Analysis and Development of a Sailboat With Self-Trimming Wing Sail

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by

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SUMMARY

In order to eliminate some of the variables which are normally present, a sailboat has been developed with a self-trimming wing sail mounted above a trimaran. The ultimate purpose is to measure the forces transmitted from the sail to the hull, measurements that would be extremely difficult to make on a conventional sailboat. These measurements, together with those of the relative wind and water velocities, will enable the systematic improvement of the performance analysis of sailboats.

A theoretical analysis supported by wind tunnel model tests has been made for a symmetrical uncambered sail with trimming tailplane. This investigation confirmed the static and dynamic stability of the sail and gave lift and drag coefficients in good agreement with existing data for the same aerofoil section at comparable Reynolds numbers.

The above investigation formed the basis for the design of a small, full-scale sailing craft having a rectangular sail mounted above a 16 ft. canoe fitted with leeboards and outriggers. The sail was statically mass balanced about a pivot line at the quarter chord. Although somewhat cumbersome to rig, the boat was adequately man-

oeuverable under sail. Nevertheless, measurements of the air and water speed indicated that the performance was not as good as had been anticipated. This is attributed to the high inertia of the wing combined with its lack of local mass balance (product of inertia not zero about the roll and pivot axes) which produced a tendency for the wing to oscillate up to and through the stall. The measured sail angles for zero forward speed also showed that the aerodynamic drag of the hull and occupants was comparable to that of the sail.

The performance was improved considerably by increasing the sail area with a fully mass balanced extension. Experience with this extended sail indicated that conditions may be sufficiently steady for the sail force to be measured.

It is proposed to continue the work using a larger sail mounted above a trimaran with a fine central hull containing a rotating centre board. The sail will be fully mass balanced and the force transmitted to the hull will be measured together with the sail angle, the tail angle, the centre-board angle, the rudder angle, and the relative wind and water velocity vectors.

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NOTATION

a_t - lift curve slope of tail

a_w - lift curve slope of wing

A - inertia parameter $\frac{\rho l^3{}_t S_t a_t}{2I}$

Æ - aspect ratio

B - static stability criterion $1 - \frac{\partial\epsilon}{\partial\alpha} - \frac{\lambda a_w}{\mu a_t}$

$\bar{c}$ - mean chord of sail

C_D - drag coefficient

C_L - lift coefficient

C_{Lw} - lift coefficient of wing

C_{Lt} - lift coefficient of tail

C_M - moment coefficient

C_{Mw} - moment coefficient of wing

H - height of wing sail

i_t - tail setting angle

I - polar moment of inertia about the pivot axis

l_t - distance of tail aerodynamic centre from wing pivot line

L_w - lift of wing-sail

L_t - lift of tail

M - total 'nose-up' moment about the wing pivot line

M_w - 'nose-up' wing moment about the aerodynamic centre

S - wing area

S_t - tail area

t - time

$\bar{t}$ - non-dimensional time $t \frac{U_t}{l_t}$

U - free stream relative wind speed

U_t - relative wind speed at tail

α - angle of attack of the wing

α_o - angle of zero lift at the chosen flap deflection

α_e - equals α at the trimmed condition

ϵ - downwash angle

ϵ_o - downwash angle at zero α for the chosen flap deflection

θ - angle of heel

λ - distance of pivot line from the centre of pressure divided by $\bar{c}$

μ - $\frac{l_t S_t}{\bar{c} S} \left(\frac{U_t}{U}\right)^2$

ν - kinematic viscosity

ρ - density of the air

Φ - $\alpha - \alpha_e$

1. INTRODUCTION

Research on sailing was initiated at McGill in 1964 with modest financial help from the University and the National Research Council of Canada. The intention is to assess and improve the methods of performance prediction for sailboats by making measurements on a full-scale craft. Work of this sort has been going on at Southampton University for several years and some full scale measurements on a Dragon class yacht have been made [1]. Under sail these measurements have been limited to the relative wind and water velocity vectors, the angle of heel and the rudder angle. It would be extremely difficult to measure the nett force transmitted from such a conventional sail to the hull, and this is only being attempted with the yacht tethered on a pond in open country, the nett aerodynamic force being determined by measuring the tensions in three tethering cables.

The work at McGill is seen to be complementary to the Southampton research. We have chosen to study a simpler sailboat in which some of the variables have been eliminated and in which the performance is not dominated by hull drag. The angle of heel has been made small by using a trimaran arrangement (at present a 16 ft. canoe with outriggers). The variation of sail shape with porosity and relative wind speed have been eliminated by using a rigid wing sail. The forces have been transmitted from the sail to the hull at a single point by using a self-trimming sail which eliminates the standing rigging and the sheets.

The first, self-trimming, sailboat was apparently made in Norway by Utne during the Second World War [2]. It had a symmetrical wing section (modified R.A.F. 30) with two trailing edge booms on which was mounted the trimming tail-plane. The wing area was about 40 ft.^{2} and it was statically mass balanced about the axis of rotation (25% chord). It was mounted above a flat bottomed hull which was well streamlined aerodynamically and the helmsman sat well down in the hull in a reclining position. Although no measurements were made on this small craft, it appears to have been both successful and highly manoeuverable.

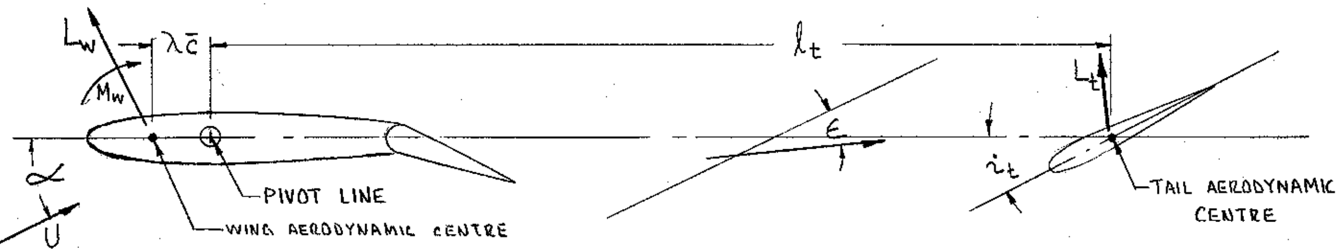
The second full scale boat was constructed as a private venture at Blackburn Aircraft in 1962 [3,4]. It has a rectangular wing of area 62.5 ft.^{2} and section NACA 0015 fitted with a 25% chord flap. The wing is pivoted at 30% chord. The trimming tailplane was also mounted on booms in a manner similar to the Norwegian boat. The complete wing-sail was mounted above a 12 ft. dinghy. Initially the sail was not statically mass balanced and the boat frequently developed divergent rolling oscillations and capsized. This behaviour was improved somewhat by mass balancing the sail and by increasing the area of the tail. Side views of both craft are shown in Fig. 1.

Mention should also be made of a similar, and quite sophisticated, model sailboat which was designed by Irbitis and built by Bodek in 1952. The model has slender catamaran hulls and the wing sail has an adjustable trailing-edge flap so that the wing camber automatically increases from a low value when close hauled to a large value on a broad reach.

In view of this background we decided to build a small boat fairly similar to Utne's and to gain some experience with it, in particular to evaluate the dynamic stability of the wing-sail, before embarking on a more ambitious design that would incorporate the complete set of measuring instruments. This proved to be a wise decision. The McGill sailing boat was built round an available 16 ft. Chestnut canoe to which two outriggers were attached. The sail has a symmetrical NACA 0012 section pivoted at 25% chord, and the trimming tailplane (NACA 0015 section) is mounted on booms in an arrangement which closely follows the Norwegian boat (see Fig. 1). The original sail was 30 sq ft. in area. Wind tunnel measurements have also been made of the lift, drag and tail angle for trim on a 1/8 scale model of the sail. Full scale measurements of relative wind velocity and water speed were also made on the boat with the original sail and with the sail extended by a further 8 ft. to give an increased sail area of 54 sq. ft. In view of the importance of sail stability this report begins with an analysis of the static and dynamic stability of the sail about the equilibrium, trim position.

2. ANALYSIS OF THE TRIM AND STABILITY OF A SELF-TRIMMING SAIL

Consider the general case of a symmetrical sail fitted with a flap and balanced by means of an all-moving tail surface of symmetrical section.



$\bar{c}$	mean aerodynamic chord of wing
S	wing area
S_t	tail area
M_w	nose-up wing moment about the aerodynamic centre

Following conventional analysis of aircraft stability, all angles are assumed small and the contribution to moment from drag forces is neglected. Thus the nose-up moment about the pivot line

$$M = M_w + L_w \lambda\bar{c} - L_t l_t$$

In coefficient form

$$C_M = \frac{M}{\frac{1}{2}\rho U^2 \bar{c} S} = C_{Mw} + \lambda\, C_{Lw} - \mu\, C_{Lt}$$

where $\mu = \frac{l_t S_t}{\bar{c}\ S} \left(\frac{U_t}{U}\right)^2$

combines the tail volume coefficient: $\frac{l_t S_t}{\bar{c}\ S}$

and the dynamic pressure ratio: $\frac{\frac{1}{2}\rho U_t^{\ 2}}{\frac{1}{2}\rho U^2}$

For sufficiently small $\frac{\dot{\alpha}\bar{c}}{U}$ and at angles of incidence below the stall, C_{Mw} is constant and

$$C_{Lw} = a_w(\alpha + \alpha_o)$$

where $-\alpha_o$ is the angle of zero lift at the chosen flap deflection.

$$C_{Lt} = a_t\ (\alpha - i_t - \epsilon + \frac{l_t}{U_t}\dot{\alpha})$$

where

$$\dot{\alpha} = \frac{d\alpha}{dt}$$

$$= a_t \left[\alpha(1 - \frac{\partial\epsilon}{\partial\alpha}) - i_t - \epsilon_o + \frac{l_t}{U_t}\dot{\alpha}\right]$$

where ϵ_o is downwash angle at zero α for the chosen flap deflection.

If I is the moment of inertia of the wing-tail combination about the pivot line

$$M = I\ddot{\alpha}$$

Thus the dynamic equation for the sail rotation is

$$\frac{I}{\frac{1}{2}\rho U^2 S\bar{c}} \ddot{\alpha} + \frac{\mu a_t l_t}{U_t} \dot{\alpha} + \left[\mu a_t\left(1 - \frac{\partial\epsilon}{\partial\alpha}\right) - \lambda a_w\right] \alpha$$

$$= C_{Mw} + \lambda a_w \alpha_o + \mu a_t(\epsilon_o + i_t)$$

For equilibrium at the trimmed condition $\alpha = \alpha_e$

$$\left[\mu a_t\left(1 - \frac{\partial\epsilon}{\partial\alpha}\right) - \lambda a_w\right] \alpha_e = C_{Mw} + \lambda a_w \alpha_o + \mu a_t(\epsilon_o + i_t) \qquad \ldots(2\text{-}1)$$

Putting $\Phi = \alpha - \alpha_e$

$$\ddot{\Phi} + \frac{1}{2} \frac{\rho l_t^3 S_t a_t}{I} \left(\frac{U_t}{l_t}\right) \dot{\Phi} + \frac{1}{2} \frac{\rho l_t^3 S_t a_t}{I}\left(\frac{U_t}{l_t}\right)^2 \left[1 - \frac{\partial\epsilon}{\partial\alpha} - \frac{\lambda a_w}{\mu a_t}\right] \Phi$$

$$= 0 \qquad \ldots(2\text{-}2)$$

This equation is similar to that describing the short-period longitudinal oscillation of an aircraft[6].

For static stability the coefficient of Φ must be positive

i.e. $1 - \frac{\partial\epsilon}{\partial\alpha} - \frac{\lambda a_w}{\mu a_t} > 0$ if l_t is + ve (rear tailplane)...(2-3)

< 0 if l_t is − ve (canard arrangement)

Since

$\frac{1}{2} \frac{\rho l_t^3 S_t a_t}{I}\left(\frac{U_t}{l_t}\right)$ is positive the above condition is also sufficient for dynamic stability.

For a rear tailplane the non-dimensional time $\bar{t} = t \frac{U_t}{l_t}$

$$\frac{d^2\Phi}{d\bar{t}^2} + A\frac{d\Phi}{d\bar{t}} + AB\Phi = 0$$

where

$$A = \frac{\frac{1}{2}\rho l_t^{\,3} S_t a_t}{I}, \text{ the inertia parameter.}$$

$$B = 1 - \frac{\partial\epsilon}{\partial\alpha} - \frac{\lambda a_w}{\mu a_t}, \text{ the static stability criterion.}$$

The motion is oscillatory if

$B \geqslant \frac{A}{4}$ and the non-dimensional period $= \frac{4\pi}{\left[A(4B-A)\right]^{1/2}}$

The non-dimensional time for the amplitude modulation to halve is $\frac{1.386}{A}$ (2-4)

and the number of cycles to achieve this

$$= 0.11\left[\frac{4B-A}{A}\right]^{1/2}$$

It is therefore apparent that the combination of inertia, tail arm and tail area represented by term A must not be too small if the wing is to realign itself quickly with a change of wind direction. Thus, for example, the moment of inertia of the wing must not be too large. It is also advantageous to increase l_t, for with large l_t, I tends to increase like l_t^2; on the other hand, an increase of S_t may not be so useful since I will tend to increase in proportion.

A wing-sail is frequently working near maximum lift. Thus the wing may oscillate up to and through the stall. In so far as the quasi-static assumption for C_{Lw} and C_{Mw} remains valid, this will not alter term A. However, U_t may decrease and hence the physical time to damp will be increased. Also the aerodynamic centre will usually move rearwards and $\frac{\partial \epsilon}{\partial \alpha}$ will be reduced: both these changes increase B. Thus the number of cycles for damping to half amplitude will increase.

It may be concluded therefore that the inertia parameter A should be made as large as possible and the static stability criterion B should be positive but not large compared with A.

2-1 Application to Symmetrical Wing-Sails

For a symmetrical wing sail $C_{Mw} = \alpha_o = \epsilon_o = 0$

Thus (2-1) becomes

$$\left[1 - \frac{\partial \epsilon}{\partial \alpha} - \frac{\lambda a_w}{\mu a_t}\right] \alpha_e = i_t \qquad \ldots(2\text{-}5)$$

Hence, from (2-3), i_t must be positive for stability with a rear tailplane.

In equilibrium the lift coefficient on the tail

$C_{Lt} = \frac{\lambda}{\mu} a_w \alpha_e$.

In order to reduce the structural loads on the booms and tailplane, thereby making them as light as possible and reducing the ultimate moment of inertia of the balanced wing, it is desirable to make $\lambda=0$ i.e. place the pivot line at the aerodynamic centre of the wing.

This is the arrangement chosen by Utne.

Thus the criteria for static stability becomes

$\frac{\partial \epsilon}{\partial \alpha} < 1$

It is interesting to note that this puts a lower limit on the effective aspect ratio A of the wing. $\frac{\partial \epsilon}{\partial \alpha}$ is least for downstream (l_t large compared with sail height) where for an elliptic wing $\frac{\partial \epsilon}{\partial \alpha} = \frac{4}{2+\mathcal{R}}$ if the vortex sheet does not roll up.

Thus the effective aspect ratio of the sail cannot be less than about 2 and for a feasible tail position must usually be significantly greater than 2.

2-2 Canard Trim for a Symmetrical Wing-Sail

In view of the difficulty of mass balancing the wing about the 1/4 chord point (in all self trimming sails designed so far it has been necessary to add weight ahead of the pivot point) the use of a tail first or canard arrangement is attractive.

l_t and μ are now negative and the criterion for static stability (2 - 3) becomes

$$1 - \frac{\partial \epsilon}{\partial \alpha} - \frac{\lambda a_w}{\mu a_t} < 0 \qquad \ldots(2\text{-}6)$$

$\frac{\partial \epsilon}{\partial \alpha}$ is now likely to be negative (upwash ahead of the wing due to the influence of the bound vortex). Thus $\frac{\lambda a_w}{\mu a_t}$ must be larger and positive i.e. λ must be negative. The pivot line must therefore be ahead of the wing aerodynamic centre.

From equation (2-5) i_t is negative and $C_{Lt} = \frac{\lambda}{\mu} a_w \alpha_e$ is positive. Hence the Canard surface contributes to the overall lift.

However

$$\frac{C_{Lw}}{C_{Lt}} = \frac{\mu}{\lambda}$$

and since

$$\frac{\lambda a_w}{\mu a_t} > 1 \text{ from (2-6)}$$

$\frac{C_{Lw}}{C_{Lt}}$ tends to be less than unity

unless a_t is significantly less than a_w. This would entail the use of a canard surface of low aspect ratio.

Thus for the canard arrangement the wing tends to be at a smaller lift coefficient than the trimming surface, and the trimming surface tends to stall before the wing. Aside from the undesirable oscillations which would ensue, it would also be difficult to operate near maximum lift on the wing sail. For these reasons the use of a canard arrangement was abandoned for the present.

3. SAILBOAT WITH SELF-TRIMMING SAIL

3-1 Preliminary Design of the Wing-Sail

The trim and stability analysis in section 2 shows that:

a) It is simpler to position the trimming surface downstream of the wing-sail. The alternative, a canard surface, would have to be of low aspect ratio to achieve high lift on the sail, and there would be some uncertainty about the effect of its trailing vortices on the flow over the wing.

b) To minimize the load on the tail and tailbooms, and with it the inertia of the sail, the sail should be pivoted about the centre of pressure, which should itself be fixed. Thus a wing with symmetrical section pivoted about the quarter-chord line was indicated.

c) For static stability the effective aspect ratio of the wing would have to be chosen so that $B = 1 - \frac{\partial\epsilon}{\partial\alpha}$ at the tail is positive. This puts a lower limit on the aspect ratio of 2.

d) The downstream position and area of the tail, and the materials chosen for its construction, must be such that $A = \frac{\rho l^3_t S_t a_t}{2I}$ is sufficiently large to be comparable with the static stability criterion 4B. In this way

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d) The downstream position and area of the tail, and the materials chosen for its construction, must be such that $A = \frac{\rho l^3_t S_t a_t}{2I}$ is sufficiently large to be comparable with the static stability criterion 4B. In this way the wing would respond rapidly to a disturbance with near-optimum damping.

Further the wing-sail should:

e) have a wing section with good stalling characteristics at low Reynolds numbers ($\sim 1/4 \times 10^6$). A section with a sudden loss of lift at the stall, or noticeable hysteresis through the stall would not be acceptable.

f) have sufficient area to give a reasonable boat performance.

g) be mass balanced about the pivot line to reduce wing-sail oscillations due to hull roll.

Practical considerations suggested a rectangular plan form and a construction that would make the sail both rugged and unsinkable.

The preliminary design is shown in Fig.2, and consisted of a wing of aspect ratio (with reflection) equal to 6 2/3 and with an aerofoil section NACA 0012. The trim tail, with area 1/10th that of the wing has a section NACA 0015 and is mounted 1.3 chord lengths behind the wing.

3-2 Model Tests of the Wing-Sail

A one-eighth scale model of the proposed wing-sail was tested in the McGill 3 ft. x 2 ft. wind tunnel in order to determine the overall lift and drag coefficients and the angle of attack α for each tailsetting angle i_t. The model wing was mounted above a reflection plane and was freely pivoted in ball bearings about the quarter-chord line. The forces were measured at the root bearing by means of a simple mechanical balance. The reflection plane was 18 ins. long and the boundary-layer thickness at the model was therefore relatively very thin. The downwash angle ϵ, equal to $\alpha - i_t$ for this sail, was also determined and the static stability could therefore be verified quantitatively. For these measurements the model was statically mass balanced about the pivot line by means of a leading-edge root fairing made of lead. It was anticipated that a similar fairing would be required on the full scale wing.

Fig. 3 shows the tail setting angle i_t and the downwash angle ϵ for various angles of attack and below the stall. Both curves are linear, the wing is statically stable and $\frac{\partial \epsilon}{\partial \alpha} = 0.58$. This value may be compared with 0.60 predicted from section data (7) and lifting line theory which assumes that the vortex sheet remains plane (8). At the same downstream position, but on the reflection plane, the same method gives $\frac{\partial \epsilon}{\partial \alpha} = 0.52$. This may be compared with the value 0.48 at the same position when the vortex sheet is assumed to be fully rolled up into two trailing vortices. Applying a proportional correction to allow for the offset from the reflection plane, gives $\frac{\partial \epsilon}{\partial \alpha}$ = 0.55 at the tail for fully rolled up vortices. Thus the measured value lies convincingly between the two theoretical predictions, with and without vortex roll-up.

The C_L/α curves from section data at low Reynolds number (7) and corrected for aspect ratio (9) are compared with the experimental data at two Reynolds numbers in Fig.4. The agreement is good.

The experimental values of C_L/C_D are shown in Fig. 5 where they are compared with those predicted from section data and also, as a matter of interest, with those obtained experimentally by Millward on a model of the Blackburn wingsail and by Chapleo and Marchaj (10) on a model of a conventional cambered mainsail with mast.

The discrepancy between the measured and predicted values for the present sail is attributed mainly to the additional drag of the leading-edge root fairing and the tail. It is estimated that these components account for about 40% of the total drag at a C_L of 0.7.

When compared with the other sails in Fig. 5, it is apparent that under close-hauled conditions, the present wing sail provides a slightly larger forward driving force than the Blackburn wing sail and is definitely superior to the conventional single main sail under these conditions. On a broad reach however the cambered sails are superior.

The dynamic response of the model was investigated by measuring the response of the model following a disturbance. The moment of inertia I of the model was determined from the measured frequency of oscillation in still air when spring mounted as a torsion pendulum. The values of I and A are listed in table I. Together with the theoretical time to damp to half amplitude, the period for one oscillation and the amplitude after one cycle as a proportion of the initial amplitude for U_t = 10 m.p.h. and 20 m.p.h. At 20 m.p.h. the measured period was between 0.7 to 1.0 seconds and is therefore in reasonable agreement: however, the amplitude after one cycle was about 1/5 of the initial value. This increased damping is possibly due to friction in the ball-bearings.

3-3 Final Design of the Wing-Sail Craft

The model tests indicated that the preliminary sail design was both statically and dynamically stable, and that the aerodynamic drag was sufficiently small.

Thus the full scale prototype sail would also be stable and, at a representative relative wind speed over the tail of 20 m.p.h., would have a period of oscillation of 7 seconds and would require 5 seconds to damp to half amplitude. These values are higher than was thought to be desirable and hence some attempt was made to reduce the moment of inertia I and increase the parameter A for the prototype wing.

To be both rugged and buoyant the sail was built of styrafoam covered with fibreglass. Provision was made for inserting lead for mass balancing internally near the leading edge in the lower third of the wing. The tail was made as light as possible using a glider type of construction with ribs and thin plywood covering. To complete the static mass balance of the wing a streamlined sheet metal body was added to the leading edge near the root and was filled with the requisite amount of lead shot. The geometry and relative size of this body was similar to the lead fairing tested on the model. The weight of the statically balanced wing sail (10 ft. high and 3 ft. chord) was 100 lbs. The moment of inertia was determined by oscillating the wing elastically as a torsion pendulum, and was 3.45 slug-ft.^{2}. Thus the parameter A of the prototype sail is 0.25 and is considerably larger than that of the model. The other computed parameters for windspeeds over the tail of 10 m.p.h. and 20 m.p.h. are listed in table I.

To improve the performance of the full scale craft, an extension to the sail was built. This increased the height of the sail to 18 ft., and increased the area from 30 ft.^{2} to 54 ft.^{2} (Figs 1 and 7). The extension was built using conventional glider construction but with a solid nose and fabric covering the rear 70% of the chord: thus static balance was achieved locally at all sections and the wing mass per unit area was reduced to about one lb. per ft.^{2}.

The wing sail was mounted above a small deck which held the two ball bearings in which the wing rotated about its quarter chord line. The trim tail angle was set manually against interchangeable stops which provided tail angles $i_t = \pm 2\ 1/2°$, $\pm 5°$ and $\pm 7\ 1/2°$. The deck was mounted upon an available 16 ft. Chestnut canoe* and leeboards were attached to each side such that the quarter chord lines of the leeboards and wing were coplanar. The deck was clamped to the hull of the canoe and could be moved fore and aft to alter the longitudinal trim. Two outriggers with low wave drag (fineness ratio= 0.07) were mounted on two 1 1/2 ins. dia. aluminum tubes 6 ft. on either side of the centre line, to provide adequate lateral stability and to reduce the angle of roll as much as possible. A hand-held paddle served as rudder.

The craft is shown schematically in Fig. 6 and photographically in Figs. 7 a) and b). Further details of the construction are given in the Appendix.

3-4 Sailing Experience

The boat was easy to sail and adequately manoeuverable. Once the trimming sail was set for the particular tack, the sail required no further attention and the rudder forces were quite small to maintain any particular course. The outriggers provided good lateral stability although the boat rolled noticeably when the waves were about 1 ft. high and the forward speed was low. In this condition the wing-sail oscillated at the rolling frequency with an amplitude of about 5 degrees. This is attributed to a lack of dynamic mass balance i.e. the product of inertia of the sail about the pivot line and the roll axis was not zero.

Preliminary measurements of the relative wind and water speeds indicated that the performance was not as good as had been anticipated. Moreover the performance with a tail angle $i_t = \pm 7\ 1/2°$ was just as good as that with $i_t = \pm 5°$, despite the fact that the model tests indicated that the wing was stalled in the former case. Tufts attached to the wing indicated that the wing was stalled part of the time in <u>both cases</u>, but with more time stalled at $i_t = \pm 7\ 1/2°$. This intermittent stalling is attributed mainly to the wing oscillation due to roll, but is also due partly to the inability of the wing to respond quickly enough to changes in wind direction. Thus the wing was below the stall part of the time even when the tail angle was 7 1/2°. It is possible therefore that although the mean drag was higher with $i_t = \pm 7\ 1/2°$, the mean lift was also higher resulting in a similar forward driving force for the two tail angles. Since it is desirable to obtain near-maximum C_L without even intermittently increasing C_D due to incipient stalling, it is apparently most important to balance the wing dynamically, and also have a value of the inertia parameter A which is large and comparable with four times the static stability parameter B.

The sail angle was measured when the boat was just hove to at zero forward speed into wind. This measurement was made with both the original sail (30 ft.^{2}) and the extended sail (54 ft.^{2}). Assuming the wing was operating at C_L max. with $i_t = \pm 7\ 1/2°$, these measurements gave values for the aerodynamic drag of the wing and the aerodynamic drag of the hull and occupants. The calculated aerodynamic drag coefficient of the wing was 0.22 indicating a stalled wing on the average. The aerodynamic drag of the hull and occupants was equivalent to a side area of 18.5 ft.^{2} assuming a bluff-body drag coefficient of one for these components. Bearing in mind the existence of the boundary layer structure of the wind, the latter value is plausible (Fig. 1) and about half of it is due to the two occupants (see Fig.1). It is clear that some effort should be made to reduce this source of drag in future designs.

The performance was greatly improved by the extension of the sail from 30 ft.^{2} to 54 ft.^{2}. Under similar close-hauled conditions (about 60° to the relative wind) the water speed increased from some 3 m.p.h. to 5 m.p.h. at a relative wind speed of 12 m.p.h. Furthermore under these conditions rolling oscillations were reduced and the sail angle was judged to be sufficiently steady for force measurements to be made.

The boat was somewhat difficult to transport. At least two cars, one a station wagon, were required to move the dismantled boat. Hence a trailer is desirable for mobility. In light winds and after some practice, the boat could be rigged by two people in less than one hour. It is evident however that with a larger sail a collapsible crane would almost be a necessity for rigging the boat. This crane could be part of the trailer.

The tests indicated that the outriggers, ball bearings and trimming tail were all satisfactory features of the design.

4. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

It has been demonstrated that a sailboat with a self-trimming solid wing sail will operate satisfactorily and our experience suggests that conditions can be sufficiently steady for the sail force to be measured.

The outriggers with fine entry, the ball bearing supports for the wing and the trimming tail were all satisfactory features of the present design. The performance was however affected by the comparatively high aerodynamic drag of the hull and occupants and it was also apparent that more attention must be paid to the dynamic stability of the wing and the prevention of incipient wing stall.

It is concluded that a self-trimming sailboat should have:

i) A wing sail with low moment of inertia about the pivot axis and zero product of inertia about the pivot and roll axes. It should be noted that no full-scale boat has so far incorporated the latter feature.

ii) The trimming tail should be designed and positioned so that the wing is statically stable and so that the inertia parameter A is as large as possible.

iii) The hull should be fine with sharp entry and be fitted with one or two outriggers. The aerodynamic drag of the hull should be reduced as much as possible and the crew should be seated within the hull.

iv) The relative wing-sail area should be increased.

v) The craft should be collapsible, and should be transported by trailer. The trailer should be fitted with a light crane to assist in the erection of the sail.

Our analysis of the sail forces, and of the static and dynamic stability of the sail are in reasonable agreement with the model tests, and appear to be sufficiently sophisticated for the purposes of initial design and the prediction of performance.

It is suggested that the work should be continued by building a fully instrumented craft with a fully mass-balanced, self-trimming sail, about 120 ft.^{2} in area. This would be of glider construction with a trimming tailplane and would be mounted above a single slender hull (one hull of a high performance catamaran is proposed) fitted with an alternative arrangement of one or two outriggers. The centre board should be adjustable to give mean leeway angle under sail. The measurements would be photographically recorded and would include the forward and lateral components of sail force transmitted to the hull, the sail angle, the tail angle, the centre-board angle, the rudder angle and the relative wind and water velocities.

APPENDIX

The purpose of this Appendix is to describe the detailed construction of the boat and the difficulties which were encountered.

The wing was constructed with a fibreglass skin covering a buoyant core. The core was made of Styrafoam (4 lbs./ft.^{3}) slabs glued to form a wedge ten feet long with slightly larger cross section than the rear 75% of the desired aerofoil section (NACA oo12). The wedge was filed with a very coarse rasp and sanded to the correct shape. It was then cut into three spanwise lengths. Two 1/8 inch thick marine plywood ribs served as solid end pieces for the wing and two others were sandwiched between the three lengths of Styrafoam to act as supports for the tail booms. A two inch diameter aluminum tube which formed the pivot axis was anchored at the 1/4 chord line of the aerofoil section to the two lower ribs in solid wooden blocks. A four foot long 1 1/4 inch dia. steel pipe was also secured to the two lower ribs near the leading edge. This was filled with lead shot when the wing was mass balanced. The space between the two pipes and the ribs was then filled with Styrafoam slabs which were finished to the desired contour. The whole wing was then covered with fibreglass. Thus a buoyant and rugged wing sail was obtained.

The construction of the sail was not as simple as expected. It was difficult to shape the Styrafoam. Small chunks of the material broke off at several places during filing leaving depressions which had to be filled and smoothed before the wing could be covered with fibre-glass. The weight of the wing, having an area of 30 ft.^{2}, was 100 pounds. This included the lead shot balance weight contained in a streamlined sheet-metal fairing which was mounted at the leading edge near the bottom of the sail.

The eight foot sail extension (Fig.1) was built with a laminated plywood leading edge designed to carry the loads in bending and torsion. Light wooden ribs spaced at 1 foot intervals were glued to the leading edge. A light plywood trailing edge was provided and the resulting structure was covered with fabric which was then doped. Thus the extension was locally mass balanced about its pivot axis, and its weight was somewhat less than one pound per square foot of sail area. The extension was attached to the original sail by means of metal dowels and bushings.

The tail (NACA 0015 section) was made of very light construction. Ribs, spaced at 6 in. intervals and drilled to reduce their weight, were connected by light leading and trailing edges and a spar ; these were all made of 1/16 inch thick plywood. The spar was stiffened by four wooden 1/8 inch square strips to form flanges top and bottom. Brass studs for pivoting were anchored to the spar and to the end ribs in hardwood blocks. The framework was covered by 1/32 inch thick aircraft plywood. The complete tail of area 3 $ft.^2$ weighed 1.3 pounds.

The tail booms were made of mahogany with a cross section of 1/4 inch x 1 inch oriented to resist side loads, some of the vertical load being carried by a thin diagonal nylon bracing rope. The tail pivot studs rotated in brass bushings . Simple interchangeable stops could be attached to the lower boom to limit the tail angle to $\pm$ 2 1/2°, $\pm$ 5° $\pm$ 7 1/2°. The tail booms were attached to extensions to central wing ribs by brass machine screws. The arrangement was satisfactory. It was found, however, that the plywood ribs were crushed after the tail booms have been mounted several times. The insertion of metal bushings or the use of metal tabs is desirable at these joints.

Two short stainless steel sleeves were mounted on the aluminum wing pivot axis to support two 55 mm i.d. x 90 mm o.d. ball bearings. The general arrangement of the wing tail combination is shown in Figure 2.

A strongly braced plywood deck supported the sail bearings, the outrigger booms, and the two leeboards. The side forces and rolling moments produced by the sail were therefore directly transmitted to outriggers and leeboards. The bearing supports in the deck were made of solid maple and the fit between bearings and the wooden blocks was a push fit. When the boat was at anchor with the wing sail in position, and the boat rolled with the waves the bearings rapidly enlarged the holes in the maple blocks. The wooden blocks were therefore bored out to take metal lines which were bolted and glued in place. The fit between bearings and metal lines was a push fit. This arrangement was very satisfactory.

The leeboards had elliptical plan form with NACA oo12 section and were designed to operate at a C_L less than 0.3. They were made of 1/2 inch thick marine plywood, could be rotated about bolts which fastened them to the deck, and they were firmly supported in a slot when lowered into the water.

The outrigger booms, 1 1/2 inch dia x 13 ft. long aluminum tubes, were pushed through tightly fitting holes in the upper portion of the deck. They were anchored in place very simply by wrapping them with friction tape on both sides of the deck.

The outriggers were 99 inches long with cross section in the form of an equilateral triangle, the sides of which were a maximum of 7 inches. The keel line in profile was a segment of a circle. Consequently the outriggers were symmetrical fore and aft, and the fineness ratio varied only slightly with depth of immersion. The outriggers were constructed of 1/8 inch plywood on a frame of 1/4 inch plywood ribs and 3/4 inch wooden keel and corner longerons. The outrigger booms were attached to two 3/4 inch plywood ribs which extended through the outrigger deck. To provide additional buoyancy a 3 inch thick slab of Styrafoam having a rectangular cross section was glued to the top of the deck. The wooden structure and Styrafoam were then covered with fibreglass. The weight of each outrigger was about 12 lbs.

The sail was erected by assembling the boat in the following manner. The sail was stood on its leading edge in cradles, the deck with the bearing supports was pushed over the sail pivot bearings, and the trim tail was mounted. Then the canoe was laid on its side in a few inches of water and the deck was clamped in position. The two outrigger booms were pushed into the deck and were used as levers for righting the boat. When the canoe and sail were in the upright position the outrigger booms were pushed through the deck and the outriggers were mounted. Finally the outrigger booms were taped in position and the leeboards were attached. After some practice this could be accomplished by two people in light winds in about an hour.

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TABLE I

WING - SAIL PARAMETERS

	MODEL	FULL SCALE PROTOTYPE
a_t estimated	4.06	4.06
S_t ft.^{2}	0.0469	3.0
l_t ft.	0.4875	3.9
I slug - ft.^{2}	0.00073	3.45
A	0.0358	0.25
B	0.42	0.42
Amplitude ratio after one cycle	0.398	0.27
Period sec. at U = 10 m.p.h.	1.7	5.6
20 " " "	0.86	2.8
Time to damp to 1/2 amplitude sec.		
at U = 10 m.p.h.	1.29	1.46
20 " " "	0.65	0.73

BOAT PROFILES

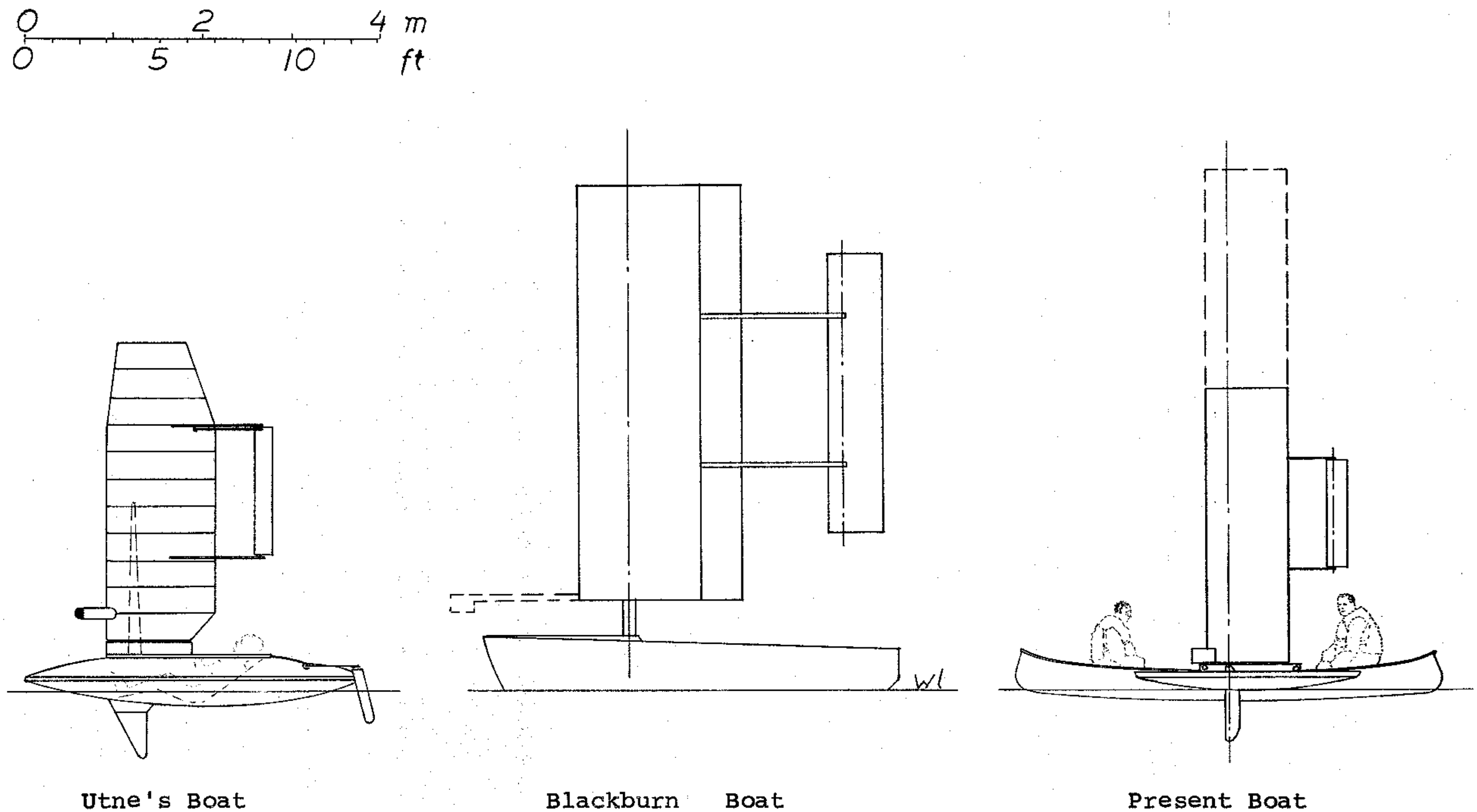


Fig.1

WING-SAIL DETAIL

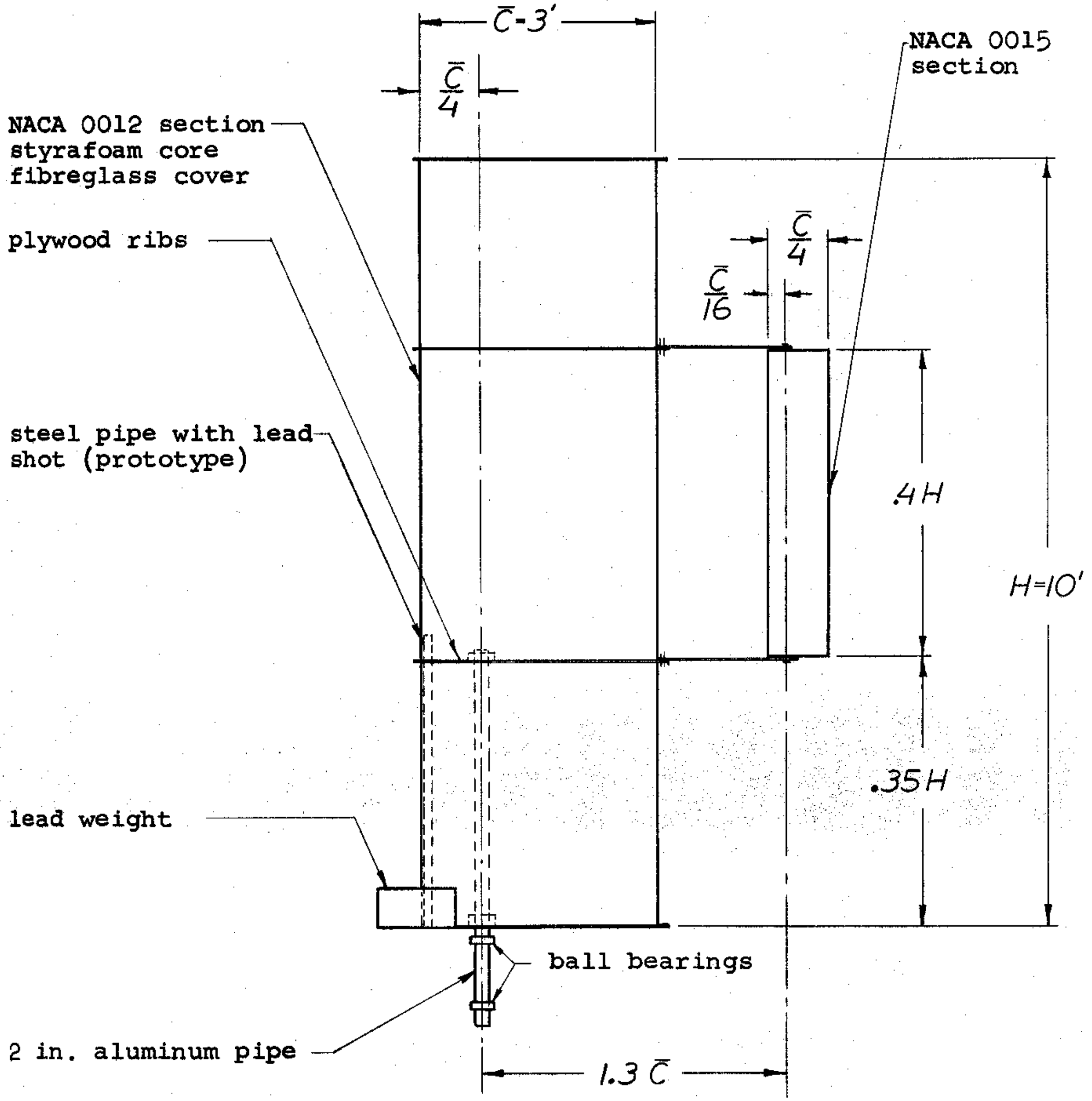
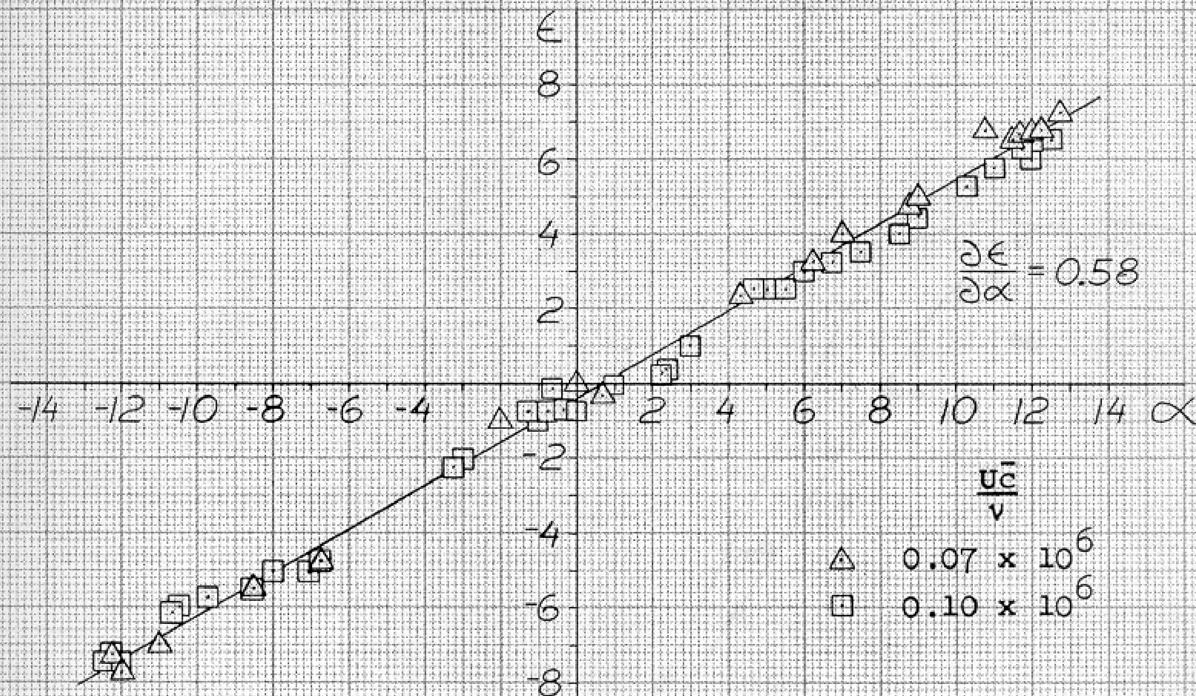


Fig.3

Downwash at Tail vs. Angle of Attack



Tail Setting Angle vs. Angle of Attack

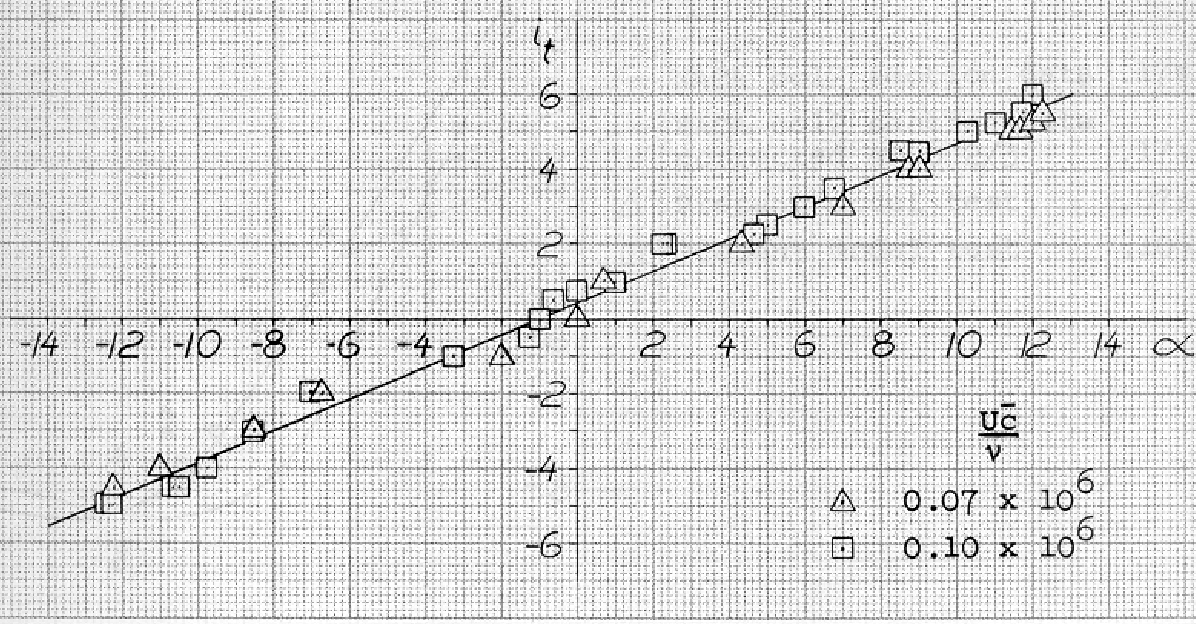


Fig.4

Lift Coefficient vs. Angle of Attack

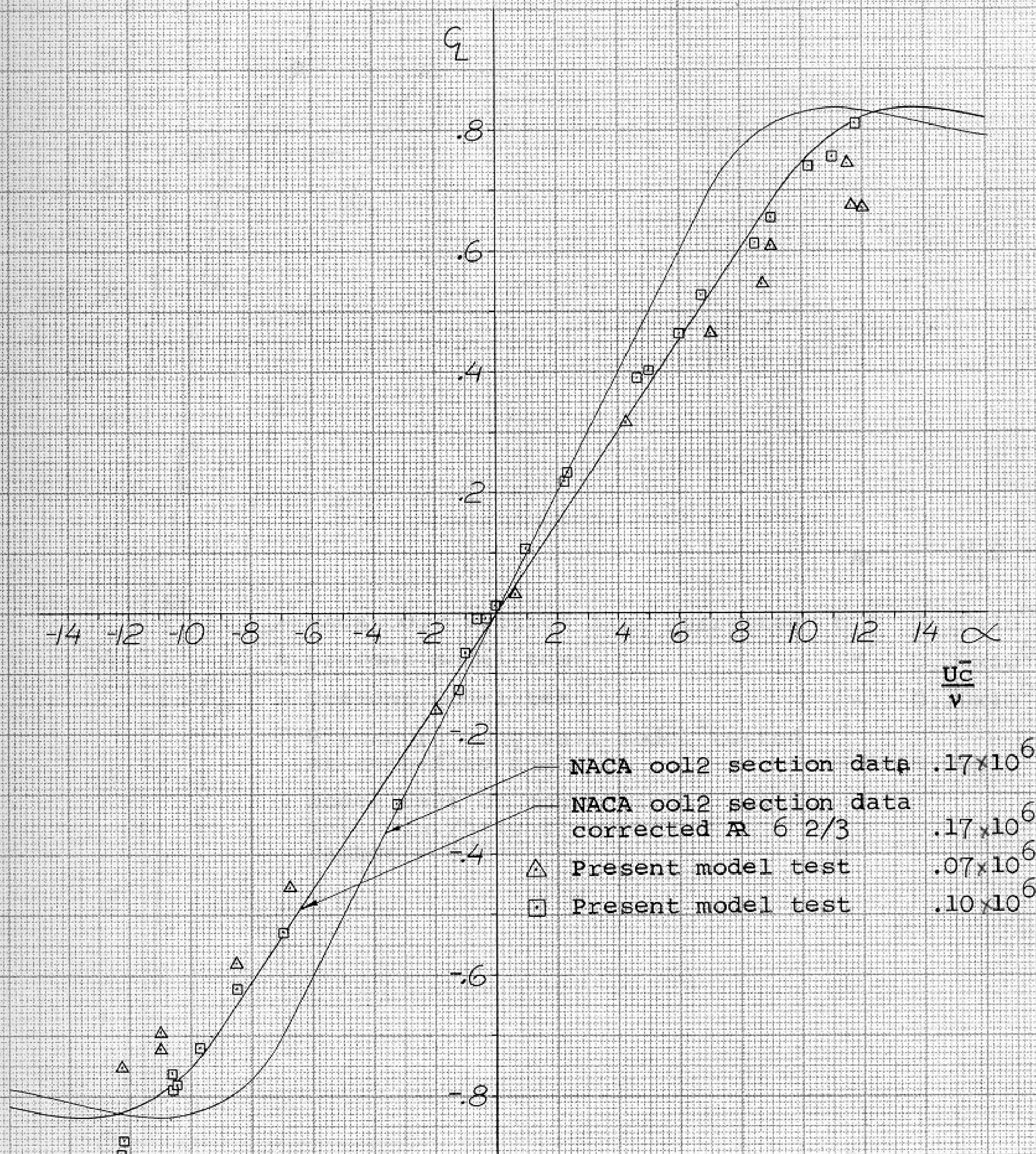
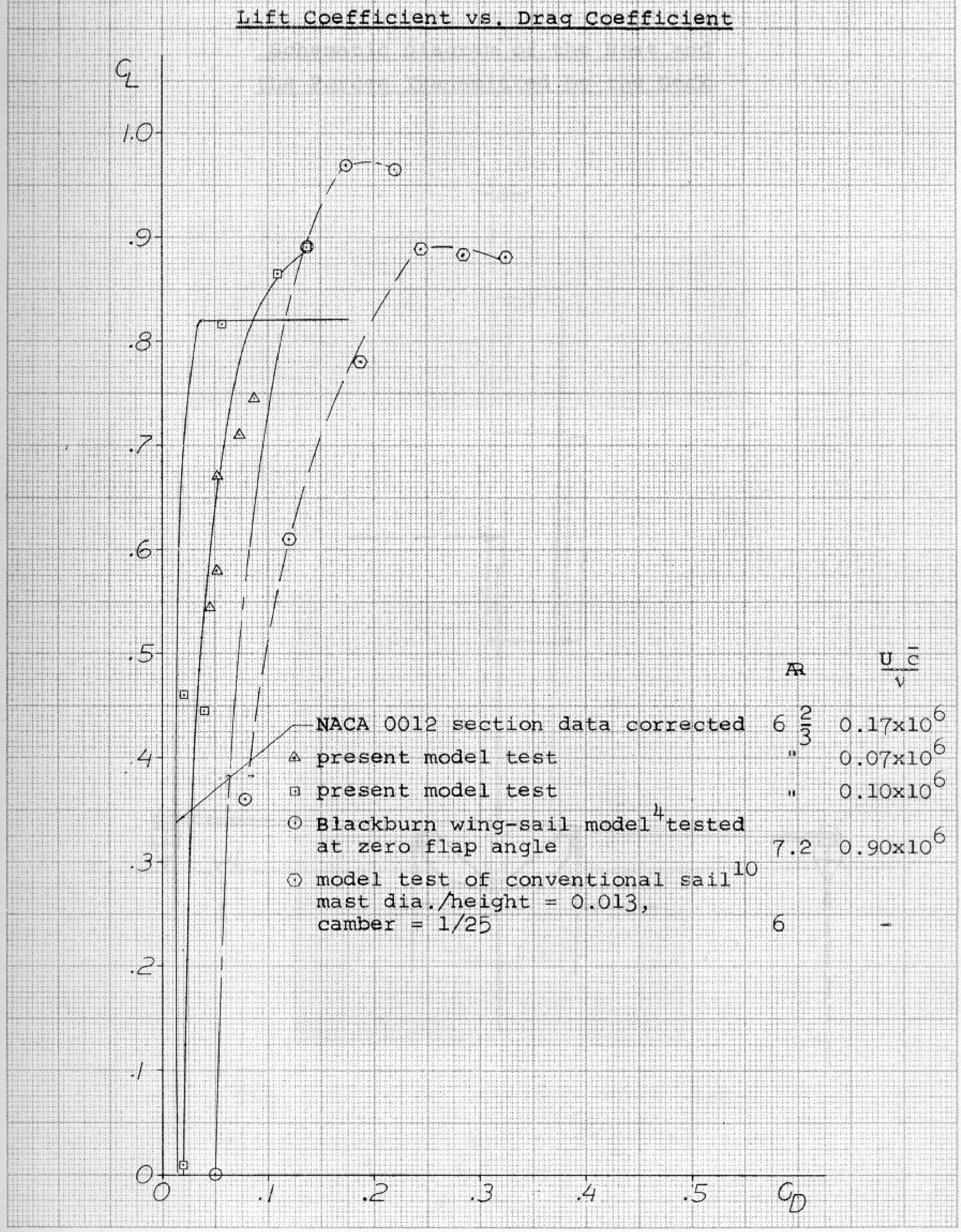
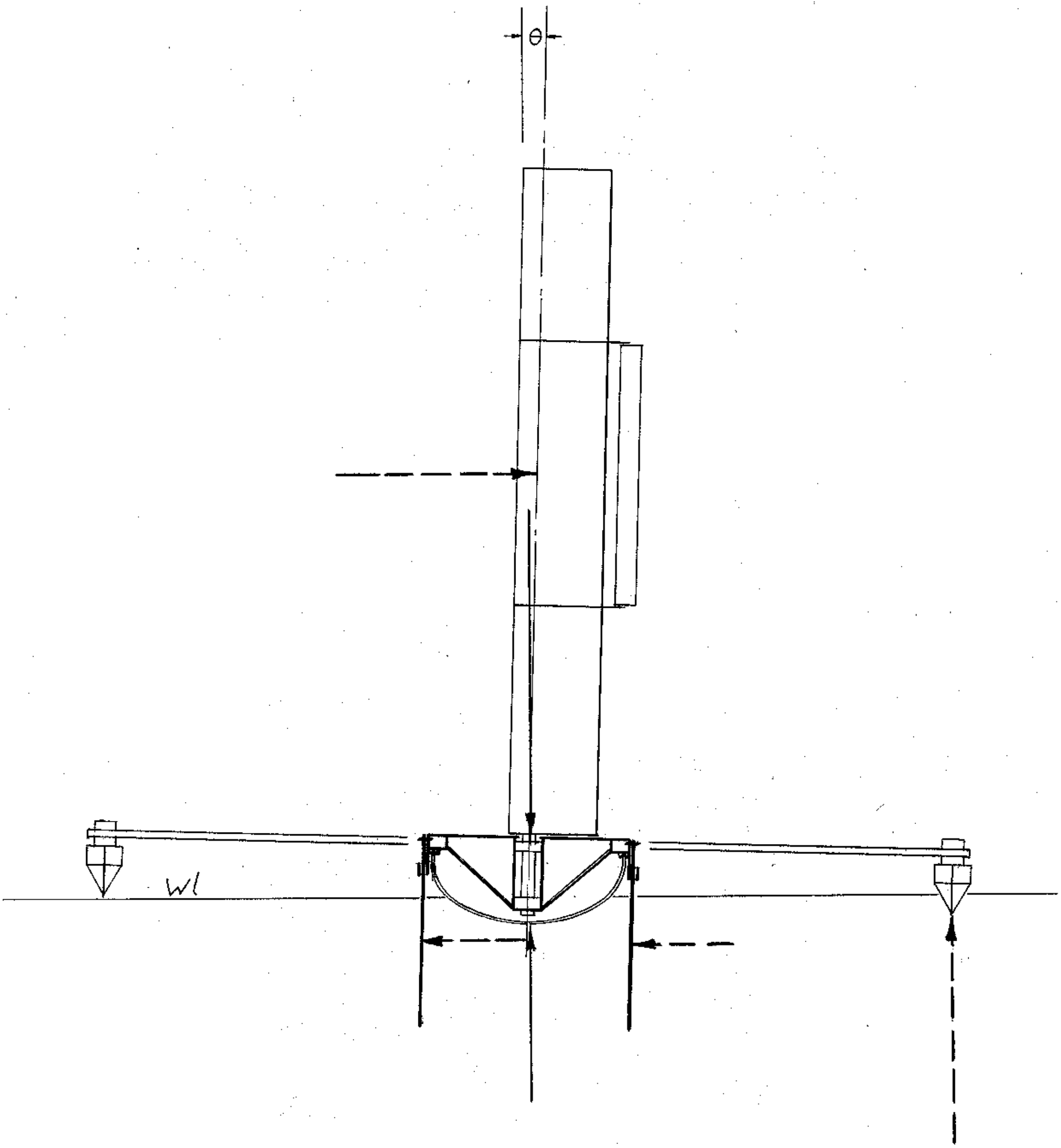


Fig.5



Lift Coefficient vs. Drag Coefficient
C_L
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
C_D
AR
$\frac{U \bar{c}}{\nu}$
NACA 0012 section data corrected 6 2/3 0.17x10^6
present model test " 0.07x10^6
present model test " 0.10x10^6
Blackburn wing-sail model[4] tested at zero flap angle 7.2 0.90x10^6
model test of conventional sail[10] mast dia./height = 0.013, camber = 1/25 6 -

Schematic Diagram of the Boat and the Forces Transmitted by the Deck



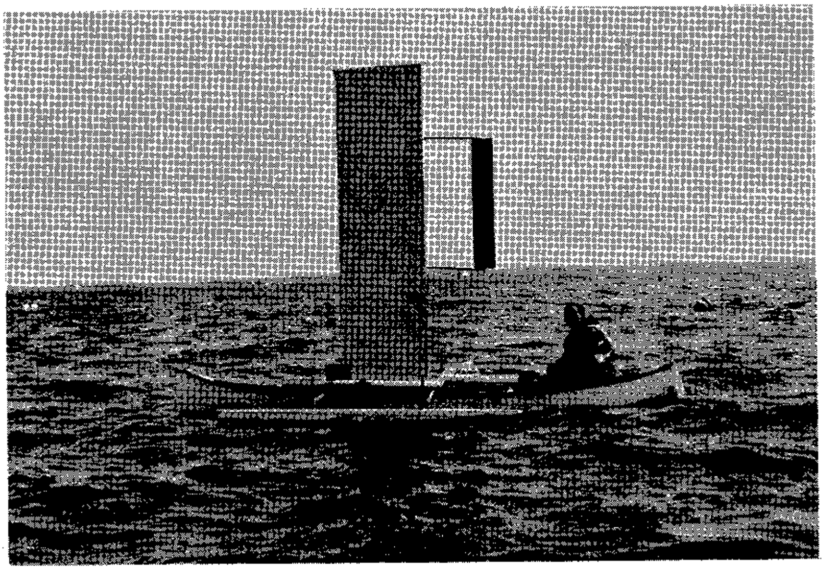


Fig. 7 a 16 ft. outrigger canoe with self-trimming wing sail of 30 ft. sq. area

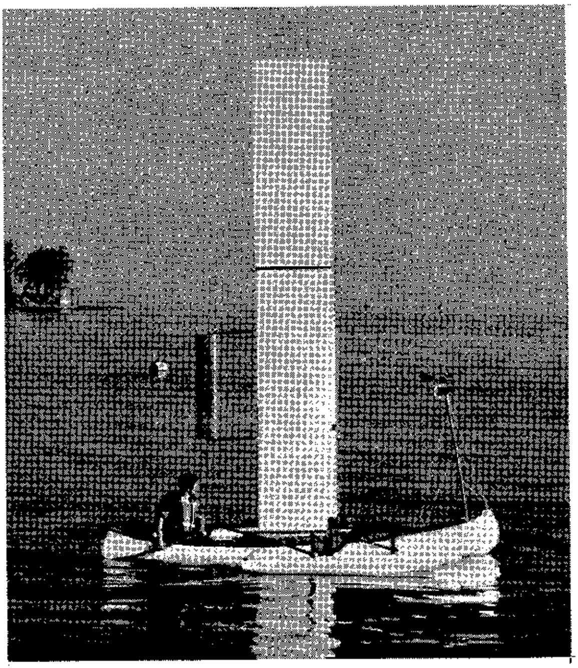


Fig. 7 b 16 ft. outrigger canoe with self-trimming wing sail of ~~50~~ 54 ft. sq. area