram defines the circulation distribution over the span of the sail as the Fourier series:

$$\Gamma = K \sum_{n=1}^{\infty} A_n \cdot \sin n\psi \quad (4)$$

where  $\cos \psi = -2y/b$

and provides tables of the 'ideal'  $A_n$  for a range of wind shear and gap beneath the sail. Using these data the 'ideal' chord distributions were calculated for two critical conditions in a 20 knot beam wind: takeoff at 12 knots, hullborne, and flying at 20 knots (Fig. 17). It can be seen that the 'ideal' sails are too broad near the top to allow for the backstay.

The circulation distribution was then modified to give a narrower top to the sail and a suitable chord distribution, Fig. 17, was found to have only 1/4% penalty in increased in-



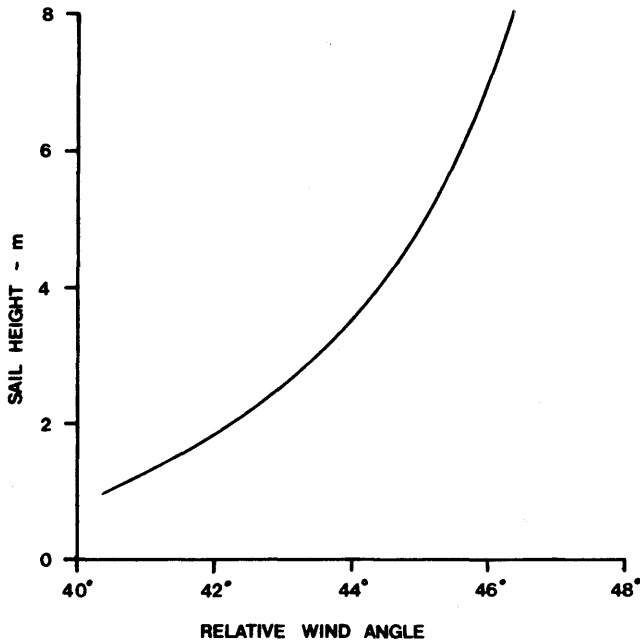


Fig. 16. Typical Twist in Relative Wind at 20 knots in 20 knot wind

duced drag over the 'ideal' shape. The effect on the maximum lift coefficient before stall was far more severe.

#### 4.4.3 Section Shape and Stall

Provided that the sail is not stalled, most of its drag is induced drag (in the sail described above at a lift coefficient of only 0.8, section drag was estimated to be less than a quarter of the total). The critical property of the section shape is therefore the maximum useable lift coefficient. The  $R_n$  of the sail sections at 12 knots is about  $0.6 \times 10^6$  near the head and  $2.2 \times 10^6$  at maximum chord. At these low  $R_n$  the traditional NACA 4 digit sections seem to have the highest lift coefficients. The structural arrangement of the wingmast requires a full section near the nose and the NACA 0015 was chosen. Ref. 13 suggests that at  $R_n 0.6 \times 10^6$  the maximum lift coefficient of this section is 1.03 at a section angle of attack of about  $10^\circ$ .

#### 4.4.4 The Effect of Sail Taper

Any departure from the 'ideal' chord distribution means that the induced angle will vary along the span of the sail. In this case the narrow top causes a local increase in the angle of attack which is added to the twist in the relative wind. Thus the top sections always see a much higher angle of attack than the large area of the sail lower down, Fig. 18, and the maximum lift coefficient of the sail before the top stalls out is only about 0.8.

Considering the multitude of highly tapered fabric sails in everyday use, this result underlines the great importance of sail twist and shows that the twist in the relative wind may not be the major reason.

For a symmetrical, untwisted wingsail the tapered planform is thus a serious disadvantage, increasing the tendency for the top to stall prematurely. To reduce this effect it was decided to add high lift devices to the top of the sail. By adding a flap to the upper part of the sail not only would more lift be developed, but, because the circulation would be increased relative to the rest of the sail, the downwash would also increase locally. An untapered flap tends to improve the circulation distribution shape and the final arrangement of the sail is shown in Fig. 19. The unusual curved outline comes straight from the chord distribution of Fig. 17. The tip shape at the top of the wing is designed for efficiency, but to clear the helmsman's head the foot of

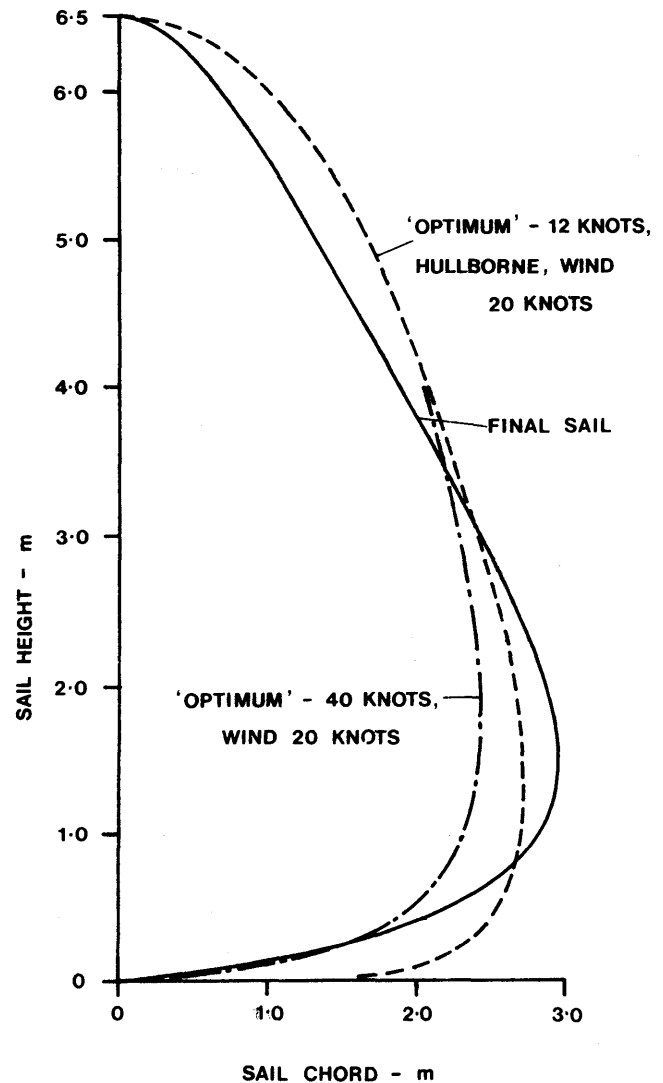


Fig. 17. Optimum Sail Chord Distribution at Two Speeds, with Final Chord Distribution

the sail is cut away at the trailing edge. This must lead to higher end losses and reduced lift but the effect is probably not too harmful as this part of the sail is not highly loaded.

#### 4.4.5 Flap Design

As in previous wingsails such as MISS NYLEX, the external aerofoil type of flap was chosen. Ref. 14 reports the aerodynamic performance of a NACA 23012 wing with a 20% flap of the same section. These data were used to design the NACA 0015 section flap and hingeing arrangement shown in Fig. 20. The stall angle of the main wing is not affected by the addition of the flap, but 1.2 m below the tip of the sail where the flap chord is 20% of the wing chord, the maximum lift coefficient is approximately doubled.

#### 4.4.6 Vortex Generators

The NACA 0015 section stalls progressively from the trailing edge. It is possible to delay stall by the use of vortex generators on the suction side of the sail, Ref. 15, and simple design rules are given in Ref. 16. A single row of triangular vanes was fitted to the top of the sail as shown in Fig. 19, but on one side of the sail only. The vanes were fitted along the quarter chord line of the sail and, based on the local chord, were 1.5% chord in height, 3% chord in length and 6% chord spacing, angled at  $15^\circ$  to the local flow. Unfortunately, no difference in performance between the two tacks was noted in practice.

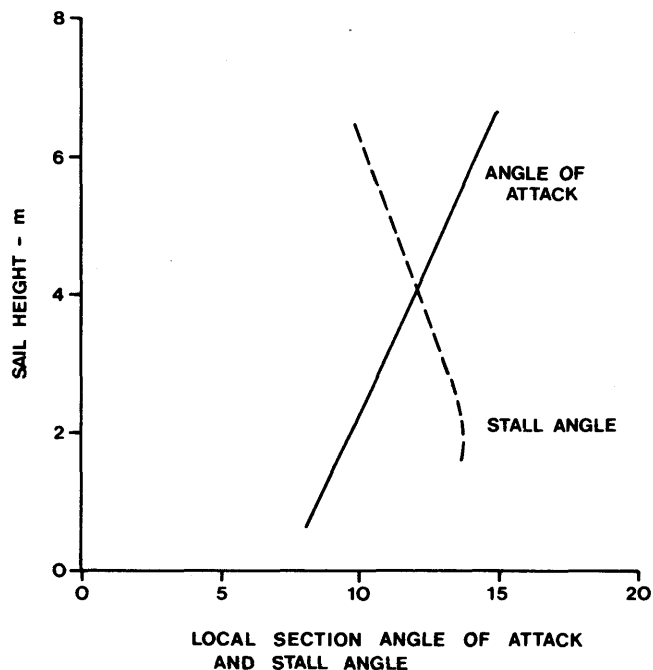


Fig. 18. Typical Local Angle of Attack and Stall Angle of Wingsail

#### 4.4.7 Control of the Wingsail

It was discovered when the boat was first sailed that the wingsail did not feather when the mainsheet was released, but stayed at a stable angle of attack like a kite. The windward shrouds, being positioned well away from the centreline because of the thickness of the wing, act as kite strings, the loads on forestay and backstay being much smaller. The flap could then be used as a tab to adjust the overall lift on

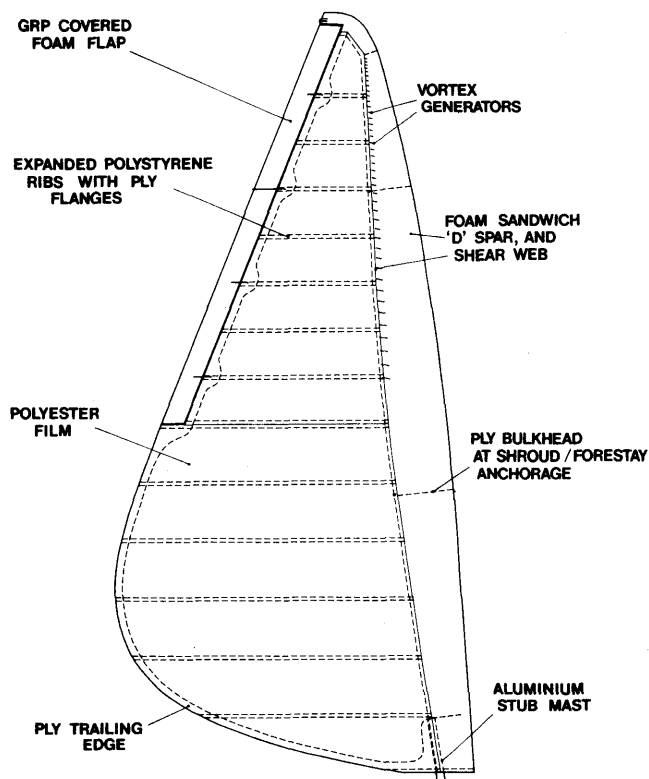


Fig. 19. Wingsail Arrangement

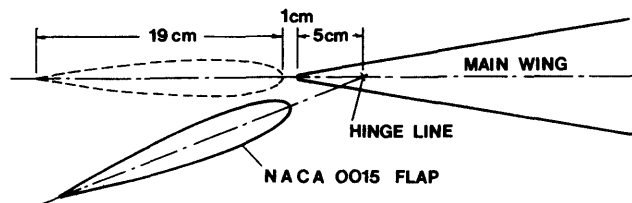


Fig. 20. Geometry of External Aerofoil Flap

the sail—Fig. 21. By luck, the range of angles of attack available in this way is reasonably satisfactory.

The arrangement of the mainsheet was then changed so that it may be used to reduce the lift on the wing to stop the boat or prevent capsize, Fig. 4. The craft will now lie beam to the wind fairly happily, with the mainsheet cleated and the sail athwartships. As the main sheet is released the boat accelerates and once 4-5 knots is reached the mainsheet is freed for the rest of the run, any minor adjustments being made with the flap.

The trailing edge of the flap is fitted with woollen tell-tales to warn of stalling and a graduated wind direction indicator is attached to the leading edge of the wingsail. A check was carried out with a more comprehensive set of tell-tales to find what angle of attack caused stall and it was shown that, at any section, both wing and flap stall simultaneously.

## 5. STRUCTURAL DESIGN AND CRAFT CONSTRUCTION

Some highly stressed parts were fabricated in aluminium, and this work was done professionally. The remainder of the craft, and most of the fittings, were built by amateurs in a small domestic garage. Because of the generally flimsy structure a great deal of attention was paid to the detailed design of highly loaded areas, and this has been rewarded by very few structural failures despite numerous capsizes, groundings, and even a few collisions.

### 5.1 Hull and Floats

The hull and floats were built in foam sandwich using 10 mm low density expanded polystyrene sheet and glass reinforced epoxy resin skins. This lightweight material, which has proved most successful and far more robust than it sounds, was suggested by Leif Wagner-Smitt who used it in his C class catamaran designs.

The foam was tacked to a lath male mould and the outer skin of glass cloth applied. 8 oz/yd<sup>2</sup> satin weave cloth was used, which produces a smooth finish and has very good draping properties, so that a single piece covered the complete hull surface. For added robustness an extra thickness of cloth was added to the middle third of the hull. Araldite 219 system was used throughout the craft. It has low viscosity for easy application, and is unaffected by moisture during cure, so that paraffin heaters can be used. The hull was then

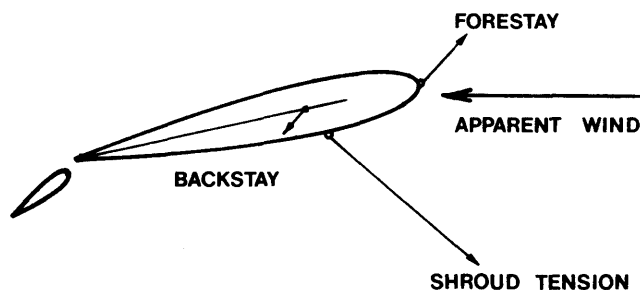


Fig. 21. Analogy of Wingsail Rig as a Kite

removed from the mould and placed in crude female jigs to retain the overall shape. Where fittings or bulkheads were to be attached the polystyrene foam was cut away and replaced with a rigid lightweight filler, before the inner skin was applied.

This filler was made by adding Fillite, tiny hollow silicate spheres, to the resin, and it was widely used also as a gap filling adhesive. The outside of the hull was smoothed using a brushing filler, but this adds considerably to the weight of the structure and all other surfaces were merely painted. The bulkheads and deck of the main hull and the components of the floats were fabricated in the same way.

## 5.2 Foils and Struts

The small original foils were made from solid GRP around a machined 25 mm diameter stainless steel stock. The GRP was laid up in the bottom half of the mould using a mixture of glass cloth where high tensile loads were expected, and chopped strand mat in areas of high shear.

The later foils were built up around the core of the original solid foils, but the method is so simple and effective that it would be used for any future foil design; a thin shell of GRP (3-4 layers of cloth) was laid up in each half of the mould. When these had cured the mould was assembled and the stock and solid core positioned. The gap was then filled with Fillite/resin mixture.

The struts and pods were fabricated from corrosion resistant EN8 aluminium. The alloy was used in the half hard condition and care was taken to keep welds away from highly stressed areas. The foil stocks run in polyacetal bearings in the pods.

## 5.3 Crossbeam

The primary loading in the crossbeam is simple bending caused by the compression in the mast resisted by foil lift at one end and shroud tension at the other. With only a single transverse member, torsional strength and stiffness is also important. After designing a complex streamlined beam in timber and foam sandwich, a large extruded aluminium yacht mast of elliptical section was chosen, for simplicity and ruggedness. The aluminium beam was also just as light and the design of connections was far simpler. Brackets to support the main foils are welded to each end of the crossbeam.

At speed this crossbeam contributes 55% of the total windage drag of the boat, and by adding a fairing the total windage drag of the boat could be halved. A suitable light but rugged fairing has yet to be found, however.

## 5.4 Sail

A cross section through the sail is shown in Fig. 22 and the structural arrangement is also shown in Fig. 19. The main strength member is the foam sandwich D spar at the leading edge, which is of similar size to the mainhull and was built in the same way. For lightness the sandwich has faces of a single layer of 8 oz cloth (thickness 0.4 mm). The resulting panels have a mass of only 1 kg/m<sup>2</sup> which is equivalent to 2 mm plywood. The panels have a stiffness equal to solid GRP about 6 mm thick.

The critical loading in the mast is transverse bending combined with compression, and even with two pairs of shrouds to reduce the bending moment, the sandwich alone was not sufficiently strong. Two 20 mm × 10 mm spruce stringers

were added to increase the cross-sectional area and inertia of the section. (Other stiffening materials such as carbon fibre, steel, or unidirectional glass were investigated, but spruce proved most suitable with the same Young's Modulus as the GRP and about the same strain to failure as the sandwich).

The methods of Ref. 17 were used to estimate the compressive failure of the sandwich. The polystyrene is a very inefficient core material, leading to a wrinkling stress of only 28 MPa (1.8 tonf/in<sup>2</sup>) but is, of course, much lighter than other suitable materials. In this design, failure would probably come by overall panel buckling in one of the curved sides of the mast.

The after part of the sail consists of ribs covered with fabric. The ribs have 25 mm thick, low density expanded polystyrene shear webs with 3 mm plywood flanges. The largest ribs have GRP stiffening tapes on the centreline to avoid shear buckling. The fabric covering is 125 micron Melinex polyester film which was glued to the mast and ribs. This film has the useful property of shrinking slightly when heated, and a domestic iron was used to remove wrinkles from the panels. The flap was cut from expanded polystyrene using a hot wire cutter and covered with a single thickness of GRP.

The wingsail is a large and rather fragile structure and difficult to handle without damage. A rigid plywood A frame has been built, which bolts to the shroud attachments and a strong point at the trailing edge. With this attached the sail can safely be lashed to a trailer or left lying on the beach.

## 6. SAILING PERFORMANCE

The craft is assembled at the waters edge with the main foils, rudder and surface sensors hinged up and supported by temporary strops. In high winds once the wingsail is in position it must be tended all the time to prevent it 'taking charge'. The boat is then carried into the sea and pulled out to a depth of about 1.5 m where the foils can safely be lowered. At least two, (preferably tall) men are needed to control the boat in addition to the helmsman who tends the wingsail. The release of the craft in shallow water is a most unseamanlike business, as at low speed there is always the danger of a gust heeling the boat suddenly and grounding the foils.

While hullborne the boat can be handled more or less like a normal dinghy, except that gybing the wingsail is not recommended! The large rudder gives excellent manoeuvrability and the unusual mainsheet arrangement gives precise control at low speeds. As speed increases so does the righting moment available from the foils, and in a wind speed of about 15 knots the boat will beat to windward at 10 knots while still hullborne. The low freeboard makes this very wet but the bow can be raised a little by the main foils.

The boat will take off most readily on a beam reach. The mainsheet is released and as the boat accelerates the roll bias from the control column must be reduced to keep the boat upright. Above about 8 knots the control column is eased back to take off, still reducing the roll bias as the boat accelerates more rapidly. The transition to foilborne flight is almost imperceptible and the overriding impression of foilborne flight, at least below 20 knots, is one of smoothness.

The boat also becomes far more manoeuvrable without the drag of the hull. Because of the high design speed the craft is very rugged, and, provided all of the foils stay in the water, there are no structural constraints to limit manoeuvring at speeds below 20 knots. From a beam reach the boat will easily turn past head-to-wind before losing way and dropping onto the hull and this is the normal method of tacking. On one occasion in 1979, FORCE 8 was tacked rapidly with an approach speed of over 20 knots and remained foilborne throughout.

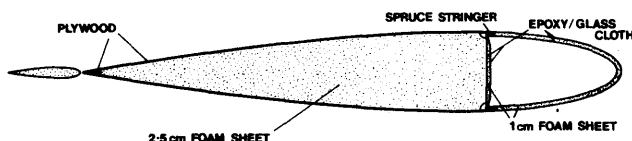


Fig. 22. Structural Section of Wingsail

The wingsail is hardly seamanlike, as the sail cannot be reefed or even dropped altogether at sea. Handling on the shore and trailing are also difficult. Once familiar with the unusual controls, however, sailing with the wingsail is a delightful experience, the rig being very close winded and very well behaved on all points of sailing. Only gybing is forbidden—the boom was not designed with this in mind.

Roll control of the boat is simple and effective at all speeds. Height keeping is more variable, and even though the problem of foil jamming has now been solved, precise height control is sometimes difficult at high speed in waves. At speeds above 20 knots spray from the surface sensors also becomes a problem, severely reducing visibility for the helmsman, and brief ventilation of the rudder has occurred from time to time. The fastest speed recorded over 500 m at the Weymouth speed trials was 17.5 knots in 1980, but the craft has sailed consistently at speeds above 20 knots off the course. The highest speed reached so far on the boat's own speedometer is about 23 knots.

FORCE 8 has been sailed on several occasions in company with MAYFLY, the surface piercing hydrofoil boat which currently holds the A Class World Speed record. The two craft, compared in Ref. 18, were found to have similar performance over a wide range of conditions. MAYFLY proved faster in calm water whereas in waves her surface piercing foils began to ventilate badly and the fully submerged foils of FORCE 8 were superior.

## 7. FUTURE DEVELOPMENTS

FORCE 8 took nearly five years to design and build, and four more years to 1980 to achieve regular and stable flights at about 50% of the design speed. In this form she was certainly capable of recording speeds above 20 knots and might in time reach the current World Record in her class of 23 knots. There are three main ways in which she can be modified for improved performance.

### 7.1 Reduced Drag

There seems little chance of major reduction in the drag of the foils or struts, but it is possible to halve the windage drag of the boat by streamlining the crossbeam. This is calculated to give an extra 2-3 knots in top speed.

### 7.2 Increased Thrust

The wingsail was not designed to be used as a freely pivoting, self-tending rig, and there is considerable doubt about its performance at high speed. The sail may simply not be 'sheeting in' sufficiently as the apparent wind comes forward with higher speeds. A new sail design is being investigated which would not have a backstay, but instead a rod forestay to support the mast—Fig. 23. The wingmast would be designed for 30 knots instead of 40 and could therefore probably have a higher aspect ratio and also be lighter. A sail section similar to MISS NYLEX seems most suitable and should result in double the lift coefficient. A computer program has been written to find if there is a suitable shroud position to make this rig self-tending.

### 7.3 Higher Winds

Higher speeds may be possible in more wind but at the moment FORCE 8 cannot be sailed safely in winds above Force 5 because of the difficulties of launching. A far more seamanlike procedure would be to launch with a crew on board and sail to open water to lower the foils. The crew would then be dropped. This would mean a trampoline between the floats and the hull for the crew to balance the boat, and probably large floats to give more buoyancy.

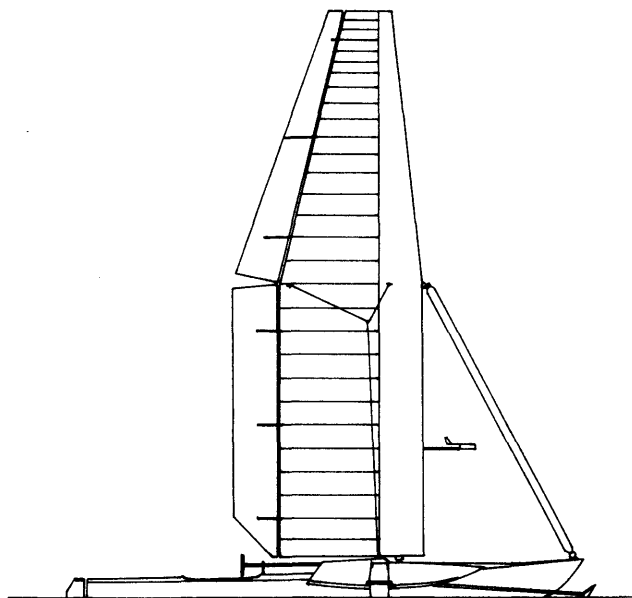


Fig. 23. MISS NYLEX Wingsail Rig

## 8. CONCLUSIONS

A unique high speed sailing machine has been developed which, while reaching so far only half its design top speed, has shown that fully submerged foils can be used effectively in a sailing craft. Comparison at sea with MAYFLY, a similar sized surface piercing hydrofoil, suggests that the expected benefit of improved control in a seaway is obtained. An unusual way of controlling a rigid wing sail has been discovered, that makes a wing with conventional rigging self-tending. With all the experience that has been gained the basic design of the craft still seems sound, and it is intended to continue to develop FORCE 8 to win the World Speed Record in her class, by achieving a speed of 30 knots.

## ACKNOWLEDGEMENTS

The author would like to thank the many friends and colleagues who have helped to design, build, sail and repair FORCE 8.

## NOMENCLATURE

A	Coefficient in expression for circulation distribution over the span of the sail
b	Span of sail
h	Height above sea surface
V	Wind speed
$V_{5m}$	Wind speed 5 m above sea surface
y	Spanwise co-ordinate of sail measured from mid span
$\Gamma$	Circulation
$\psi$	Polar spanwise co-ordinate $\cos\psi = -2y/b$

## Appendix I

D	Differential operator
H	Height above mean sea surface
l	Characteristic length
x, y, z	Co-ordinates along body area

U	Velocity of CG
w	Component of velocity along z axis
$\theta$	Pitch angle
$\delta$	Angular deflection of foils
Z	Force along z axis
M	Moment about y axis
$\xi$	Local wave elevation about mean sea surface
$\rho$	Density of water
Derivative notation	(' indicates non-dimensional value)
m, m'	mass of craft $m' = m/^{1/2}\rho l^3$
I, I'	Inertia about y axis $I' = I/^{1/2}\rho l^5$
$Z_w, Z'_w$	Force derivative with respect to component velocity $Z'_w = Z_w/^{1/2}\rho l^2 U$
$Z_{\dot{w}}, Z'_{\dot{w}}$	Force derivative with respect to component acceleration $Z'_{\dot{w}} = Z_{\dot{w}}/^{1/2}\rho l^3$
$Z_{\dot{\theta}}, Z'_{\dot{\theta}}$	Force derivative with respect to pitch velocity $Z'_{\dot{\theta}} = Z_{\dot{\theta}}/^{1/2}\rho l^3 U$
$Z_{\ddot{\theta}}, Z'_{\ddot{\theta}}$	Force derivative with respect to pitch acceleration $Z'_{\ddot{\theta}} = Z_{\ddot{\theta}}/^{1/2}\rho l^4$
$Z_{\delta}, Z'_{\delta}$	Force derivative with respect to foil angle $Z'_{\delta} = Z_{\delta}/^{1/2}\rho l^2 U^2$
$M_w, M'_w$	Moment derivative with respect to component velocity $M'_w = M_w/^{1/2}\rho l^3 U^2$
$M_{\dot{w}}, M'_{\dot{w}}$	Moment derivative with respect to component acceleration $M'_{\dot{w}} = M_{\dot{w}}/^{1/2}\rho l^4 U$
$M_{\dot{\theta}}, M'_{\dot{\theta}}$	Moment derivative with respect to pitch velocity $M'_{\dot{\theta}} = M_{\dot{\theta}}/^{1/2}\rho l^4 U$
$M_{\ddot{\theta}}, M'_{\ddot{\theta}}$	Moment derivative with respect to pitch acceleration $M'_{\ddot{\theta}} = M_{\ddot{\theta}}/^{1/2}\rho l^5$
$M_{\delta}, M'_{\delta}$	Moment derivative with respect to foil angle $M'_{\delta} = M_{\delta}/^{1/2}\rho l^3 U^2$

## REFERENCES

- World Sailing Speed Record Rules, Royal Yachting Association, 1982.
- Smith, Bernard: 'The 40-Knot Sailboat'. Grosset and Dunlop, New York, 1963.
- Alexander, A., Grogono, J. and Nigg, D.: 'Hydrofoil Sailing'. J. Kalerghi, London, 1972.
- Abbott, I. H. and von Doenhoff, A. E.: 'Theory of Wing Sections'. Dover Publications, New York, 1959.
- Hoerner, S.: 'Fluid Dynamic Drag', published by the author.
- Johnston, R. J. and O'Neill, W. C.: 'The Development of Automatic Control Systems for Hydrofoil Craft'. Proc. Int. Hovering Craft, Hydrofoil and Advanced Transit Systems Conference, Brighton, May, 1974.
- Mandel, P.: 'Some Hydrodynamic Aspects of Appendage Design'. Trans. SNAME, November, 1968.
- Coverdale, A.: 'Interaction between a Strut and Foil on a Sailing Hydrofoil Craft'. BSc Project Report, Mech Eng Dept, University College London, 1979.
- 'Principles of Naval Architecture'. Ed. Comstock, J. P., SNAME.
- Whicker, L. F. and Fehlner, L. F.: 'Free Stream Characteristics of a Family of Low Aspect Ratio Control Surfaces for Application to Ship Design'. DTMB Report No. 933, 1958.
- Molland, A. F.: 'Rudder Design Data for Small Craft'. University of Southampton Ship Science Report No. 1/78, 1978.
- Milgram, J. H.: 'The Analytical Design of Yacht Sails'. Trans. SNAME, November, 1968.
- Loften, K. and Smith, H. A.: 'Aerodynamic Characteristics of NACA Airfoils at Varying  $R_n$ '. NACA TN 1945, October, 1949.
- Platt, R. C. and Abbott, I. H.: 'Aerodynamic Characteristics of NACA 23012 and 23021 Airfoils with 20-percent-Chord External-Airfoil Flaps of NACA 23012 Section'. NACA Report No. 573, 1936.
- 'Boundary Layer and Flow Control Vol. I'. Lachmann Ed. Pergamon Press, Oxford, 1961.
- Hoerner, S.: 'Fluid Dynamic Lift', published by the author, 1976.
- Allen, H. G.: 'Analysis and Design of Structural Sandwich Panels'. Pergamon Press, Oxford, 1969.
- Pattison, D. R. and Wynne, J. B.: 'Surface Piercing versus Fully Submerged Foils for Sailing Hydrofoils'. Proc. High Speed Surface Craft Symposium, Brighton, 1980.

## APPENDIX I

### Hydrofoil Control Equations

Motions in the vertical plane of symmetry are analysed to give height control equations. Using axes fixed in the body and with the origin of axes at the craft centre of gravity:

$$(m - Z_{\dot{w}}) \cdot \dot{w} = Z_w \cdot w + (Z_{\dot{\theta}} + m) \cdot \dot{\theta} + Z_{\ddot{\theta}} \cdot \ddot{\theta} + Z_{\delta} \cdot \delta \quad (5)$$

$$(I - M_{\ddot{\theta}}) \cdot \ddot{\theta} = M_w \cdot w + M_{\dot{\theta}} \cdot \dot{\theta} + M_{\dot{w}} \cdot \dot{w} + M_{\delta} \cdot \delta + m \cdot \gamma \cdot \theta \quad (6)$$

The reference point S is on the craft X axis above the surface sensor ( $\bar{x}$  ahead of the CG). The height of S above the mean sea surface is H, Fig. 24:

For small  $\theta$ :

$$\dot{H} = U \cdot \theta - w - \bar{x} \cdot \dot{\theta} \quad (7)$$

By inspection the hydrodynamic added masses and inertias are small and may be neglected. Using non-dimensional derivatives, indicated by ' and D to denote the operator  $\partial/\partial t$ , these equations reduce to:

$$(m' \cdot D - Z'_w) \cdot w' = (Z'_{\dot{\theta}} + m') \cdot D \cdot \theta + Z'_{\delta} \cdot \delta \quad (8)$$

$$(I' \cdot D^2 - M'_{\ddot{\theta}} \cdot D - m' \cdot \gamma) \cdot \theta = M'_w \cdot w' + M'_{\delta} \cdot \delta' \quad (9)$$

$$w' = (1 + K \cdot D) - D \cdot H' \quad (10)$$

where  $K = \bar{x}/L$ .

Eliminating  $\theta$  and  $w$ ;

$$H' = f(D)\delta = \frac{A + B \cdot D + C \cdot D^2}{D(E + F \cdot D + G \cdot D^2 + L \cdot D^3)} \quad (11)$$

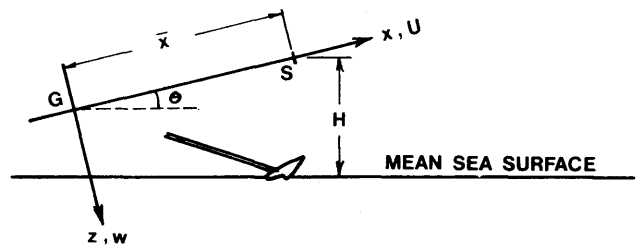


Fig. 24

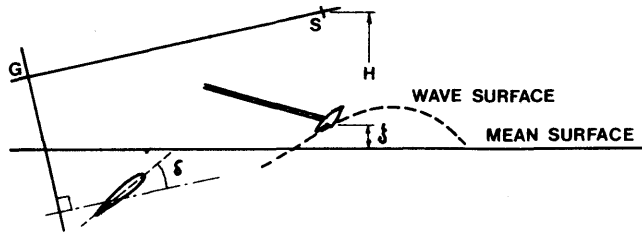


Fig. 25

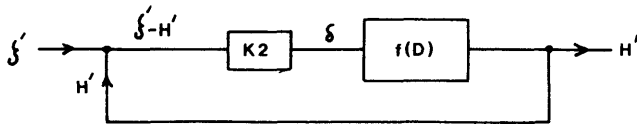


Fig. 26. Control Feedback Loop

where:

$$\begin{aligned} A &= M'_W \cdot Z'_\delta - Z'_\delta - Z'_W \cdot M'_\delta + m' \cdot \gamma \cdot Z'_\delta \\ B &= M'_\theta \cdot Z'_\delta - Z'_\theta \cdot M'_\delta + K \cdot M'_W \cdot Z'_\delta - K \cdot Z'_W \cdot M'_\delta \\ C &= K \cdot m' \cdot M'_\delta - I' \cdot Z'_\delta \\ E &= m' \cdot \gamma \cdot Z'_W \\ F &= M'_\theta \cdot Z'_W - Z'_\theta \cdot M'_W - m'^2 \cdot \gamma - M'_W \cdot m' \\ G &= -m' \cdot M'_\theta - I' \cdot Z'_W \\ L &= I' \cdot m' \end{aligned}$$

The relationship between the foil angle  $\delta$  and the wave height  $\xi$  at the surface sensor, Fig. 25, is given by:

$$\delta = K_2 \cdot (H - \xi) \quad (12)$$

Combining equations (11) and (12):

$$\begin{aligned} H' &= f(D) \cdot K_2 \cdot (\xi' - H') \\ &= \frac{K_2 \cdot f(D)}{1 + K_2 \cdot f(D)} \cdot \xi' \\ &= \frac{K_2 \cdot (A + B \cdot D + C \cdot D^2)}{K_2 \cdot A \cdot \xi (K_2 \cdot B + E) \cdot D + (K_2 \cdot C + F) \cdot D^2 + G \cdot D^3 + L \cdot D^4} \end{aligned}$$

## DISCUSSION

**Mr D. K. Brown, M.Eng., R.C.N.C. (Fellow):** This is rather an older project than the author led us to believe, because when he was a student at the Royal Naval College in 1967/68 he was working on sailing hydrofoils. I think in fact Mrs Pattison deserves some credit for the success of the project, and I should like to congratulate both of them on the work.

What I wonder is whether we can perhaps pick up some of the points that came up in connection with HMS SPEEDY this morning in which we commented that the boat was capable of higher speeds under manual control rather than under automatic control. Supposing the rules did permit, would the author see an automatic control system for this boat being of great value?

**Cdr G. C. Chapman, M.A., R.N.:** If the main foil assemblies were to be angled outwards as much as  $35^\circ$  but retaining the inverted T configuration, then the foils will develop vertical lift and horizontal leeway resistance, the struts will experience much less bending moment with reduced risk of ventilation, so less total wetted foil and strut surface might

be needed. The only objection seems to be that the outward foil tips come nearer the surface.

**Mr J. B. Wynne, M.Sc., Ph.D. (Associate-Member):** I used to have a boat called MAYFLY which is mentioned in the paper, and have just about managed to hold off Doug Pattison's; I have done 23 knots which he has not quite been able to obtain on the course yet. My boat has now gone to the Science Museum, so the way is now clear for him to go on to better things!

I would pay tribute to Doug and his brothers together with his entourage for their perseverance and ingenuity. It is a most ingenious boat. It is also remarkable how he has been able to motivate the extensive Pattison family.

Perhaps I might point out that Doug Pattison's is the first successful fully-submerged sailing hydrofoil in the world, and Doug probably has as much experience of designing fully submerged hydrofoils as anybody in this country today. I was fortunate to witness his tack on the foils which again is a world first.

I should like to amplify a point which the author touched on. Fig. 27 shows a drag breakdown for a typical sailing hydrofoil, if there is such a thing. What you find if you do some simple calculations is that if you divide the drag into hydrodynamic drag from the water and aerodynamic drag from the air, two-thirds of the drag is coming from the water, and most of this is due to the struts. Nearly all the hydrodynamic drag is viscous + spray drag and induced drag from lifting the boat and generating side force is fairly small. The induced drag from the sail is only about 15% of the total.

There is a theory which the author and I published in 1980, Ref. 18, which shows that for maximum speed we would like half the total drag of the boat to be induced drag from the side force foils and from the sails, see Fig. 28.

In other words, we would like half the total drag to be due to developing water and air side forces, with the rest of the drag composed of profile drag of the foils and sails, windage on the hulls and induced drag from the lifting foils. This is

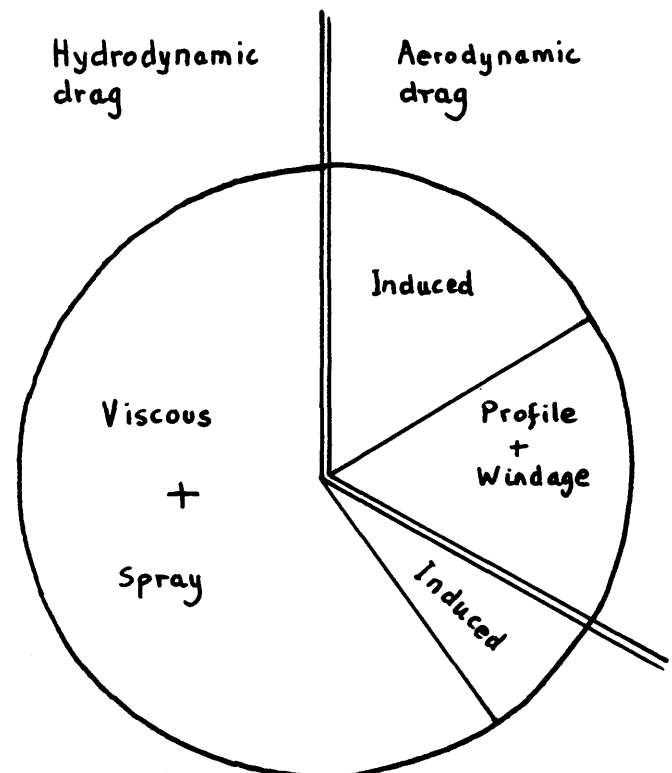


Fig. 27. Drag Breakdown for Typical Sailing Hydrofoil

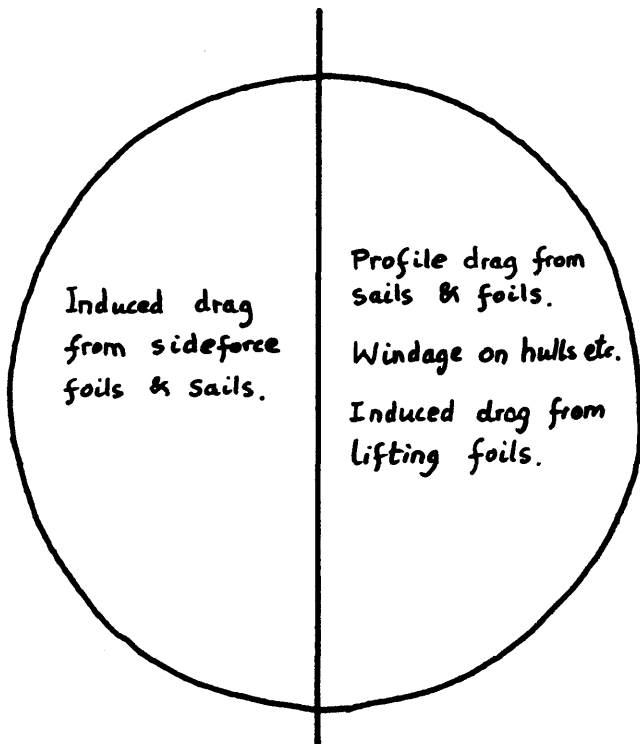


Fig. 28. Optimum Drag Breakdown for Maximum Speed

analogous to the case of a high performance sailplane which for maximum gliding ratio needs to have half the total drag induced and half profile drag. So the point I am making is that we would like to see much more sail induced drag than we are getting in practice for efficiency. What we could do is to increase the induced drag quite a lot by using a high lift coefficient on the sail without suffering, and we should go a lot faster because of the increased thrust. If we put in the numbers we find we want a lift coefficient of around 2, and the author points out in his paper that he is only getting about 0.8 and would like to have more. So he would be better off with a high lift coefficient sail.

**Mr P. V. MacKinnon:** I was once the Chairman of the Council of the Royal Yachting Association, and I once sailed a 10 m<sup>2</sup> canoe which in those days was considered a fast boat.

As regards the paper, I should like to start by congratulating Mr Pattison on his perseverance, because I know that anybody can have a good idea, but what takes time and trouble is developing it and making it work as the author evidently has done.

I shall ask him one or two questions, not by way of being awkward, but because I hope his answers will be interesting. First, I am not quite clear why the craft is stable in pitch without control of the foil on the rudder. Secondly, it is stated that the sail controls are brought into the cockpit. It would be interesting to know a little about the way the flap control is brought to the pilot's hand because that must be fairly complicated.

I am going to make one or two suggestions, again not because I think I have a better idea than the author, but because it would be interesting to hear his comments on them. First of all the sail cannot be reefed or dropped at sea. This is of course acceptable in the speed trials, but if the problem could be overcome, it would make the owner's development trials easier, and make the whole craft nearer to being of interest to the general sailing public. I wonder whether it is possible that the idea of an inflatable aerofoil would help. I have no experience of it, but I do know from reading<sup>(1,2)</sup> that in connection with the man powered flight trials, a wing

was built of 250 ft<sup>2</sup> with a span of 33 ft and a weight of 13 lb. This was built of very light material indeed, but it seems to me that for the purpose we are now discussing an inflatable aerofoil built of the lightest inflatable dinghy material would be comparable in weight to what we have been told about.

I shall perhaps ask the author to embark on another point of discussion. I appreciate that this product is only intended for the speed trials, but as a matter of interest if the trials had been for speed around a triangular course, would this machine have required modification or would it have been suitable? Speed around a triangular course naturally is of interest to yachtsmen. It may be surprising to realise that in the 1930s 10 knots round a triangular course was achieved by an American J class yacht. Since the C class and Tornado catamarans have been in existence that average speed must have been considerably exceeded.

The author was quite frank that his sail incidence control was achieved by luck as well as by good judgment. I wondered whether the self-tending of the sail could be improved by applying spring loading to the boom as well as leaving it to tend to itself under control of the shrouds and the flap.

I am surprised by the suggestion that further improvement will follow from the use of a higher lift coefficient. I would have thought that a more profitable way to improve performance would be to use a sail of considerably larger area without attempting to achieve a higher lift coefficient than can be obtained from a symmetrical aerofoil with a fairly small flap. This it seems to me would also allow speed attempts to be made in a lighter true wind than 20 knots, which must happen more often, and must be more pleasant both for the pilot of the craft and the shore helpers.

I think the author will agree that he is lucky to have modern materials and computer assistance. I did once try to estimate performance of a craft with a wing sail; the wing sail was constructed of wood, fabric and dope, and the performance estimates were all made by drawing triangles on large pieces of paper.

I simply repeat by way of conclusion that one should realise that hard work and detailed development have gone into this craft.

#### Added in writing after the meeting

It seems unfortunate that so much induced drag should be incurred by having an up load greater than the total weight on the lee foil and down loads on the other two. These loads would be reduced if the main beam were made wider and set further forward in relation to the centre of gravity. I realise that these alterations would have repercussions on the structural design and on the lead of the shrouds and so on the self-trimming of the wing; but the wider shroud spread would mitigate the structural problem, and perhaps a positive tension (a spring loading) on the 'mainsheet' would control the angle of attack.

Reducing the down-load on the rear foil would also reduce the chance of its breaking surface, when I think the automatic fore and aft stability mentioned by the author in discussion would break down catastrophically.

Referring to the suggestion made in discussion that the best choice of lift coefficient would be that which makes the induced drag half the total drag, it is true that for aircraft the speed for minimum drag gives rise to this equality of induced and profile drag. Pilots of propeller driven aircraft used to be recommended, for maximum range, to fly at a speed *higher* by a sufficient margin to make control easier and flight conditions therefore steadier, and I believe the same applies to gliders. Induced drag is then somewhat less than half the total.

By analogy, I would expect the best choice of area for a wing sail to be such that, at the conditions for optimum performance, the induced air drag is somewhat less than half the total air drag. It would be interesting to know if the author

agrees, and if this argument points to an increase of wing area above 13 m<sup>2</sup>.

I doubt if the same argument can be applied to the foils when one is lifting and two are pulling down, but it is obvious that the greatest scope for improved performance is to be found in reducing the profile drag, especially of the struts. It is possible that the most effective improvement would be to use exotic materials to allow reduced strut size while maintaining strength.

## REFERENCES

19. Sherwin, K.: To Fly like a Bird. Bailey Bros and Swinfen, 1976.
20. Turnill, R. and Reed, A.: Farnborough—The Story of RAE. Robert Hale, 1980.

**Mr H. M. Barkla, M.A., B.Sc.** (Associate) (read by the Secretary): In a paper which I presented to this Institution nearly a third of a century ago, I analysed the requirements for sailing speeds of the order of 30 or 40 knots. Though sail areas of no more than 400 sq ft per ton were seen to be adequate, stability had to be sufficient to meet a lateral sail force more or less equal to the vessel's weight. The effect of the overall aerodynamic drag/lift ratio on performance was demonstrated. A keel drag/lift ratio of 0.1 was assumed in the original standard curves which I used at that time for my graphical solutions; this is quite representative of a centreboard below an immersed hull. It is possible to use my Fig. 5, for example, to make a comparison with the vessel now described.

By the time that the lee foil is lifting 1½ times the weight and the weather foil is pulling down half the weight, induced drag is rising pretty fast, and this may be taken as an arbitrary stability limit. There would have to be some such limit set by foil size and structural strength. In this case the maximum lateral force would be 1.1 times the weight. A maximum sailing speed of 32 knots would then be expected in an 18-knot wind if the overall aerodynamic drag/lift were no better than 0.24. This compares with the author's present prediction of 35 knots in a 20-knot wind. In FORCE 8 the aerodynamic efficiency may well be quite a bit better than that, but the keel drag/lift must be much worse than 0.1.

Let me give a crude illustration of the importance of keel efficiency. Even when reaching at 110° to the true wind at 1¾ times true wind speed, the resultant aerodynamic force is so little forward of the beam that the lateral force, which has to be equalled by the keel force, is of the order of 3 times the forward driving force or 3 times the resistance including the keel drag. Let us take it as 3. Then if the keel drag/lift is 0.1 the lateral force has to be 4.35 times the resistance excluding keel drag; if the keel drag/lift is 0.2 the lateral force from the rig has to be 7.5 times the resistance, that is 73% more,—needing that much more sail area and giving that much more stress in the structure.

Any benefits that may accrue from the use of an efficient wingsail can so easily be squandered by lack of an equal care in the generation of keel force. Surface-piercing struts running in yaw, especially if designed for low spray-drag, must have a worse drag/lift than a fully immersed foil, even when they have the same aspect ratio; and in FORCE 8 the strut aspect ratio is much lower than that of the lifting foil.

I would like to ask the author why he chose not to use tilted foils to generate all or most of the keel force at the same efficiency as the lift. It should be pointed out that what the author calls the Hydrofin system and shows in Fig. 6 is only the crudest version of the earlier system; Hook never used feeler arms without a heavy damper, for one thing, and from at least as early as 1966 (11 years before his death) Hook's New Hydrofin separated the roll and pitch signals. The intervention of a pilot-override similar to the control-box of Fig. 8 between feelers and foils was always, as far as I can trace, basic to the Hydrofin.

Writing in 'Yachts and Yachting' in 1968, declaring my faith in hydrofoils for fast sailing, I called it 'no undertaking for the amateur', and I suggested that it needed what 'only a professional organisation of some size could give'. The author has given this some very professional consideration and done some admirable practical work which I hope to see crowned by further success.

**Cdr G. C. Chapman:** I have a supplementary point which was mentioned in Mr Barkla's comments and it was touched on, but I should like the author to say a little more about damping. If you can try and imagine some sort of sensor going along on the surface of the water, and you think of sitting in a boat and every time a wave hits something you get a face full of spray, to convey the mean of that sea surface level to a foil and not have the foil doing the same sort of thing is highly desirable, and I wonder why you have not got a damper.

*The Chairman then proposed a vote of thanks to the author which was carried with acclamation.*

## WRITTEN DISCUSSION

**Mr N. Bose, B.Sc., Ph.D.** (Junior Member): This paper describes what is certainly one of the most advanced wind-driven hydrofoil boats in existence and one which it is felt incorporates many features which will predominate on future designs.

On powered craft the automatic control system for a fully submerged hydrofoil system is electronic, based on the input from accelerometers and wave sensing equipment. This would be unacceptable for the sailing speed event because there would almost certainly have to be some form of power storage, even if it could be shown that the electrical power had been generated from the wind, say from a small windmill. The same problem would arise for a larger wind-driven hydrofoil craft which might compete in an ocean race, not to mention the problems of electronics and salt water, which always seem to be present on a small yacht. The mechanical control system described is delicate and again for a larger boat, would be prone to damage during a race.

The surface piercing hydrofoil system, on the other hand, can be designed to have inherent geometrical stability and the best overall systems will probably be found to be those with inclined surface piercing foils with controllable tips for 'flap' and 'aileron' control. Present day designs for surface piercing systems are, in any case, really hybrid systems since they normally use a fully submerged stern foil for trim control in a similar manner to the stern foil of FORCE 8. In such a system, the advantages of manual input to control described in the paper would be added to this inherent stability.

There are, of course, other arguments between the two types of system. For example, the friction and form drags of a fully submerged system including the pods increase as the square of the velocity but this is not true for surface piercing system whose immersed surface area reduces as the speed increases and which could be designed with fewer immersed pods or foil intersections at the maximum design speed. On the other hand, the aspect ratio and hence the lift/drag ratio of the surface foils reduces as they emerge and in addition these foils are more prone to ventilation problems because of their closer proximity to the water surface. In the end analysis, there would be little difference between the two types from these considerations.

It is stated that the boat flew slower than was predicted. The methods of Ref. 5 do not adequately take into account all of the factors which increase the drag and reduce the lift of a foil operating in very close proximity to the water surface. A more comprehensive method was formulated by the Canadian Defence Research Establishment Atlantic<sup>(21)</sup>, and this was developed at the University of Glasgow<sup>(22)</sup>, and eventually programmed<sup>(23)</sup>. The lift curve slope stated in Table II for the main lifting foils of 0.6 the ideal value



agreed with that calculated from the programs of Ref. 3 for this foil but it is not actually clear whether this value was used in the speed prediction.

The choice of foil section is surprising. Cavitation can become important at speeds below 40 knots because of the range of angles of attack at which these foils are required to operate. To get the complete picture, a cavitation 'bucket diagram' must be calculated<sup>(21)</sup> and the foil operated in the region within the bucket. A glance at the pressure distributions of the NACA foils 0012-64, 0015, 16-012 and 16-015 in Ref. 4 show how the latter two are much more uniformly loaded than NACA 0015. The peaked distribution of NACA 0015 when added to the pressure distribution which occurs at an angle of attack would mean that cavitation would occur sooner than on either of the sections 16-012 or 16-015 or, in other words, the width of the 'bucket' would be less.

It is also surprising that such a large sweep back angle was chosen, especially after trouble had been experienced with the centre of pressure. For a symmetrical section, the pitching moment about the quarter chord point is zero at an angle of incidence of zero degrees but it does vary slightly as the angle of attack is altered. To keep the control forces to a minimum it makes sense to taper the foil about the quarter chord line and to place the axis of rotation here or nearby also. With the large angle of sweepback, the centre of pressure becomes difficult to predict because it is also dependent on the spanwise pressure distribution. On the design shown, the inner sections of the foil will have their centres of pressure forward of the stock axis and will be more heavily loaded than the outer sections and it is these sections which are contributing to the instability mentioned.

## REFERENCES

21. Eames, M. C. and Du Cane, P. (Editor): 'High Speed Small Craft', David and Charles, 1974.
22. Bose, N.: 'Hydrofoils—Design of a Wind Propelled Flying Trimaran', Ph.D. Thesis, University of Glasgow, April, 1982.
23. Bose, N.: 'Design Programs for Hydrofoils', RINA Small Craft Group International Conference on Sailing Hydrofoils, Nov. 1982.

**Capt. R. J. Johnston, USNR (Ret'd):** The author is to be congratulated for his spirit and hard work in keeping the achievement of high sailing speeds alive. To challenge the sea with a hydrofoil sailing rig indeed requires the perseverance of a successful insurance salesman and considerably more technical knowledge. The scientific approach used to accomplish a record with submerged hydrofoils has been well documented by the author. This discussor truly believes that the way to the record is with submerged foils although this foil system requires a more complex rig.

This discussor was also pleased to see Mr Christopher Hook's mechanical genius applied to FORCE 8. Reviewing Fig. 7 and the author's results of height keeping analysis suggests a couple of lessons learned while experimenting with the Hook system some years ago. The Hook float had a leaf spring attached to the trailing edge of the float. It was this leaf spring that made contact with water surface. By the proper selection of the leaf spring, the small surface chop could be eliminated from an input to the control system. The float only became effective with large waves. Also a variable dash pot between the feeler arm and the strut was most helpful in stabilising height.

During the early fifties this discussor worked with Mr Gordon Baker on the design of his sailboat. We also planned to use a rigid sail for improved sail effectiveness. In fact it was our plan to use twin, rigid sails to gain the advantage of a biplane effect. This good theoretical approach to maximum sail effectiveness was overcome by costs and neither the rigid sail nor the biplane concept was ever built.

One other comment regarding the sails concerns the thickness ratio. After considering the Reynolds number of high sailing speed (we were very ambitious and designed for 40 knots), we concluded that a 24% thickness ratio was optimum.

Our big concern was pitch poling which had occurred on earlier models. Here Gordon Baker's mechanical genius was displayed. He calculated the forces on the stays that caused the boat to pitch pole. As the author has done the aft foil was controlled to hold the stern down. Baker's aft foil was controlled by an on-board mechanical computer which used the summation of the stay forces to adjust the angle of attack.

These comments are made with the sole purpose of placing a few suggestions before the author as food for thought for a few more knots. They are not made to degrade the effort that has gone into FORCE 8 or the expense. In fact it can well be the expense that prevents many good ideas from being incorporated in a project of this nature. Rigid sails, biplane sails, and onboard computers are not small investments even when a few knots are at stake.

**Mr A. P. Farrar (Fellow):** I have known FORCE 8 for most of her active life, having followed her development from her first appearance at the RYA Speed Trials at Portland; and in my capacity as official measurer, I had the interesting job of measuring her wing sail for sail area under the IYRU measurement rules.

Having been involved in the design and construction of wing sails myself, going back over more than 25 years, I can sympathise with the decision to go for a symmetrical airfoil, having done the same thing myself before realising that it really needs some camber and that trailing edge flaps are no real substitute. I note that a new sailplan with much larger flaps is under consideration.

The symmetrical airfoil has very low drag, but also low lift; and the author had to increase the area by 30% from the 10 m<sup>2</sup> originally considered to get the performance which would have been achieved with a cambered 10 m<sup>2</sup> sail; thus moving into a larger sail area class. The compromise of part wing mast—part fully battened soft sail indicated in Fig. 1(c), as used on LADY HELMSMAN and described in Ref. 24, would probably have served well.

The author speaks of the wind velocity gradient producing twist in the relative wind. The rigid wing sail has no twist—which he regrets—but which is really just as well, as the velocity gradient just does not apply at this scale. Experiments carried out by the late General Parham and myself (Ref. 25) showed that the presence of a boat's hull causes the wind speed to be accelerated in rising over the hull and almost exactly cancels out the velocity gradient up to the height of the sail plan.

In large sailing ships where the height of the rig is greater in proportion to the hull, there certainly is a twist in the apparent wind; but in small yachts if the sails are sheeted to reduce their twist to a minimum there is still more than the effective twist in the apparent wind.

## REFERENCES

24. Parham, H. J. and Farrar, A. P.: 'Class "C" Racing Catamarans', Trans. RINA, Vol. 110, 1968.
25. Marchaj, C. A.: Sailing Theory and Practice, pp. 370-372, Dodd Mead & Co.

**Professor D. F. Rogers, Ph.D.:** The author is to be commended on his professional approach and persistence in designing, producing, and testing this craft. The following brief discussion suggests a way to improve the aerodynamic efficiency of the wing sail. The NACA 0015 airfoil section has been extensively tested both in two-dimensional (wall-to-wall) and three-dimensional wing configurations in student

experiments in the Aerospace Engineering Department at the US Naval Academy. Most of these tests are at an  $Rn$  of approximately  $0.6 \times 10^6$ . The stall results are characteristic of laminar boundary layer separation at or near the minimum pressure peak on the airfoil. This is characterised by a sharp drop in  $C_L$ . In contrast at higher  $Rn$  number a more gradual stall characteristic of turbulent boundary layer separation progressing forward from the trailing edge is observed. These observations suggest an explanation for the ineffectiveness of the vortex generators fitted: they were too deep in the already separated flow.

Wind tunnel tests at an  $Rn$  of approximately  $0.6 \times 10^6$  show that a leading edge slat or slot easily delays the laminar boundary layer separation until higher angles of attack with minimum increase in drag coefficient. This observation suggests the fitting of either a slat or slot to approximately the upper 25-35% of the wing sail will improve the aerodynamic performance.

**Mr C. V. Betts, M.A., M.Phil., R.C.N.C. (Fellow):** This excellent paper, with its demonstration of a wide range of the naval architect's professional skills in microcosm, makes a fascinating addition to our Transactions. The author is in the unusual position of having personally conceived, designed, built and successfully tested a craft of advanced concept. This must have given him a somewhat unique insight into not only the current state of naval architectural knowledge but also into the nature of design. The author's reflections on this are invited. In particular, I would be interested to discover if the author found himself following the traditional 'design spiral' approach to his design or whether some other process comes into play in developing a craft such as FORCE 8.

#### AUTHOR'S REPLY

Mr Betts asks whether the traditional design spiral was followed, and, on reflection, I do not think it was. The various elements of this design, foils, sail, controls, structural design and weight, seemed almost sufficiently independent to be considered as separate design tasks. Perhaps each had its own spiral. Compared with a conventional displacement vessel the basic design task was more straightforward. The hull was designed and built long before details of the foils, or even the type of sail had been decided, and this made the design of all of the other elements simpler by reducing the number of options.

Mr MacKinnon asks if the performance would not be improved by a wider spread of foils. The induced drag would certainly be reduced but at the expense of greater structural weight, which might require larger foils. I recently investigated adding a metre to the beam without altering the foils but the increase in speed was insignificant. In 'round the buoys' racing FORCE 8 could be beaten easily by a Tornado catamaran—she is too slow to windward and also well off the wind. The boat has made 11 knots to windward in a wind of about Force 5, but would go faster with ballast out to windward. Off the wind, it is certainly the low lift coefficient of the sail which limits the speed.

Mr Brown is quite correct when he suggests that my wife, Gail, deserves much credit for the success of the boat ... it is, of course, named after her.

#### Foil Control System

Mr Brown asks if an automatic control system would be of great value. The advantages would be to remove the awkward and vulnerable mechanical surface sensors, to reduce the added drag due to foil flapping, and possibly to remove the need for the helmsman's input once foilborne. For any ocean-going craft the last advantage would be of great importance. The penalties of greater cost and complexity would be considerable, but the major drawback in going away from purely mechanical controls would be the power needed to move the

lifting foils. I believe that manual input would still be required, at least before takeoff, and for the time being I will persevere with mechanical engineering.

Mr Barkla is quite correct when he points out that Fig. 6 shows only the basic stabilising action of Christopher Hook's Hydrofin System, not the sophisticated arrangement used in his powered craft. Cdr Chapman asks why no damper was used on the sensor to reduce foil motion. The equations of motion given in Appendix 1 describe a 'low pass filter', and it was clear that high-frequency movements of the surface sensor would have negligible effect on the motion of the craft. The addition of a damped spring to the end of the sensor, as in the Hydrofin, will therefore affect only the motion of the foils, not the craft as a whole. It was decided to omit this extra complication in the first instance and see what happened. So far the only drawback is the extra drag expected due to foil flapping, and adding damping to the sensors may be a way of increasing boat speed.

Mr MacKinnon asks how stability in pitch is achieved without control of the tail foil: the problem is similar to that of the longitudinal stability of an aircraft (not the phugoid motion), in the 'stick fixed' condition, and is assessed by the margin of stability. There is, of course, no control over the pitch angle that may be reached, and extensive calculations were made to check that the tail foil would not broach the surface.

#### Foil Design

Mr Barkla and Cdr Chapman ask why tilted foils were not used to resist leeway with greater efficiency. The size of the main foils is determined by the lift required at takeoff, so if they were also to generate side force they would have to be larger and would create more drag at high speed. The top part of the struts is sized to withstand a large bending moment, but the lower part which is submerged when foilborne is not highly loaded by the side force, and is sized for general robustness. It could not be much smaller even if the struts saw no side force at all. If the main foils were given dihedral, then, to keep the same depth at the tips, the struts would be longer, with more wetted area, and would lead to more drag. The little data I have found for surface-piercing struts generating side force suggest that the drag penalty of using my struts to resist leeway is negligible, because of the low angle of attack. All fully-submerged-foil boats suffer the parasitic drag of struts, and for FORCE 8 this is about 30% of the total foil drag. I see no practical way to reduce this without making the struts too frail, even using exotic materials. At least in this craft I seem to get the side force generated with little drag penalty.

Dr Bose asks if the value of lift curve slope in Table II was used in the speed predictions; it was in the latest ones, but not in 1976. He also questions the foil section and the sweep angle used. The first two sets of foils were designed with cavitation in mind, but unfortunately with these foils the boat would not go fast enough to make it matter. There is no real requirement to delay cavitation inception in this craft, but it is necessary to delay the serious drop in the lift to drag ratio of the foils which comes with major cavitation. I am not sure of the foil section required in this case. I am sure that Dr Bose is right about the sweep angle used, and it will be reduced on future foils. Why there should be much variation in the spanwise distribution of load on such a simple wing at low lift coefficients is not clear to me.

#### Sail Design

Mr MacKinnon makes a number of points concerning the design and construction of the sail, but also points out the value of modern materials and of computers. In this I feel he is quite correct. Until fairly recently the cost and design effort needed for a boat like this one would have been prohibitive. Returning to the sail, the controls for the flap are in fact extremely simple—lines from two projections on the flap are brought down the sail and back to two cleats at the cockpit. There is no attempt at precise angling and flap deflection is not even calibrated. A sail that could be reefed

would make the boat far more seaworthy, but the loading on the sail at high speed is such that I doubt that an inflatable sail could be supported. I am investigating a part solid part fabric sail similar to LADY HELMSMAN, as suggested by Mr Farrar, so that at least the sail could be shortened at sea.

Dr Wynne mentions the theory that half the total drag should be induced drag from the sail and struts, and states that a sail lift coefficient of about 2 is needed. I have approached this problem from a totally different viewpoint in my program to predict the craft performance, but the results do confirm that as the lift coefficient is increased there is a maximum speed and that this occurs at a lift coefficient approaching 2. Certainly I am working towards this rather than a much larger sail. I cannot see how to detect in FORCE 8 the effect suggested by Mr MacKinnon, that control may be better with less induced drag. If it were to apply to this type of craft, it still might be swamped by the craft motion in waves and gusting wind.

Mr MacKinnon asks if the self-tending of the sail could be improved by spring loading of the boom. In effect, this is already done by applying tension to the forestay and backstay. The basic drawback of this type of control is that as the relative wind speed increases, the aerodynamic moment

acting on the sail increases as the square of the speed, while the moment due to the spring remains constant. Thus the spring effectiveness reduces rapidly as the boat speed increases. This may help to explain why FORCE 8's sail appears to work well only at relatively low speeds.

Mr Farrar suggests that my twist-free sail is not really a disadvantage. Even Marchaj in his later book (Ref. 26, page 533) says that 'To be on the safe side, we should assume that it is rather likely that at least some apparent wind gradient will often occur'. The real problem is that any twist in the apparent wind will be enhanced by the variation in the induced angle of attack and will always work against the increasing tendency of the narrow tip sections to stall.

I am grateful to Professor Rogers for his explanation of why the vortex generators fitted to the sail appeared not to be effective.

#### REFERENCE

26. Marchaj, C. A.: 'Aerohydrodynamics of Sailing'. Adlard Coles, Grenada, 1979.