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THE PREDICTION OF
FLAP-CONTROLLED HYDROFOIL SHIP
STEADY STATE PERFORMANCE

DREA TECHNICAL MEMORANDUM 75 /A

RESEARCH AND DEVELOPMENT BRANCH
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THE PREDICTION OF FLAP- CONTROLLED HYDROFOIL SHIP STEADY STATE PERFORMANCE

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ABSTRACT

A method is presented for prediction of the steady state performance characteristics of craft with hydrofoil systems of the fully-submerged type. The principles have fairly general application but the emphasis is on a canard hydrofoil system of type and size suitable for open ocean operation. Considerable use is made of empirical expressions, with some discussion of their underlying physical basis. Limited comparison is made with experimental data.

SOMMAIRE

On présente une méthode de prédiction des caractéristiques de performance d'un hydroptère, à vitesse constante, cap en avant, par temps calme, les ailes entièrement submergées. Les principes sont d'une applicabilité asses générale, mais on met l'accent sur l'hydroptère "canard", de modèle et de dimensions convenant à l'exploitation en pleine mer. On s'appuie dans une grande mesure sur les expressions empiriques, tout en abordant leur fondement théorique. On fait quelques comparaisons avec les données expérimentales.

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NOMENCLATURE

(See Figures 2, 3, 4 & 5 for identification of suffixes)

Lower Case

a'_0	theoretical section lift curve slope
b	projected foil span
b_f	projected flap span
c	foil chord
d	pod diameter
f_b	flap span ratio
f_c	flap chord ratio
g	standard gravitational acceleration
h	foil depth of immersion
i_1	foil incidence setting above zero lift angle
ℓ_F	foil base length
ℓ_P	length of pod
ℓ_s	projected strut length
n_s	number of pods
q	dynamic pressure = $\frac{\rho V^2}{2}$
t	section thickness
x	x coordinate measured forward from cg
y	y coordinate measured to port from cg
z	z coordinate measured upwards from cg

Upper Case

A	aspect ratio
B	buoyancy
C_{DH}	coefficient of air drag for hull
C_{DI}	coefficient of induced drag
C_{DP}	coefficient of profile drag
C_{DS}	coefficient of spray drag
C_F	coefficient of friction drag
C_{PF}	form factor for profile drag
C_l	section operating lift coefficient
C_{li}	ideal section design lift coefficient
C_{lo}'	practical uncorrected design lift coefficient
C_{lo}	depth-corrected design lift coefficient
C_L	foil operating lift coefficient
C_{L_α}	foil lift-curve slope
C_M	foil moment coefficient
C_{m_δ}	rate of change of moment coefficient with flap deflection
C_{PD}	pod profile drag coefficient
D_A	air drag of hull
E	edge correction factor
F	Froude number
F_D	induction factor for drag
F_α	induction factor for angle
H_b	hull depth from main superstructure top to keel
H_w	maximum hull width

K_a	depth correction factor for section lift-curve slope
K_e	section efficiency factor
K_f	depth correction factor for two-dimensional flap effectiveness
K_o	depth correction factor for section lift coefficient
L_n	total lift due to foil element n
M	foil pitching moment
R	Reynolds number
S	projected foil area
S_f	projected foil area in way of flaps
U	ship speed
W	ship weight

Greek

α	angle of attack
α_δ	foil flap effectiveness
$\alpha'_{\delta o}$	uncorrected two dimensional flap effectiveness
$\alpha_{\delta o}$	depth-corrected two dimensional flap effectiveness
α_i	initial foil incidence setting
α_0	depth-corrected zero lift angle
α_I	induced angle
γ	Breslin's wave function
δ	flap angle
ε_B	net downwash angle at bow foil
ζ	auxiliary function used in establishing induction factor
η	auxiliary function used in establishing biplane factor and wave function

λ	foil taper ratio
μ	flap correction factor
ν_{α}	Glauert's planform factor for lift
ν_{D}	Glauert's planform factor for drag
ρ	density of water
ρ_{A}	density of air
σ	Prandtl's biplane factor
τ	ship trim
ϕ	section trailing edge angle
ω_{b}	downwash velocity at bow foil
Ax	distance of center of pressure aft of quarter chord
Ah	difference in depth between bow and main foils at zero trim
ΔC_{F}	coefficient of friction drag increment due to surface roughness
Λ	quarter chord sweepback angle
Γ	foil dihedral angle (to horizontal)
Γ_{1}	strut slant angle (to vertical)

1. INTRODUCTION

The accurate prediction of the steady state characteristics of hydrofoil ships is fundamental to the success of early planning in a development program. It is essential to forecast, with reasonable confidence, range capability and power requirements in order to determine the size of ship required for a given operational application and to make objective comparisons with other vehicles. At a later stage in the design process, accurate prediction techniques can lessen dependence on an extensive model test program and greatly improve the understanding of the model test results.

The objective here is to obtain an overall appreciation of the characteristics rather than detailed hydrodynamic analysis of a particular hydrofoil configuration. The prediction methods are based largely on empirical expressions and in consequence, apply primarily to the particular hydrofoil system chosen in this case, a propeller driven, canard arrangement, generally typical of current military hydrofoil design and suitable for fairly wide ranges of size and speed. There often exists a theoretical basis for the empirical expressions, making it possible, with care, to extend the methods to other practical design cases.

The hydrofoil system is first described and expressions derived to define the geometry. The hydrofoil section characteristics are then treated, with expressions given for the lift, pitching moment and drag for the section operating in two-dimensional flow, close to the water surface. The more practical case is then given of a wing of finite span operating in three-dimensional flow close to the water surface. Various miscellaneous drag effects are also considered. The generalised lift balance and moment equations are given for the foilborne, steady state case, with reference to the way in which the expressions for lift and moment are incorporated. Finally, in an appendix, the use of the expressions is demonstrated by determining the flap angles required and the total resistance for given speeds and foil depths of immersions.

The method has limitations. There is little information available on the characteristics of sections with simple, sealed flaps. Increase in lift with flap angle is probably not linear, although that is the assumption here. Also, it is assumed that the flow is cavitation free. The method is thus good for only small flap and trim angles and for the normal foilborne speed range. In particular, take-off drag would require special study. Resistance estimates are generally harder to make than lift, being dependent for example, on quality of manufacture and intersection design details.

Unfortunately there are very few experimental data available from full scale hydrofoil ship trials, allowing no comparison of flap angles and only limited comparison with resistance estimates. Nevertheless, the methods outlined here are thought suitable for preliminary estimates and it is anticipated that some refinement will be possible as further model and full scale trials data become available.

2. FOIL AND SYSTEM GEOMETRY

2.1 GENERAL CONFIGURATION

The hydrofoil arrangement is assumed to be canard in form, as shown in Figure 1, with the "inverted T" bow foil supporting less than 35% of the all up weight. The bow foil is continuous and horizontal with a planform which employs both taper and sweep. It has constant angle of attack and constant thickness-to-chord ratio (t/c). Lift is varied by a flap with constant flap-chord ratio.

A two-strut main foil supports the remaining ship weight. It is composed of two anhedral elements joined at the centre to form an "inverted V". Angle of attack and the t/c are constant over its length and the foil has taper outboard of the support struts. Flaps are full-span, except for necessary breaks at intersections. They have constant flap-chord ratio and zero sweep angle at the flap hinge lines.

The main foil struts are inclined to the vertical with a chord and t/c which vary continuously over their lengths. Propulsion is by marine screw propellers located with fairly large transmission pods at the main foil-strut intersections.

2.2 FOIL PLANFORM GEOMETRY

The planforms are shown in Figure 2. Geometrical relationships are straight forward for the -most part and are given here for definition and completeness. It should be noted that all these expressions are for the main foil geometry but reduce to the equivalent bow foil expressions when the main foil span between struts, b,, becomes zero.

Taper Ratio

$$\lambda = \frac{c_2}{c_1} \qquad (2.1)$$

Flap Chord Ratio

$$f_c = \frac{c_{f1}}{c_1} = \frac{c_{f2}}{c_2} \qquad (2.2)$$

Foil Span

$$b = b_1 + 2b_2 \qquad (2.3)$$

Projected Foil Area

$$s = b_1 c_1 + b_2 c_1 (1 + \lambda) \qquad (2.4)$$

or

$$s = S_1 + 2S_2$$

where S_1 is the area inboard of the main struts

S_2 is the area of each outboard element

Projected Foil Area in way of Flaps

$$S_f = S - c_1 \; [b - 2(b_{f_1} + b_{f_2})] \qquad (2.5)$$

Angle of Sweep

For the particular case considered, with the flap hinge lines arranged to have zero sweep angle, the angle of sweep for the outboard elements is given by:

$$\Lambda = \tan^{-1} \frac{c_1}{b_2} \left(\frac{3}{4} - f_c\right)(1 - \lambda) \qquad (2.6)$$

Net Angle of Sweep

For the composite foil

$$\Lambda = 2\frac{S_2}{S}\tan^{-1} \frac{c_1}{b_2}\left(\frac{3}{4} - f_c\right)(1 - \lambda) \qquad (2.7)$$

Mean Depth

For the integrated main foil unit shown in Figure 2, elliptical lift distribution is assumed over the outboard spans, b_2, giving the effective hydrodynamic depth:

$$h = h_1 + \tan\Gamma\,(0.25b_1 + 0.405b_2) \qquad (2.8)$$

$$\text{for } 0.25b_1 < b_2 < 0.56b_1$$

Mean Chord

$$c = \frac{S}{b} \qquad (2.9)$$

Lateral Centre of Pressure

The lateral distance of the centre of pressure of an outboard element from the axis of intersection is given by:

$$y = \frac{b_2}{2}\left[1 - \frac{L}{3}\,\frac{O}{(1+\lambda)}\right] \qquad (2.10)$$

Longitudinal Centre of Pressure

The distance of the centre of pressure of an outboard element aft of the quarter chord point of the centre section is given by:

$$Ax = \frac{y}{S}\, b_2 c_1 (1 + A) \tan A \qquad (2.11)$$

Aspect Ratio

The aspect ratio of the main foil is effectively increased by the presence of the struts which act as "end plates" to reduce spanwise flow. Effective aspect ratio is dependent on the spanwise position of the struts and on the foil depth. It can be derived from expressions given by Hoerner[1] as:

$$A = \frac{b}{c} \left[1 + \left(\frac{b_1}{b}\right)^3 \frac{h}{b}\right] \qquad (2.12)$$

Foil Buoyancy

$$B_F = 0.7\, c \frac{t}{c}\, ps \qquad (2.13)$$

2.3 STRUTS AND PODS GEOMETRY

The strut and pod geometries common to both bow and main foil assemblies are shown in Figure 3. The strut span is assumed to extend to the foil axis of intersection which is taken to be coincident with the pod axis.

Mean Immersed Chord

$$c_m = c_{s_2} + \frac{h_1}{2\ell_s} (c_{s_1} - c_{s_2}) \qquad (2.14)$$

Chord at the Waterline

$$c_w = c_{s_2} + \frac{h_1}{\ell_s} (c_{s_1} - c_{s_2}) \qquad (2.15)$$

Mean Immersed Thickness - Chord Ratio

$$\left(\frac{t}{c}\right)_m = \left(\frac{t}{c}\right)_{s_2} + \frac{h_1}{2\ell_s} \left[\left(\frac{t}{c}\right)_{s_1} - \left(\frac{t}{c}\right)_{s_2}\right] \qquad (2.16)$$

Waterline Thickness - Chord Ratio

$$(\frac{t}{c})_w = (\frac{t}{c})_{s2} + \frac{h_1}{\ell_s}\left[(\frac{t}{c})_{s1} - (\frac{t}{c})_{s2}\right] \quad (2.17)$$

Immersed Strut Area

$$S_s = \frac{c_m h_1}{\cos \Gamma_S} \quad (2.18)$$

Immersed Strut Buoyancy

$$B_s = 0.7 S_s c_m (t/c)_m \quad (2.19)$$

Pod Frontal Area

$$S_P = 0.25\,\pi d^2 \quad (2.20)$$

Pod Buoyancy

Using a Prismatic Coefficient of 0.7,

$$B_P = 0.55\,\rho\, d^2\, \ell_P \quad (2.21)$$

2.4 AXIS OF COORDINATES

The axis system is shown in Figure 4. It is taken as fixed with respect to the ship, has its origin at the center of gravity and polarities as shown. Coordinates are measured to the quarter chord points of the foils but forces are assumed to act at the centers of pressure, which are not necessarily in the same location.

2.5 SHIP GEOMETRY

Foil Base Length

$$\ell_F = x_B - x_M \quad (2.22)$$

Ship Trim

$$\tau = \frac{h_{1M} - (h_B + \Delta h)}{\ell_F} \quad (2.23)$$

Bow Foil Depth

$$h_{1B} = h_{1M} - \Delta h - \tau \ell_F \qquad (2.24)$$

3. SECTION CHARACTERISTICS

3.1 SECTION TYPE

It is assumed that an NACA section of the 16 Series will be used with a uniform-load mean line and a thickness-to-chord ratio of 10% or less. The 16 Series sections have found several applications in hydrofoil design. Little is known about the section characteristics with a flap but the uniform pressure distribution of the unflapped section should give good cavitation characteristics and the section offers the best basis for design at present.

3.2 LIFT-CURVE SLOPE

A general expression for the section lift-curve slope is given in Reference 2 in terms of t/c and the included angle at the section trailing edge, ϕ (degrees), as:

$$a''_0 = 2\pi + 4.7 \left(\frac{t}{c}\right) (1 + 0.00375\phi) \qquad (3.1)$$

The relation between ϕ and t/c for 16 Series sections is:

$$\phi = 238 \ (t/c)$$

so that for these sections:

$$a''_0 = 2\pi + 4.7 \ (t/c) + 4.18 \ (t/c)^2 \qquad (3.2)$$

Lift-curve slope is reduced in practice by viscous effects which increase the boundary layer thickness in the area of adverse pressure gradient, particularly towards the trailing edge. This results in an efficiency factor dependent on Reynolds Number, R, and trailing edge angle, ϕ, which must be applied to Equation 3.2. The efficiency factor can be derived from curves given in Reference 2 as follows:

$$K_e = 1.25\ (6.8)^{-\frac{1}{\log_{10} R}} - 6.92\ (t/c)\ R^{-0.09} \qquad (3.3)$$

For infinite depth, section lift curve slope then becomes:

$$a''_\infty = K_e\ [2\pi + 4.7\ (t/c) + 4.18\ (t/c)^2] \qquad (3.4)$$

In the hydrofoil case, the presence of the free surface modifies the section flow and reduces the lift curve slope appreciably for submergences below one chord. Bernicker[3] gives a theoretical treatment of two dimensional depth effects from which an approximate expression for the depth correction can be derived as:

$$K_a = \frac{20(h/c)^2 + 1}{20(h/c)^2 + 2} \qquad (3.5)$$

Hence, the expression for section lift curve slope for horizontal, unswept hydrofoils operating near a free surface becomes:

$$a'_0 = K_a\ K_e\ [2\pi + 4.7\ (t/c) + 4.18\ (t/c)^2] \qquad (3.6)$$

The effective section characteristics are modified by dihedral or anhedral angle, I', of the foil. Angle of attack changes due to ship trim or foil setting angle are measured in the vertical plane so that the effect of dihedral is to introduce the factor cos Γ, reducing the section lift curve slope. Sweep angle, A, also affects the characteristics. The effective angle of attack, measured normal to the quarter chord line, is increased by introduction of the factor cos A while the speed over the section is decreased by the factor cos A. In detail, lift per unit area, L/S, is given by:

$$\frac{L}{S} = \frac{1}{2}\rho\ (V\cos\Lambda)^2\ a'_o\ (a \sec A \cos \Gamma) \qquad (3.7)$$

Hence, the effective section lift curve slope becomes:

$$a_0 = K_a K_e\ [2\pi + 4.7\ (t/c) + 4.18\ (t/c)^2]\ \cos A \cos A \qquad (3.8)$$

3.3 LIFT COEFFICIENT

NACA 16 Series airfoils, in common with other sections using a uniform - load type (a = 1.0) mean line, do not achieve in practice lift coefficients as high as the idealized design values. Lindsey et al[4] give the following empirical relation for 16 Series sections:

$$C'_{\ell o} = C_{\ell i} [1 - 5 (t/c)^{1.35}] \qquad (3.9)$$

where $C'_{\ell o}$ and $C_{\ell i}$ are the practical and ideal design lift coefficients respectively.

Again, in the hydrofoil case, the practical lift coefficient is reduced by flow curvature wihen near the surface. The correction factor can be derived from Bernicker's work[3] as:

$$K_o = \frac{36(h/c)^2 + 1}{36(h/c)^2 + 2} \qquad (3.10)$$

Bernicker also identifies an effect of thickness on the lift of a thin hydrofoil which can be approximated by:

$$\Delta C_\ell = - \frac{0.05(t/c)}{(h/c)^2} \qquad (3.11)$$

Thus, the practical depth-corrected lift coefficient for a 16 Series section is:

$$C_{\ell o} = K_o \, C'_{\ell o} - \frac{0.05(t/c)}{(h/c)^2} \qquad (3.12)$$

It should be noted that the expression for ΔC_ℓ is unbounded, becoming $-\infty$ at h = 0. It is therefore necessary to introduce a limiting value for $C_{\ell o}$ in any computations.

3.4 ZERO LIFT ANGLE

Using Equations 3.8 and 3.12, the depth-corrected zero lift angle is:

$$\alpha_0 = -\frac{C_{\ell o}}{a_0} \qquad (3.13)$$

where α_0 is measured in the vertical fore and aft plane.

3.5 LIFT DUE TO FLAPS

It is assumed that use is made of a plain, sealed, trailing-edge flap with flap-chord ratio, f_c, of less than about 0.3. The effect of flap angle is to modify the incidence and camber of the foil section and consequently, use is made of a flap effectiveness factor, defined as:

$$\alpha_\delta = \frac{da}{d\delta} \qquad (3.14)$$

where α is the angle of attack of the foil section and δ is the angle of flap deflection.

For flap-chord ratios < 0.3, theoretical flap effectiveness is given by:

$$\alpha''_{\delta o} = \frac{4}{\pi}\sqrt{f_c}$$

In practice, experimental data suggest that the empirical expression given by Hoerner[1]

$$\alpha'_{\delta o} = 1.1\sqrt{f_c} \qquad (3.15)$$

gives a better fit and is satisfactory at least for flap angles $< +5°$. Above $5°$, some decrease may be expected due to increasing thickness of the boundary layer. Corrections for trailing edge angle and for section t/c tend to cancel and have not been included.

Bernicker's depth correction for flaps[3] is different from the one given earlier for foils. It can be approximated by:

$$K_f = \frac{G(h/c)^2 + 1}{G(h/c)^2 + 2} \qquad (3.16)$$

where $G = 25\ (1.5 - f_c)$

Since the foil correction factor, K_a, is already included in section lift curve slope (Equation 3.8), flap effectiveness must be modified by the ratio of the two. Section lift-curve slope also includes factors for foil inclination and sweep angles which do not apply to flap effectiveness since the flap hinge line is at zero sweep and flap angle is defined in the plane normal to the foil. It is convenient to compensate for these by re-correcting α_δ. Hence,

$$\alpha_{\delta o} = 1.1 \sqrt{f_c}\ \frac{Kf}{Ka} \sec \Gamma \sec A \qquad (3.17)$$

3.6 EFFECTIVE CAMBER AND INCIDENCE WITH FLAPS

Pitching moment and profile drag are dependent on the proportions of lift due to flap deflection which are appropriate to camber and incidence change. Thin airfoil theory shows that

$$\Delta C_\ell = 26 \sin^{-1} \left(2\sqrt{f_c(1-f_c)}\right) + 4\delta\sqrt{f_c(1-f_c)} \qquad (3.18)$$

where the first term represents the effect of change of incidence and the second term change of camber. These terms are very similar for $f_c < 0.3$ so that flap lift can be taken as equally divided between camber and incidence effects.

3.7 PITCHING MOMENT

The pitching moment of an airfoil section is primarily a function of its camber. For the NACA mean camber line, a = 1.0, used in standard 16 Series sections, quarter chord pitching moment is $-0.25C_{\ell i}$, which depth effects modify in practice to $-0.25C_{\ell o}$.

For a section in a swept, inclined foil, the moment per unit area, measured in the plane of the foil and in the direction of the quarter chord line, is:

$$\frac{M}{S} = \frac{1}{2}\rho\ (V \cos \Lambda)^2\ (c \cos A)\ (-0.25\ a_o')\ (\alpha_o \sec A \cos I')$$

$$= \frac{1}{2}\rho\ (-0.25\ a_o)\ \alpha_o\ c \cos \Lambda$$

In the fore-and-aft plane this becomes:

$$\frac{M}{S} = \frac{1}{2}\rho\ (-0.25 a_o)\ \alpha_o\ c\ \cos^2 \Lambda$$

Hence for a section used in a swept, inclined foil the basic pitching moment is:

$$C_M = -0.25 C_{\ell o} \cos^2 \Lambda$$

In addition, thin airfoil theory shows that the effective camber change due to flap angle deflection gives a moment curve slope of:

$$C_{Mb} = -2\sqrt{f_c (1-f_c)^3}$$

Experimental data suggest that about 80% of this is realised in practice. Since the flap hinge line is unswept and flap angle, 6, is measured in the plane of the foil, sweep and inclination have no effect on this term. Thus the total pitching moment for a section, including sweep and inclination correction terms, becomes:

$$C_M = -0.25\ C_{\ell o} \cos^2 \Lambda - 1.6\delta\sqrt{f_c (1-f_c)^3} \qquad (3.19)$$

4. PROFILE DRAG

4.1 PROFILE DRAG AT IDEAL INCIDENCE

The minimum drag of a hydrofoil or strut profile occurs generally at ideal incidence, i.e. at $C_\ell = C_{\ell_o}$.

The drag is composed of both friction and form drag. Friction drag is primarily a function of Reynolds Number and the standard empirical relationship' for viscous flow over a flat plate, assuming a fully turbulent boundary layer is:

$$C_F = 0.075 \ (\log_{10} R - 2.0)^{-2} \tag{4.1}$$

To this must be applied a form factor which is dependent on thickness-to-chord ratio, camber ratio and the location along the chord of maximum thickness. Hoerner[6] gives a basic section thickness factor of 1.2 (t/c) for "laminar flow" sections like the 16 Series, with maximum thickness at 40 to 50% of the chord. There is an additional pressure drag component which arises from thickening or separation of the turbulent boundary layer at the trailing edge of the section. This comprises a basic section thickness term of 120 $(t/c)^4$ and a section camber term of 60 $(t/c + 0.2\ C_{\ell i})^4$. Thus the form factor for the 16 Series and similar profiles is given by:

$$C_{PF} = 1.0 + 1.2\ (t/c) + 120\ (t/c)^4 + 60\ (t/c + 0.2C_{\ell i})^4 \tag{4.2}$$

For the profile drag of foils and struts, a factor of 2 is required to allow for skin friction on both sides. Also, for a foil operating close to the free surface, $C_{\ell i}$ is modified by flow curvature to $C_{\ell o}$. The profile drag thus becomes:

$$C_{DP} = 2C_F\ [1.0 + 1.2\ (t/c) + 120\ (t/c)^4 + 60\ (t/c + 0.2C_{\ell o})^4] \tag{4.3}$$

As noted earlier, the coefficient of friction used in this equation assumes turbulent flow over the entire surface and in consequence, the relatively low drag coefficients achieved by delayed transition to turbulent flow are not predicted. This seems to be realistic in the hydrofoil case since delayed transition to laminar flow is realisable over a comparatively narrow range of C_ℓ and the required cleanliness, profile accuracy and smooth in-flow conditions are hard to obtain in practice with a hydrofoil section.

4.2 EFFECT OF SURFACE IRREGULARITIES

Surface roughness causes an important increase in drag which must be considered even though the flow is already assumed turbulent over the section. It is extremely difficult to estimate the increment to coefficient of friction which should be allowed. Standard roughness tests on airfoils[7] indicate an increment, AC,, of more than 0.002 for conditions appropriate to fully turbulent flow. This is for a 0.011 inch grain roughness on the leading edge of a foil of 24 inches chord and does not decrease greatly for grain sizes down to 0.002 inch. However, these roughnesses are considerably greater than should occur in normal manufacture. For example, inspection of HMCS BRAS D'OR, a 200 tons auw hydrofoil ship with carefully manufactured foils, showed a surface finish of about 0.003 inch equivalent grain size for an 8 foot chord foil.

Barr[8] quotes ΔC_F values of 0.0004 to 0.0008 *as* normal allowances in standard ship design practice and recommends the latter value for a smooth, unfouled foil of five feet chord with an equivalent grain size roughness of about 0.003 inch. In fact, much will depend on size and method of manufacture. An allowance of 0.0004 seems appropriate for a smaller foil machined from the solid whereas 0.0008, as recommended by Barr, does seem to be a minimum for larger, fabricated foils. An even higher allowance should be made for foils or struts with a relatively rough or fouled finish.

Surface waviness and discontinuities of curvature can drastically affect the drag of aerofoils[9] by inducing premature transition to turbulent flow and in more extreme cases, turbulent separation. No allowance is made here since full turbulent flow is already assumed and since control of section shape ought to be good enough to prevent premature separation.

The profile drag of practical hydrofoil sections at ideal angle of attack is therefore taken to be:

$$C_{DP} = 2 (C_F + Ac,) [1.0 + 1.2 (t/c) + 120 (t/c)^4$$

$$+ 60 (t/c + 0.2C_{\ell o})^4] \qquad (4.4)$$

4.3 PROFILE DRAG AS A FUNCTION OF LIFT

Equation 4.4 applies only to the optimum lift coefficient, where "shock free" entry obtains. Drag will increase for lift coefficients above and below this due to flow around the leading edge and the resulting changes to boundary layer flow. The drag increment is of the form:

$$\Delta C_{DP} = K\,(C_{\ell} - C_{\ell o})^{n}$$

where K and n must he determined experimentally and C_{ℓ} is the operating lift coefficient for the section concerned. Suitable data are not available for 16 Series sections and it has been necessary to substitute data for the similar Type 65 Series, obtained from Reference 7 over a Reynolds Number range of 3 x 10^6 to 9 x 10^6. These give the empirical relationship:

$$\Delta C_{DP} = 0.005\,(C_{\ell} - C_{\ell o})^{1.9} \qquad (4.5)$$

In practice, C_{ℓ} must be determined from the corrected two dimensional lift curve slope and the total angle of attack, the latter comprising ship trim angle, τ, initial incidence setting if used, α_i, and no lift angle, a_o. Thus, using Equations 4.5 and 3.13:

$$\Delta C_{DP} = 0.005\,[a_o\,(\tau + \alpha_i)]^{1.9}$$

4.4 PROFILE DRAG DUE TO FLAPS

As noted in 3.6, the effect of a plain, trailing edge flap of normal size is to change the effective camber and the effective incidence of the section in essentially equal proportions. These changes are reflected as additions of $0.5 a_o \alpha_{\delta o} \delta$ to the $C_{\ell o}$ and C_{ℓ} terms of Equations 4.4 and 4.5. The final expressions for profile drag then become those listed below as Equations 4.7 and 4.8.

4.5 FINAL EXPRESSIONS

$$C_{DP}\ (\text{total}) = C_{DP} + \Delta C_{DP}$$

where:

$$C_{DP} = 2 (C_F + AC,) \{1.0 + 1.2 (t/c) + 120 (t/c)^4$$

$$+ 60 [t/c + 0.2 (C_{\ell o} + 0.5 a_o \alpha_{\delta o} \delta)]^4\} \qquad (4.7)$$

(ΔC_F should be taken as 0.0008 for the normal large ship case.)

and $$\Delta C_{DP} = 0.005 [a_o (\tau + \alpha_i + 0.5 \alpha_{\delta o} \delta)]^{1.9} \qquad (4.8)$$

5. FINITE SPAN EFFECTS

Consideration of foils of finite span introduces several basic effects which must be applied to the section characteristics determined previously.

5.1 EDGE CORRECTION

This is a relatively minor correction to allow for decrease of velocity at the wing edge, necessary since edge velocity determines the circulation and hence, the lift. For an elliptic wing, the decrease is given by the factor:

$$E = \frac{\text{Wing Semi-Perimeter}}{\text{Wing Span}}$$

and for planforms of interest to us can be approximated by:

$$E = \frac{b + \lambda c}{b}$$

The effective wing span should be used since it more accurately reflects flow conditions, so that the preferred expression becomes:

$$E = 1 + \frac{\lambda}{A} \qquad (5.1)$$

where A is the effective aspect ratio. With edge correction, lift curve slope becomes $\frac{a_o}{E}$, where a_o is given by Equation 3.8.

5.2 THE INDUCED ANGLE

The major influence of finite span is to create a trailing vortex field, influenced in the hydrofoil case by free surface effects. This results in a net downward flow with enough inclination to tip the resultant force backward, decreasing the lift curve slope and creating a significant drag component. The required increase in total angle of attack to maintain a given C_L is the induced angle, α_I.

From aerodynamic theory, the induced angle can be shown to 'be:

$$\alpha_I = \frac{C_L}{\pi A}$$

and in the hydrofoil case, this is modified to:

$$\alpha_I = \frac{C_L}{\pi A}(1 + \zeta)$$

where ζ arises from free surface effects to be discussed later.

Lift Coefficient

The three dimensional lift coefficient becomes:

$$C_L = \frac{a_o}{E}\left[\alpha - (1 + \zeta)\frac{C_L}{\pi A}\right] \tag{5.2}$$

Lift-Curve Slope

The corresponding three dimensional lift curve slope is:

$$C_{L_a} = \frac{1}{\frac{E}{a_o} + \frac{1+\zeta}{\pi A}} \tag{5.3}$$

Induction Factor for Lift

The term $\frac{1+\zeta}{\pi A}$ in Equation 5.3 contains all the terms contributing to the induced angle and is called the induction factor for lift.

$$F_\alpha = \frac{1+\zeta}{\pi A} = \frac{\alpha_I}{C_L} \tag{5.4}$$

Induced Drag

There is a similar induction factor for drag, F_D, identical with F_α except for a small planform correction term. The induced drag, C_{DI}, is given by:

$$C_{DI} = C_L \cdot \alpha_I$$

or

$$C_{DI} = F_D \cdot C_L^2 \qquad (5.5)$$

The various terms which make up the Induction Factor for practical hydrofoils operating close to the water surface are treated separately below.

5.3 THE INDUCTION FACTOR

Breslin's analysis of induction factor[10] is used since it is a relatively simple method and takes speed effects into account. This gives:

$$F = \frac{1}{\pi A} \left(1+\nu+\sigma+\pi A \gamma \frac{gc}{V^2} + \mu\right) \qquad (5.6)$$

where ν is the Glauert planform correction,

ν_α for F_α, ν_D for F_D

σ is Prandtl's biplane factor

γ is Breslin's wave function

μ is a correction, not included by Breslin, for the influence of flap operation on the loading distribution of the foil.

Planform Correction

As plotted by' Barr', following Glauert, this is approximated, for $\lambda > 0.4$, by:

$$\nu_a = \frac{A - 0.4}{3.6} \cdot \frac{A}{2\pi} \quad \text{for lift} \qquad (5.7)$$

$$\nu_D = \frac{\lambda - 0.4}{12} \frac{A}{2\pi} \quad \text{for drag} \qquad (5.8)$$

For $\lambda \geq 0.4$, the correction is neglected.

Biplane Factor

The interaction of the trailing vortices from the hydrofoil tips with the free surface gives rise to a diverging wave system. For Froude Numbers greater than 2, the associated function in the Induction Factor remains sensibly constant with speed and becomes Prandtl's finite span Biplane Factor, with hydrofoil mean immersed depth taken to be half the biplane wing separation.

It is convenient to define an auxiliary variable:

$$\eta = \frac{\text{Mean Depth}}{\text{Effective Semi-Span}} = \frac{2h}{b} = \frac{2h}{Ac}$$

Then Prandtl's approximation for σ is:

$$\sigma = \frac{1-0.66\eta}{1.055+3.7\eta} \qquad (5.9)$$

Wave Function

This originates from the interaction of the lifting vortex with the free surface and gives rise to a transverse wave system. In the three-dimensional case, it is shown by Breslin to increase rapidly in value with speed to reach a peak at a chord Froude Number, F_c, of $\sqrt{2}$ where it is the dominant wave source. It decreases rapidly, becoming virtually zero at $F_c = 5$. For $2 < F_c < 4$ (15 to 30 knots for a 6 foot chord hydrofoil), it is a significant effect.

The use of three dimensional theory for predicting wave drag is open to question since experimental data tend to compare better with the two dimensional for $F_c < 2$ and with three dimensional for $F_c > 3$. Breslin recommends use of the three dimensional theory and for foilborne predictions this is most accurate since $F_c = 3$ corresponds about with the lower limit for foilborne operations. Below this, several factors combine to make predictions for the take-off zone doubtful in any case.

The Breslin function contains an elliptic' function $E(1+\eta^2)^{-1/2}$ but for arguments close to unity, this approximates to $[2-(1+\eta^2)^{-1/2}]$ giving the wave function as:

$$\gamma = \frac{4}{3\pi}\ \{\frac{2}{\pi}(1+\eta^2)^{3/2}\ [2-(1+\eta^2)^{-1/2}] - \frac{3}{2}\eta\} \qquad (5.10)$$

Flap Correction

The foil flaps are assumed to be full span but will have gaps at the intersection pods and at mid-span. The flap edges introduce vortices of their own and distort the spanwise lift distribution, increasing the induced angle. Reference 12 gives the increment to induced drag for a single cut-out of span 0.2b as:

$$\Delta C_{Di} = K^2 (\Delta C_L)^2$$

where K has the value 0.14 and is virtually independent of aspect ratio, at least for 4 < A < 12. The corresponding induction factor increment is:

$$\mu = \pi A \ (0.14)^2 \ \frac{\Delta C_L}{C_L}^2$$

or

$$\mu = 0.062A \ \alpha_\delta{}^2 \delta^2 \ \frac{C_{L\alpha}}{C_L}^2 \qquad (5.11)$$

This expression applies to the bow foil. For the two strut main foil arrangement considered here, it is factored by 2.

5.4 CORRECTIONS TO FLAP EFFECTIVENESS

The edge correction for flaps, E_f, is different from the one given earlier for foils (Equation 5.1). Curves presented by Lowry and Polhamus" present the correction which must be applied to flap effectiveness assuming that the factor E, of Equation 5.1 has already been applied to the foil lift-curve slope. Over the range of aspect ratios and flap-chord ratios of interest, these curves can be approximated by the expression:

$$E_f = 1 + \frac{(1-f_c)^2}{2A} \qquad (5.12)$$

Again, since flap effectiveness, when included in the final lift balance equations is referred to total foil area, a correction is required for flaps which do not extend over the full span. Thus if S_f is the total area of the foil in way of the flaps and S is the total foil area, the net three-dimensional flap effectiveness becomes, using Equation 3.17:

$$\alpha_\delta = \alpha_{\delta o} E_f \frac{S_f}{S} \tag{5.13}$$

5.5 DOWNWASH AT MAIN FOIL

The main foil is affected by the wake of the bow foil which appears as two distinct vortices, separated as shown in Figure 5.

There is both upwash and downwash on the main foil, resulting in a net downwards velocity as indicated by the hatched area. This is dependent on free surface effects, the distance aft and the difference in depth between the bow and main foils. At the bow foil,

$$\text{Net downwash velocity} = \omega_B = F_{\alpha B} C_{LB} V$$

$$\text{Net downwash angle} = \varepsilon_B = F_{\alpha B} C_{LB} \text{ (in radians)}$$

Variation with distance aft is given by the factor $(\cos \frac{g \ell_F}{V^2})$

and with depth difference by $(e^{\frac{-g(h_M - h_B)}{V^2}})$. The effect is assumed to extend over a main foil span of $\pi/4$ of the bow foil span. Thus, the effective increment to main Eoil angle of attack, in radians, is:

$$\Delta\varepsilon = - \frac{\pi}{4} \frac{b_B}{b_M} \varepsilon_b e^{\frac{-g(h_M - h_B)}{V^2}} \cos \frac{g\ell_F}{V^2} \tag{5.14}$$

5.6 PITCHING MOMENT

In the absence of data on the effect of the free surface on C_{m_δ}, this correction has been omitted. The very small additional nose down moment which should result will be a conservative factor in most applications. Using Equation 3.19, the total pitching moment coefficient for a flapped foil thus becomes:

$$C_M = -0.25 C_{L_a} \alpha_o \cos^2 \Lambda - 1.66 \sqrt{f_c(1-f_c)^3} \tag{5.15}$$

The corresponding foil pitching moment is:

$$M = q\, Sc\, C_M \tag{5.16}$$

6. MISCELLANEOUS DRAG COMPONENTS

6.1 HULL AIR DRAG

It is difficult to provide a general equation for air drag of the hull since it is very sensitive to the extent and type of deck-mounted equipment. The coefficient of drag, C_{DH}, used here is based on maximum hull frontal area. It is estimated to vary from 0.3 for an exceptionally clean design to 0.7 for a warship equipped with missiles, masthead control radar and with little attempt to streamline. Recommended normal warship value for C_{DH} is 0.6. The expression for air drag is:

$$D_A = C_{DH} \frac{\rho_A V^2}{2} H_b H_w \quad \text{(for calm conditions)} \qquad (6.1)$$

6.2 POD DRAG

Hoerner[6] uses experimental data to derive an empirical expression for the coefficient of profile drag of a streamline body, referred to the skin friction drag coefficient, C_f. The resulting profile drag coefficient is:

$$C_{PD} = (C_F + \Delta C_F)\left[1+1.5\left(\frac{d}{\ell_p}\right)^{3/2} + 7\left(\frac{d}{\ell_p}\right)^3\right]$$

where ℓ_p is pod length and d the diameter. This expression is based on wetted area and is converted to frontal area by assuming that:

$$\frac{\text{Frontal Area}}{\text{Wetted Area}} = \frac{d}{4} \cdot \frac{1}{0.75 \times \text{length} \times \text{perimeter}}$$

Based on frontal area, pod drag coefficient becomes

$$C_{PD} = (C_F + \Delta C_F)\left[3\frac{\ell_p}{d} + 4.5\left(\frac{\ell_p}{d}\right)^{-1/2} + 21\left(\frac{\ell_p}{d}\right)^{-2}\right] \qquad (6.2)$$

6.3 SPRAY DRAG

The most appropriate data seem to be due to Chapman[13]. These include measurements on round-nosed biogival strut forms with maximum thickness at 50% chord, t/c ratios of 0.11 to 0.21 and chords between 4 and 23 inches. The resulting, empirical expression for spray drag coefficient is:

$$C_{DS} = 0.011 + 0.08 \left(\frac{t}{c}\right) \tag{6.3}$$

This is based on the area ($t_w \cdot c_w$), where c_w and t_w are the water line chord and thickness respectively, measured normal to the strut.

6.4 FENCE DRAG

Ventilation fences are normally used on the foil support struts and are assumed to be flat plates projecting on either side of the strut and normal to its axis. Fence length is taken to be strut chord length and the drag co-efficient is assumed to be a representative 0.009, based on the area 2 x chord length x maximum chord thickness at the fence.

6.5 INTERFERENCE DRAGS

Only foilborne performance is considered here and hence, only the interference drag of the foil-strut inter-sections need be included. These are taken to incorporate an intersection pod, housing the transmission and control actuation components. The foil and strut areas are calculated to the intersection axes and both Hoerner[6] and Barr[8] consider the pod-strut and pod-foil interference drags to be essentially equal to the drag of those portions of foil and strut enclosed by the pod. Interference drag is thus automatically taken into account. If the pod axis is displaced vertically above the foil-strut intersection axis, strut drag will be over-estimated by this method and strut length should be taken to the pod axis only.

6.6 ADDITIONAL MINOR DRAGS

Any hydrofoil ship design must necessarily include sea water intakes, projections, bolt holes and gaps of various kinds. Although individually small, these components will be significant in total. In the absence of specific information, a miscellaneous drag allowance of 2% total drag is recommended.

7. STEADY STATE PERFORMANCE CALCULATION

Equilibrium conditions are determined from a vertical force equation and a longitudinal moment equation:

$$\Sigma_1^n L_n - W = 0 \tag{7.1}$$

$$\Sigma_1^n L_n x_n - M_n = 0 \qquad (7.2)$$

ΣL_n is the sum of the lifts of all the foil and flap elements, together with the buoyancy, B_n, of the submerged components. ΣM_n is the sum of the moments of these elements, together with any moments due to thrust and drag. Buoyancy moments are taken as $M_n = B_n (x_n - 0.25c_n)$ where x_n is the distance of the centre of pressure from the ship c.g.. Generally for foil element lift:

$$L_n = q S_n C_{L_a} (\alpha + \alpha_\delta \delta)$$

where C_{L_α} is the fully-corrected lift-curve slope

α is the total angle of attack

α_δ is the corrected flap efficiency

δ is the flap angle.

For designs with propeller drive located at main foil-strut intersections, the thrust drag moment is assumed negligible.

The depth and trim are specified for each speed and the remaining unknowns are then the flap angles at the bow and main foils. Equations 7.1 and 7.2 become:

$$W-B_B-B_M =$$

$$qS_B C_{L_{\alpha B}} (\tau+i_{1B} - a_{oB}+\alpha_{\delta B}\delta_B) + qS_M C_{L_{\alpha M}} (\tau+i_{1M}-\alpha_{oM}+\Delta\varepsilon+\alpha_{\delta M}\delta_M) \qquad (7.3)$$

$$-B_B(x_B-0.25c_B) - B_M(x_M-0.25c_M) =$$

$$qS_B C_{L_{\alpha B}} (\tau+i_{1B}-\alpha_{oB}+\alpha_{\delta B}\delta_B)x_B+qS_M C_{L_{\alpha M}} (\tau+i_{1M}-\alpha_{oM}+\Delta\varepsilon+\alpha_{\delta M}\delta_M)x_M+M_M+M_B$$

(7.4)

where S_B, S_M are given by (2.4):

i_{iB}, i_{iM} are initial foil incidence angle settings, where used

α_{oB}, α_{oM} are given by (3.13)

$\Delta\varepsilon$ is downwash at main foil, given by (5.14)

M_B, M_M are given by (5.16)

$\alpha_{\delta B}$, $\alpha_{\delta M}$ are given by (5.13)

$C_{L_{\alpha B}}$, $C_{L_{\alpha M}}$ are given by (5.3)

These would be linear equations in δ_B and δ_M, the flap angles, except for the downwash correction factor at the main foil (Equation 5.14) and the flap correction terms, μ_M and μ_B (Equation 5.11). A single iteration is therefore used, with these terms omitted for the first calculation and included in the second. A thrust-drag moment term could also be included in a second calculation if considered desirable.

Appendix A gives a program listing for steady state lift and resistance calculation for a 400 ton a.u.w. fully-submerged design. A brief description of the design and an input data chart are included.

8. COMPARISON OF RESULTS

Experimental verification of predictions is very difficult because accurate full scale thrust measurement data are very few. Even for those data that are available, the exact conditions of operation are unknown, making the validity of the comparison doubtful.

The MOD "0" version of the NSRDC trials ship PCH-1, HIGHPOINT, gives the most applicable data as the configuration, propulsion and geometry correspond to that assumed here. Resistance data points are available from 1969 torque and rpm measurements used in conjunction with propeller model test data[14] and from 1972 thrust measurements[15]. These data are compared in Figure 6 with predictions. The two sets of experimental data differ considerably showing the difficulty of making experimental measurements. The predicted resistance values are given for ΔC_F = 0.0004 and 0.0008. The lower value for ACF is probably applicable in this case since the PCH foils were reportedly accurately made and very well finished. In view of the unknowns, it is difficult to draw any conclusion other than that the predictions are in general agreement with the experimental data.

More detailed comparison is possible only on the basis of other design predictions. The Boeing Company's values'[6] for the various drag components of PCH-1 MOD 1 are compared in TABLE I with corresponding values obtained by the methods outlined here. Agreement is generally good except for air drag of the hull which is predicted to be some 50% higher by the method given here.

9. CONCLUDING REMARKS

Factors have been identified which affect the lift and drag of practical hydrofoil configurations operating close to the free surface. Expressions, largely empirical in nature, have been obtained to characterise these configurations. Used with the steady state lift and moment balance equations, the expressions predict the required flap angles and the total resistance of the system. The predictions agree reasonably well with what little full scale experimental data are available.

The greatest need identified by this study is for basic hydrodynamic data on simple, flapped hydrofoil sections. Comprehensive section tests would be most useful to confirm the characteristics assumed here, to indicate the non-linear flap angle effects and to define the practical limits of cavitation-free operation. Comparison of predictions with model test data on T and π foil assemblies aiso would be very useful, leading to a better understanding of prediction and model test limitations.

Resistance values are particularly hard to predict. The assumption made here of turbulent flow over the whole section and the somewhat arbitrary selection of a value of the coefficient of friction increment due to roughness render some other factors of little consequence. It remains to be seen how well these assumptions will stand up in practice. In the meantime, the various factors have been identified and can be modified as new evidence becomes available.

TABLE I

COMPARISON OF RESISTANCE ESTIMATES FOR PCH-1 MOD-l

	BOEING (LBS)	D:REA ($\Delta C_F = 0.0004$) (:LBS)	% DIFF.
BOW POD	338	366	8.2
AFT LOWER PODS	1645	17.26	4.9
AFT UPPER PODS	1250	1062	-15.0
BOW STRUT AND SPRAY	946	881	-6.9
BOW FOIL PROFILE	2894	2671	-8.3
BOW FOIL INDUCED	1373	13'97	1.7
MAIN STRUT AND SPRAY	2964	2989	0.8
MAIN FOIL PROFILE	6418	6628	3.3
MAIN FOIL INDUCED	1823	2259	23.9
HULL AIR	1596	24158	54.0
MISCELLANEOUS		449	
TOTAL	21247	22886	7.7

N.B. Values for 45 knots and 120.0 tons a.u.w.

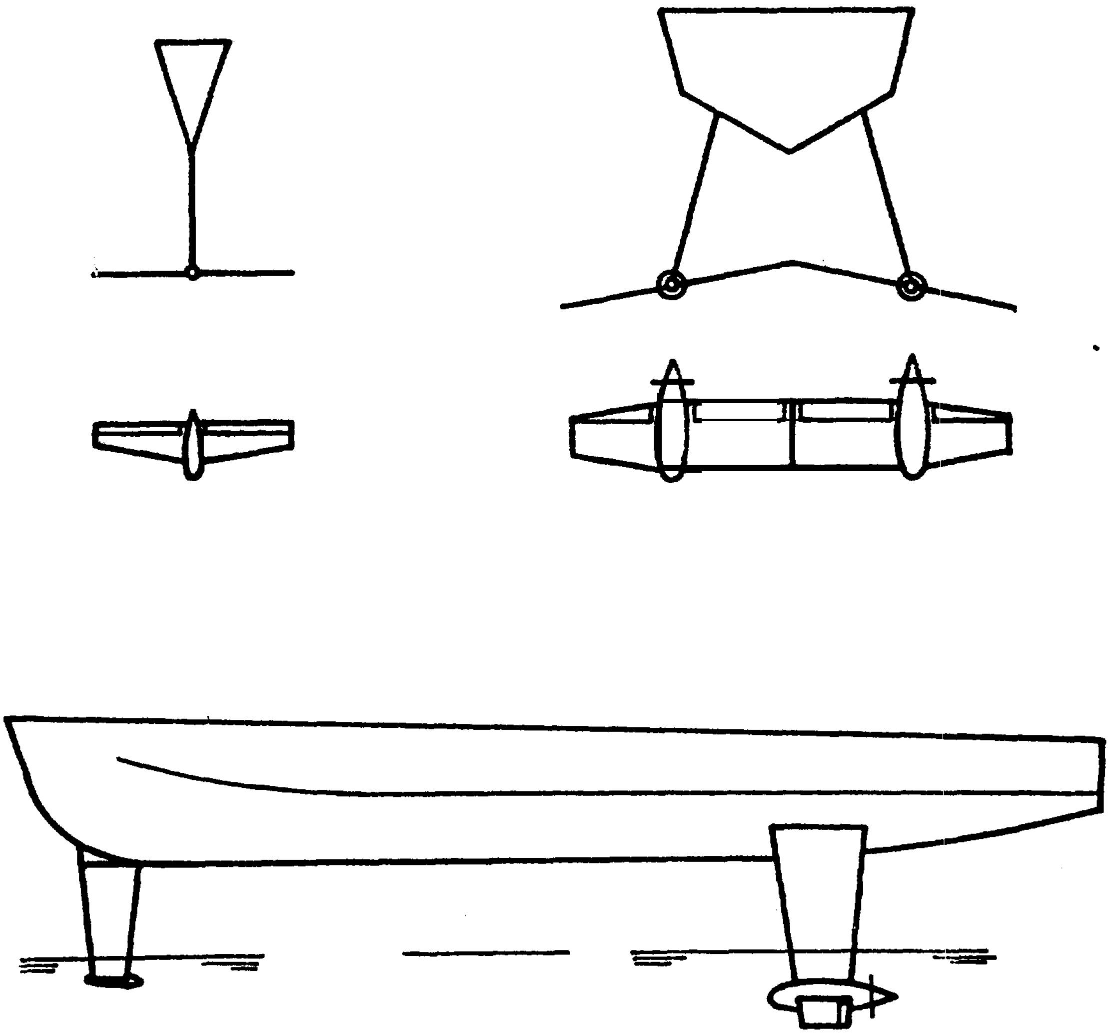

FIG I GENERAL CONFIGURATION

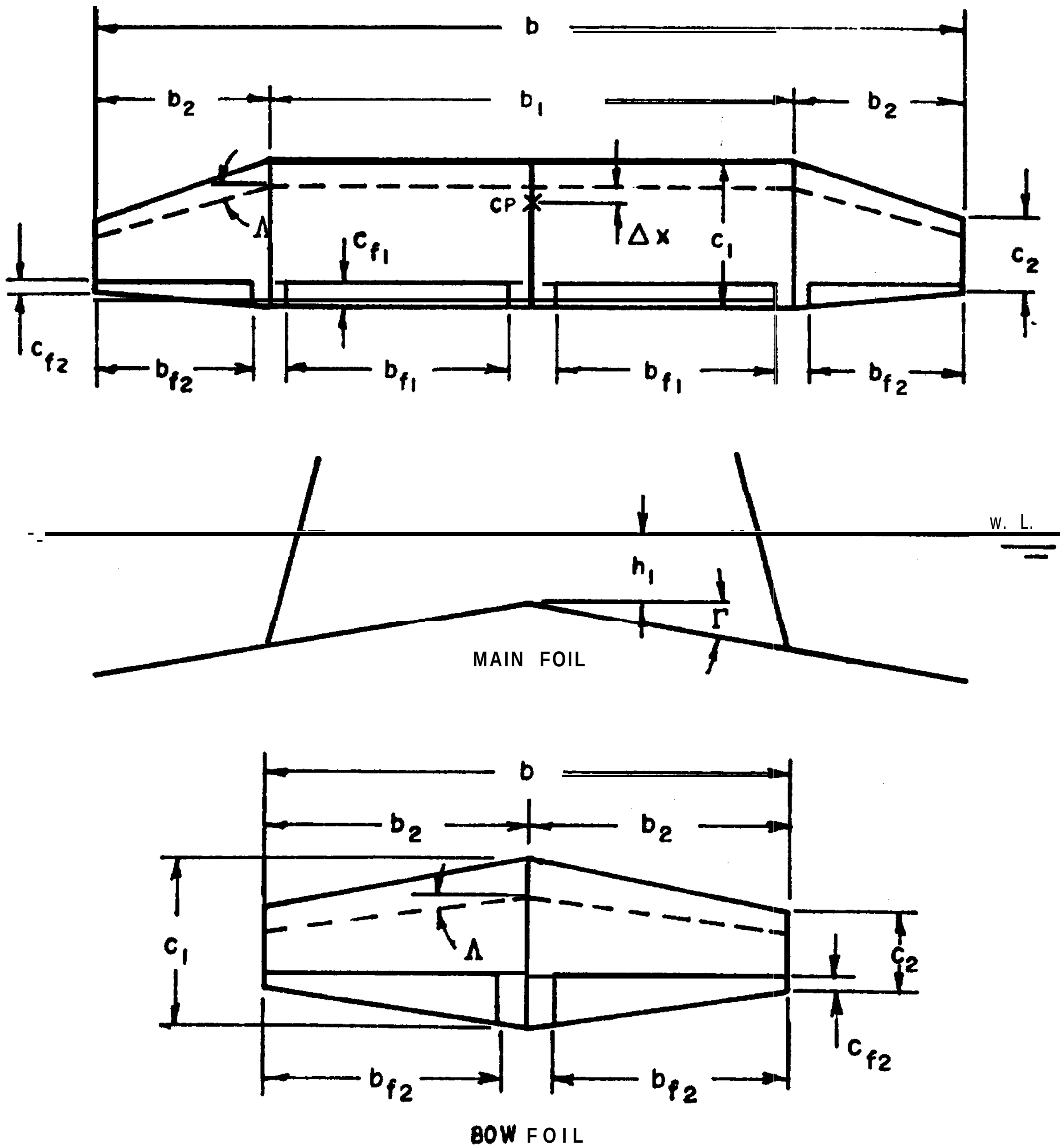

FIG 2 FOIL GEOMETRIES

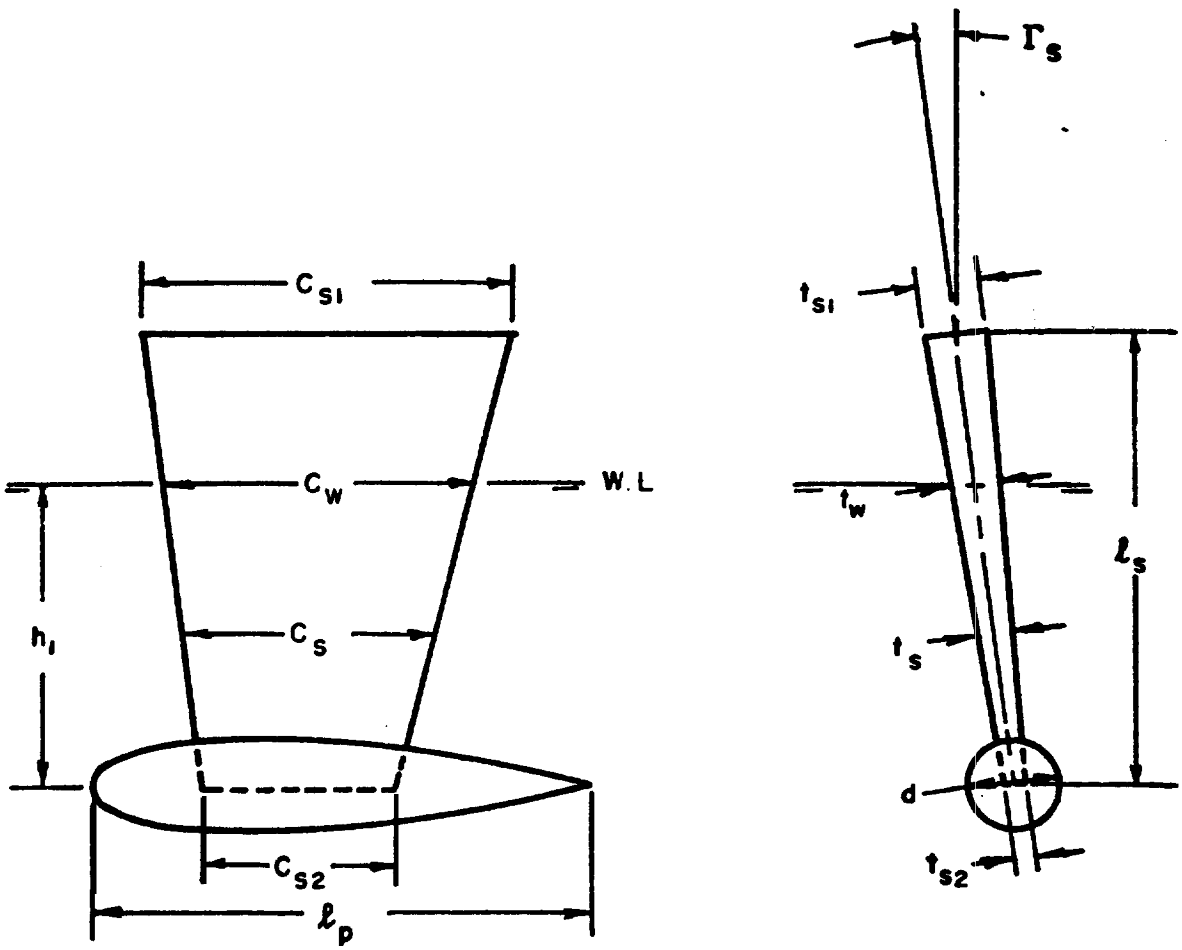

FIG 3 POD AND STRUT GEOMETRY

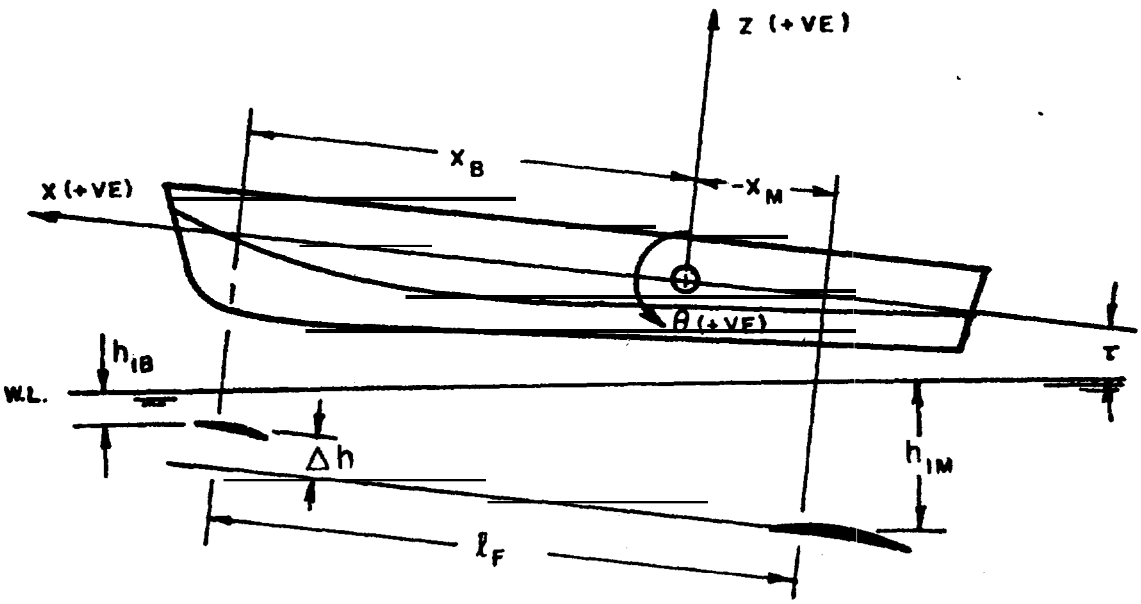

FIG 4 SHIP GEOMETRY AND **AXIS** SYSTEM

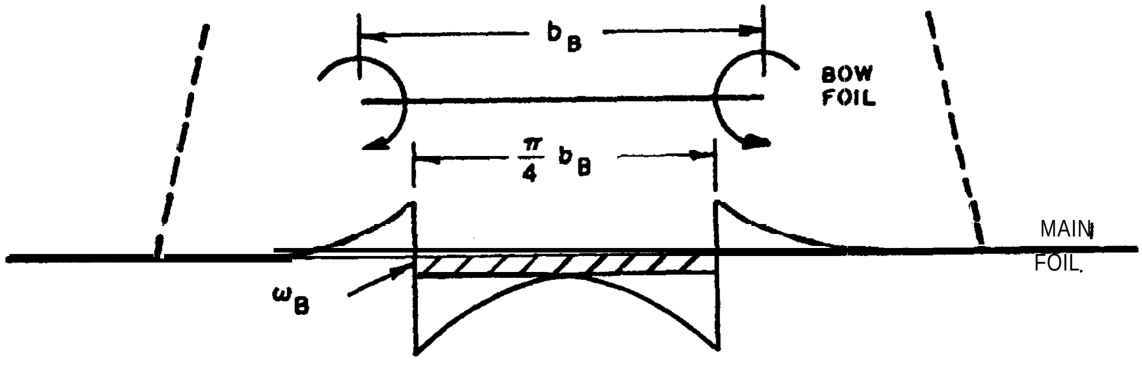

FIG 5 EFFECT OF DOWNWASH AT MAIN FOIL

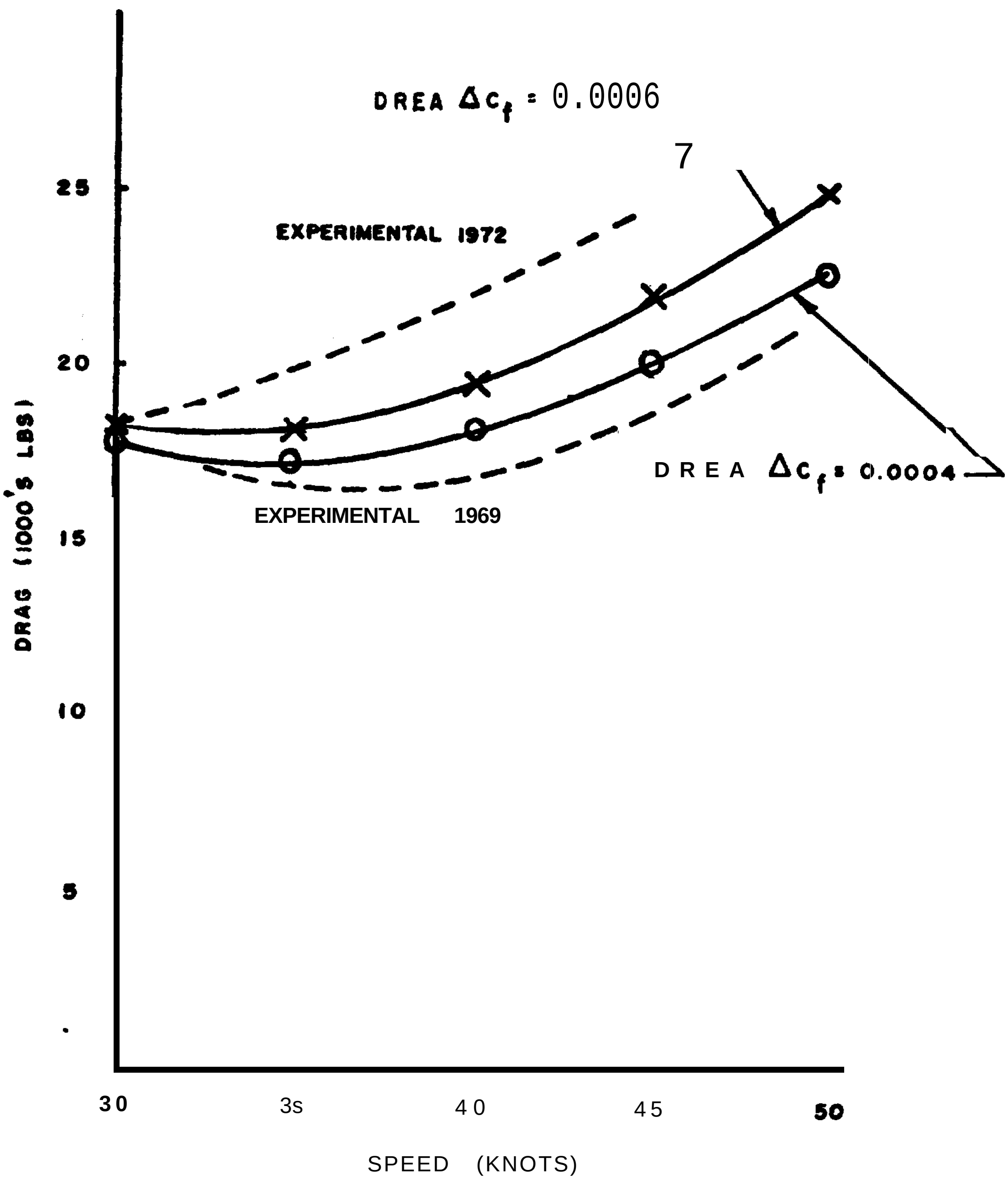

FIG 6 PCH-I (MOO 0) RESISTANCE

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APPENDIX A

Program Listing for a Typical Fully-Submerged System

The program listing is for a 360 tons all-up weight hydrofoil ship with a fully-submerged system designed for 50 knots maximum speed. Figure 1A shows the main foil arrangement and Figure 2A the bow foil. The input data required for the program are listed in the Table which follows.

PROGRAM FSSS 2

SHIP: FH Type 64 DATE: 24/1/75

PARAMETER	SYMBOL	VALUES	UNITS
Line 1			
Speed	UK	25.0 27.5 10.0 35.0 40.0 45.0 50.0	Knots
All Up Weight	EM	360.0	Tons
Foil Base Length	EL	97.5	Ft
Bow Foil Fraction, x_B/ℓ_f	FRA	0.90	
C.G. to Prop. Axis Distance	HG	22.0	Ft
Line 2			
M.F. Projected Span between Struts	B1M	29.0	Qt
N.Q. Tip Span	B2M	18.5	Ft
M.F. Root Chord	C1M	11.4	Qt
H.Q. Tip Chord	C2M	3.8	Ft
M.F. Min-Span Depth	H1M	14.5 13.80 13.25 11.90 10.20 8.93 8.33	Qt
Y.Q. t/c	TCM	0.065	
Roughness Increment	OELCQ	0.0008	
Line 3			
B.Q. Span	BB	19.5	Ft
B.Q. Root Chord	C18	6.3	Qt
B.F. Tip Chord	C2B	2.10	Ft
B.F. Intersection Depth	HB	2.47 3.48 4.3 5.0 5.0 5.0 5.0	Ft
B.Q. t/c	TCB	0.065	
$(h_{1M}-h_{1B})$ at Zero Trim	DELH	3.5	Ft
M.F. Incidence	AIMD	0.0	Degree
Line 4			
*M.F. Anhedral Angle to Hor.	GMD	0.0	Degree
M.F. Strut Dihedral to Vert.	GSD	14.0	Degree
M.F. Section Lift Coefft.	CLIM	0.33	
B.F. Section Lift Coefft.	CLIB	0.33	
B.F. Incidence	AIBD	0.0	Degree
* Anhedral only			
Line 5			
M.F. Flap Span, b_{f1}	BF1M	10.0	Ft
H.F. Flap Span, b_{f2}	BF2M	14.0	Qt
B.F. Flap Span, b_{f2}	BF2B	R.75	Qt
M.F. Flap Chord Ratio	FM	0.20	
B.F. Flap Chord Ratio	FB	0.30	
Bow Pod Length	PLB	10.0	Ft
Bow pod Diameter	PDB	1.50	Qt
Line 6			
Hull Air Drag Coefft.	COA	0.6	
Hex. Hull Beam	HUB	32.0	Ft
Hull Keel to Deckhouse Top	HKO	24.0	Ft
Main Pod Length	PLH	19.25	Qt
Main Pod Diameter	POH	3.50	Qt
Line 7			
M.S. Root Chord	CS1M	12.5	Ft
U.S. Intersection Chord	CS2M	12.5	Ft
U.S. Root t/c	TC1M	0.16	Ft
M.S. Intersection t/c	TC2M	0.08	Ft
M.S. Projected Length	SLH	21.5	Ft
U.S. Lower Fence Height (Proj)	FLM1	6.5	Ft
M.S. Upper Fence Height (Proj)	FLM2	11.5	Ft
Line 9			
B.S. Root Chord	CS1B	8.0	Qt
B.S. Intersection Chord	CS2B	6.5	Ft
B.S. Root t/c	TC1B	0.16	Ft
B.S. Intersection t/c	TC2B	0.08	Ft
B.S. Length	SLB	13.0	Ft
B.S. Lover Fence Height	FLB1	2.5	Ft
B.S. Upper Fence Height	FLB2	7.0	Ft
Line			
Main Pod Height Above Foil	DPHM	3.25	Ft
Bow Foil Pod Height Above Foil	OPHB	0.75	Ft

```
      PROGRAM FSSS2 (INPUT,OUTPUT,TAPE 5 = INPUT,TAPE 6 = OUTPUT)
C     STEADY STATE ANALYSIS OF FULLY SUBMERGED HYDROFOILS
C     PROGRAM FSSS2
      COMMON RHO,PI,G
      RHO = 1.997
      PI=3.14159
      G = 32.2
999   READ (5,1) UK,EM,EL,FRA,HG
      READ (5,1) B1M,B2M,C1M,C2M,H1M,TCM,DELCF
      READ (5,1) BB,C1B,C2B,HB,TCB,DELH,AIMD
      HEAD (5,1) GMD,GSD,CLIM,CLIB,AIBD
      READ (5,1) BF1M,BF2M,BF2B,FM,FB,PLB,PDB
      READ (5,1) CDA,HUB,HKD,PLM,PDM
      READ (5,1) CS1M,CS2M,TC1M,TC2M,SLM,FLM1,FLM2
      READ (5,1) CS1B,CS2B,TC1B,TC2B,SLB,FLB1,FLB2
      READ (5,1) DPHM,DPHB
1     FORMAT (7F10.4)
      READ (5,2000) NEXT
2000  FORMAT (I1)
      GM = GMD/180.0*PI
      GS = GSD/180.0*PI
      COSG = COS(GM)
      SING = SIN(GM)
      TANG = SING/COSG
      COSGS = COS (GS)
      AIM = AIMD*PI/180.0
      AIB = AIBD*PI/180.0
C     MARKER FOR SINGLE REPEAT
      M = -1
      U = 1.689*UK
      Q = 0.5*RHO*U**2
      XB = FRA*EL
      XM = XB-EL
      ALM = C2M/C1M
      ALB = C2B/C1B
      BM = B1M+2.0*B2M
      SM = B1M*C1M+B2M*C1M*(1.0+ALM)
      SFM = SM-C1M*(BM-2.0*(BF1M+BF2M))
      CM = SM/BM
      SB =C1B*0.5*(1.0+ALB)*BB
      CB = SB/BB
      SFB = SB-C1B*(BB-2.0*BF2B)
      HM = H1M + TANG*(0.25*B1M + 0.405*B2M)
      ARM = BM/CM*(1.0+(B1M/BM)**3*HM/BM)
      SWM = 0.0
      ARB = BB/CB
      TANLB = C1B/(0.5*BB)*(0.75-FB)*(1.0-ALB)
      YB = 0.25*BB*(1.0-(1.0-ALB)/(3.0*(1.0 + ALB)))
      CPAB = YB*TANLB*0.5*BB*C2B*(1.0 + ALB)/SB
      SWB = ATAN(TANLB)
      TANLM = C1M/B2M*(0.75-FM)*(1.0-ALM)
      YM = B2M/2.0*(1.0-(1.0-ALM)/(3.0*(1.0 + ALM)))
      CPXM = YM*TANLM*B2M*C2M*(1.0 + ALM)/SM
      DB = XB-CPXB
      DM = XM-CPXM
      FMUB=0.0
      FMUM=0.0
```

```
C      BUOYANCIES
       CALL BUOY(HB,0.,DPHB,0.,1.0,CS1B,CS2B,TC1B,TC2B,SLB,SB,CB,TCB,
      1PLB,PDB,FBOB,SBOB,PBOB)
       CALL BUOY(H1M,B1M,DPHM,TANG,COSG,CS1M,CS2M,TC1M,TC2M,SLM,SM,
      1CM,TCM,PLM,PDM,FBOM,SBOM,PBOM)
       TBOB = (FBOB . SBOB + PBOB)*RHO/2240.0
       TBOM = (FBOM + 2.0*(SBOM . PBOM))*RHO/2240.0
       DNW = 0 . 0
99     CALL SLOPE (TCM,COSG,CLIM,ALM,ARM,HM,CM,FM,SWM,SFM,SM,
      1U,CLA2DM,FMUM,AOM,CLAM,CLOM,ALFDM,CMFM,FAM,FBM)
       AOMD = AOM*180.0/PI
       CALL SLOPE(TCB,1.,CLIB,ALB,ARB,HB,CB,FB,SWB,SFB,SB,
      1U,CLA2DB,FMUB,AOB,CLAB,CLOB,ALFDB,CMFB,FAB,FBB)
       DRAGH = CDA*0.00238*U**2*HUB*HKD/2.0
       AOBD = AOB*180.0/PI
       TRIM = ATAN((H1M-DELH-HB)/EL)
C      L I F T  AND MOMENT EQUATIONS
       A11 = ALFDB*CLAB*SB
       A12 = ALFDM*CLAM*SM
       B1 = 2240.0*(EM-TBOB-TBOM)/Q-SB*CLAB*(TRIM-AOB+AIB)-SM*CLAM*(TRIM
      $-AOM+AIM+DNW)
       A21 = A11*XB . CMFB*CB
       A22 = A12*XM . CMFM*CM
       UC! = -2240.0*(TBOB*DB + TBOM*DM)/Q - SB*(CLAB*(TRIM-AOB+AIB)*XB .
      1CLAB*AOB*0.25*CB*(COS(SWB))**2)-SM*(CLAM*(TRIM-AOM+DNW+AIM)*XM+CLA
      1M*AOM*0.25*CM*(COS(SWM))**2)-DRAGH*HG/Q
       xi  = A11*A22 - A12*A21
       DELB = (A22*B1 - A12*B2)/X2
       DELM = (B1-A11*DELB)/A12
       CLB = ALFDB*CLAB*DELB . CLAB*(TRIM-AOB+AIB)
       CLM = ALFDM*CLAM*DELM . CLAM*(TRIM-AOM+DNW+AIM)
       WB = (CLB*SB*Q/2240.0+TBOB)/EM
       TRIMD = TRIM*180.0/PI
       DELBD = DELB*180.0/PI
       DELMD = DELM*180.0/PI
C      S I NGLE REPEAT
       IF  (M) 100,101,101
100    FMUB=0.062*ARB*(ALFDB*DELB*CLAB/CLB)**2
       FMUM = 0.062*ARM*(ALFDM*DELM*CLAM/CLM)**2*2.0
       DNW = -PI*BB*FAB*CLB/(4.0*BM)*EXP(-G*(HM-HB)/U**2)*COS(G*EL/U**2)
       M  =  0.0
       GO TO 99
101    WRITE (6,300)
300    FORMAT (1H1/////////////////30X10HINPUT DATA)
204    FORMAT (//8X2HUK,8X2HEM,8X2HEL,7X3HFRA,8X2HHG)
       WRITE (6,204)
       WRITE (6,201) UK,EM,EL,FRA,HG
205    FORMAT (//7X3HB1M,7X3HB2M,7X3HC1M,7X3HC2M,7X3HH1M,7X3HTCM,5X5HDELC
      $F)
       WRITE (6,205)
       WRITE (6,201) B1M,B2M,C1M,C2M,H1M,TCM,DELCF
206    FORMAT (//8X2HBB,7X3HC1B,7X3HC2B,8X2HHB,7X3HTCB,6X4HDELH,6X4HAIMD)
       WRITE (6,206)
       WRITE (6,201) BB,C1B,C2B,HB,TCB,DELH,AIMD
207    FORMAT (//7X3H MD,7X3HGSD,6X4HCLIM,6X4HCLIB,6X4HAIBD)
       WRI TE (6,207
       WRITE (6,201) GMD,GSD,CLIM,CLIB,AIBD
```

```
208   FORMAT (//6X4HBF1M,6X4HBF2M,6X4HBF2B,8X2HFM,8X2HFB,7X3HPLB,7X3HPDB
     $)
      WRITE (6,208)
      WRITE (6,201) BF1M,BF2M,BF2B,FM,FB,PLB,PDB
209   FORMAT (//7X3HCDA,7X3HHUB,7X3HHKD,7X3HPLM,7X3HPDM)
      WRITE (6,209)
      WRITE (6,201) CDA,HUB,HKD,PLM,PDM
231   FORMAT (//6X4HCS1M,6X4HCS2M,6X4HTC1M,6X4HTC2M,7X3HSLM,6X4HFLM1,6X4
     $HFLM2)
      WRITE (6,231)
      WRITE (6,201) CS1M,CS2M,TC1M,TC2M,SLM,FLM1,FLM2
233   FORMAT (//6X4HCS1B,6X4HCS2B,6X4HTC1B,6X4HTC2B,7X3HSLB,6X4HFLB1,6X4
     $HFLB2)
      WRITE (6,233)
      WRITE (6,201) CS1B,CS2B,TC1B,TC2B,SLB,FLB1,FLB2
234   FORMAT (//6X4HDPHM ,6X4HDPHB)
      WRITE (6,234)
      WRITE (6,201) DPHM,DPHB
301   FORMAT(1H1/30X11HOUTPUT DATA)
      WRITE (6,301)
302   FORMAT (/4X16HZERO LIFT ANGLES,4X17HLIFT CURVE SLOPES,6X12HLIFT C
     $OEFFTS,2X12HBOW FRACTION)
      WRITE (6,302)
      WRITE (6,200)
200   FORMAT (/7X3HAOM,7X3HAOB,6X4HCLAM,6X4HCLAB,7X3HCLM,7X3HCLB,8X2HWB)
201   FORMAT(7F10.4)
      WRITE (6,201) AOMD,AOBD,CLAM,CLAB,CLM,CLB,WB
303   FORMAT (/6X4HTRIM,7X11HFLAP ANGLES,6X8HDOWNWASH,3X18HFLAP EFFECTI
     $VENESS)
      WRITE (6,303)
      WRITE (6,202)
202   FORMAT (/6X4HTRIM,6X4HDELB,6X4HDELM,7X3HDNW,6X5HALFDM,6X5HALFDB)
203   FORMAT (6F10.4)
      WRITE (6,203) TRIMD,DELBD,DELMD,DNW,ALFDM,ALFDB
C RESISTANCE AND POWER
C MAIN FOIL ASSEMBLY
C       STRUTS
C     PROFILE DRAG OF ONE STRUT
      CALL STRUT (H1M,B1M,DPHM,TANG,CS1M,CS2M,SLM,TC1M,TC2M,U,DELCF,
     $COSGS,Q,DPSM)
C     SPRAY DRAG OF ONE STRUT
      CALL SPRAY (H1M,B1M,TANG,CS1M,CS2M,TC1M,TC2M,SLM,Q,DSSM)
C    FENCE DRAG OF ONE STRUT
      HSM = H1M + B1M*TANG*0.5
      CALL FENCE (CS1M,CS2M,FLM1,SLM,TC1M,TC2M,Q,FDM1)
      CALL FENCE (CS1M,CS2M,FLM2,SLM,TC1M,TC2M,Q,FDM2)
      IF (HSM-FLM2) 120,121,121
120   FDM2 = 0.0
121   FDM = FDM1 + FDM2
C     STRUT DRAG TOTAL
      TDSM = 2.0*DPSM + 2.0*DSSM + 2.0*FDM
C    PODS
C     ONE  MAIN FOIL POD
      CALL POD (FLM,PDM,U,DELCF,Q,DPPM)
C    MAIN FOIL POD TOTAL
      TDPM = 2.0*DPPM
C    MAIN FOIL DRAG
```

```
      CALL FOIL (DELM,U,CM,DELCF,TCM,CLIM,CLA2DM,SM,COSG,0,FRM,ALFDM,CLA
     1M,TRIM,AOM,DNM,AIM,DRAM,DPRM,DIM)
      TDFM = DRAM + DPRM + DIM
C   TOTAL MAIN FOIL ASSEMBLY DRAG
      DMF = TDSM + TDPM + TDFM
C   BOW FOIL ASSEMBLY
C    STRUT
C     PROFILE DRAG
      CALL STRUT (HB,0,0,DPHB,0.,CS1B,CS2B,SLB,TC1B,TC2B,U,DELCF,1,0,0,
     $DPSB)
C     SPRAY DRAG
      CALL SPRAY (HB,0.,0.,CS1B,CS2B,TC1B,TC2B,SLB,G,DSSB)
C    FENCE DRAG OF BOW STRUT
      CALL FENCE (CS1B,CS2B,FLB1,SLB,TC1B,TC2B,G,FDB1)
      CALL FENCE (CS1B,CS2B,FLB2,SLB,TC1B,TC2B,G,FDB2)
      IF (HB-FLB2) 124,125,125
124   FDB2 = 0.0
125   FDB = FDB1 + FDB2
C    BOW STRUT DRAG TOTAL
      TDSB = DPSB + DSSB + FDB
C    POD DRAG
      CALL POD (PLB,PDB,U,DELCF,0,DPPB)
C    FOIL DRAG
      CALL FOIL (DELB,U,CB,DELCF,TCB,CLCB,CLA2DB,SB,1.,0,FRB,ALFDB,CLAB,
     1TRIM,AOB,0,0,AIB,DRAB,DPRB,DIB)
C    BOW FOIL DRAG
      TDFB = DRAB + DPRB + DIB
C   TOTAL BOW FOIL ASSEMBLY DRAG
      DBF = TDSB + DPPB + TDFB
C     MISCELLANEOUS DRAG
      DMIS = (DMF+DBF+DRAGH)*0.02
C SHIP TOTAL DRAG
      DT = (DMF+DBF+DRAGH) + DMIS
C THRUST HORSEPOWER
      THP = DT*U/550.0
304   FORMAT (2X32HMAIN FOIL STRUTS AND TOTAL STRUT DRAGS)
      WRITE (6,304)
210   FORMAT  (/6X4HDPSM,6X4HDSSM,7X3HFDM,6X4HTDSM)
      WRITE (6,210)
218   FORMAT (5F10.0)
      WRITE (6,218) DPSM,DSSM,FDM,TDSM
306   FORMAT  (/2X19HMAIN FOIL POD DRAGS)
      WRITE (6,306)
212   FORMAT  (/6X4HDPPM,20X,6X4HTDPM)
      WRITE (6,212)
220   FORMAT (F10.0,20X,F10.0)
      WRITE (6,220) DPPM,TDPM
307   FORMAT (/2X51HMAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS)
      WRITE (6,307)
213   FORMAT  (/6X4HDRAM,6X4HDPRM,7X3HDIM,10X,6X4HTDFM,7X3HDMF)
      WRITE (6,213)
221   FORMAT (3F10.0,10X,2F10.0)
      WRITE (6,221) DRAM,DPRM,DIM,TDFM,DMF
308   FORMAT  (/2X19HBOW FOIL STRUT DRAG)
      WRITE (6,308)
214   FORMAT  (/6X4HDPSB,6X4HDSSB,7X3HFDB,10X,6X4HTDSB)
      WRITE (6,214)
```

```
222   FORMAT (3F10.0,10X,1F10.0)
      WRITE (6,222) DPSB,DSSB,FDB,TDSB
309   FORMAT (/2X41HBOW FOIL POD,MISCELLANEOUS AND HULL DRAGS)
      WRITE (6,309)
215   FORMAT (/6X4HDPPB,6X4HDMIS,5X5HDRAGH)
      WRITE (6,215)
223   FORMAT (3F10.01
      WRITE (6,223) DPPB,DMIS,DRAGH
310   FORMAT (/2X50HBOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS)
      WRITE (6,310)
216   FORMAT (/6X4HDPAB,6X4HDPBB,7X3HDIB,10X,6X4HTDFB,7X3HDBF)
      WRITE (6,216)
224   FORMAT (3F10.0,10X,2F10.0)
      WRITE (6,224) DPAB,DPBB,DIB,TDFB,DBF
311   FORMAT (/2X32HTOTAL DRAG ANO THRUST HORSEPOWER)
      WRITE (6,311)
217   FORMAT (/8X2HDT,7X3HTHP,8X2HUK,8X2HEM)
      WHITE (6,217)
225   FORMAT (2F10.0,1F10.2,1F10.1)
      WRITE (6,225) DT,THP,UK,EM
      IF (NEXT .GT. 0) GO TO 999
      STOP
      END
```

```
      SUBROUTINE SLOPE(TC,COSG,CLI,AL,A,H,C,F,SW,SF,S,U,CLA2D,FMU,
     $AO,CLA,CLO,ALFD,CMF,FA,FB)
      COMMON RHO,PI,G
C     REYNOLDS NUMBER
      R = U*C/1.28E-5
C     2D LIFT CURVE SLOPE AT INF. DEPTH
      CLA2DI = (2.0*PI + 4.7*TC + 4.18*TC**2)*(1.25/6.8**(1.0/ALOG10(R))
     1-6.92*TC/R**0.09)*COSG*COS(SW)
C     "IDEAL" 2D LIFT COEFFT.
      CL01 = CLI*(1.0-5.*(TC)**1.35)
C     EDGE CORRECTION
      E = 1.0 + [illegible]
C     PLANFORM CORRECTION FOR LIFT
      IF(AL-0.4)1,1,2
1     PA = 0.0
      GO TO 5
2     PA =(AL-0.4)/3.6*A/2.0/PI
C     DEPTH FACTOR FOR CAMBER
5     AKO = (36.0*(H/C)**2+ 1.0)/(36.0*(H/C)**2+2.0)
C     DEPTH FACTOR FOR SLOPE
      AKA = (20.0*(H/C)**2 + 1.0)/(20.0*(H/C)**2 + 2.0)
C     2D LIFT CURVE SLOPE
      CLA2D = AKA*CLA2DI
C     AUXILIARY 3D FUNCTION
      ETA = 2.0*H/ (A*C)
C     3D BIPLANE CORRECTION
      SIG = (1.0-0.66*ETA)/(1.055+3.7*ETA)
C     3D WAVE CORRECTION
      GAM = 4.0/(3.0*PI)*(2.0/PI*(1.0+ETA**2)**1.5*(2.0-1.0/(1.0+ETA**2)
     $**0.5)-1.5*ETA)
C     2D FLAP EFFECTIVENESS
      ALFDO = 1.1*SQRT(F)/COSG/COS(SW)
C     FLAP MOMENT CURVE SLOPE
      CMD = 1.6*SQRT(F*(1.0-F)**3)
C     FLAP EDGE CORWECTXON
      EF = 1.0 + ((1.0-F)**2)/(2.0*A)
C     FLAP DEPTH FACTOR
      AJ = 25.0*(1.5-F)
      AKF = (AJ*(H/C)**2+1.0)/(AJ*(H/C)**2+2.0)
C     FLAP PARTIAL SPAN FACTOR
      AKB = SF/S
C     CAMBER CORRECTED LIFT COEFFICIENT
      DDL = H/C-SQRT(0.05*TC/(AKO*CL01))
      IF(DDL-0.1) 8,8,9
8     HC = 0.1 + SQRT(0.05*TC/(AKO*CL01))
      DL = 0.05*TC/HC**2
      GO TO 10
9     DL = 0.05*TC/(H/C)**2
10    CL0 = AKO*CL01-DL
C     ZERO LIFT ANGLE
      AO =-CLO/CLA2D
C     CORRECTED FLAP EFFECTIVENESS
      ALFD = ALFDO*AKF*EF*AKB/AKA
C     INDUCTION FACTOR FOR LIFT
      FA = (1.0 + PA + SIG+FMU)/(PI*A)+ (GAM*C*G/U**2)
C     LIFT CURVE SLOPE
      CLA = 1.0/(E/(CLA2D*AKA)+FA)
```

```
C    FLAP MOMENT RATE  COEFFICIENT
        CMF  =  -CMD*AKB
C   PLANFORM CORRECTION  FOR  DRAG
        IF (AL-0.4)3,3,4
3       PB=0.
        GO  TO  6
4       PB  =  (AL-0.41 /12.0*A/(2.0*PI)
C     INDUCTION FACTOR FOR DRAG
  6     FB  =  (1.0+PB+SIG+FMU)/(PI*A)+GAM*C*G/U**2
        RETURN
        END
```

```
      SUBROUTINE STRUT (H1,B1,DPH,TANG,CS1,CS2,SL,TC1,TC2,U,DELCF,COSGS,
     $Q,DPS)
      HS = H1 . 0.5*B1*TANG-DPH
      CS = CS2 • 0.5*(CS1-CS2)*HS/SL
      R = U*CS/1.28E-5
      TC = TC2 . 0.5*(TC1-TC2)*HS/SL
      CDSF = 0.075/(ALOG10(R)-2.0)**2 . DELCF
      CDSP = 1.0 + 1.2*TC • 60.0*TC**4
      DPS = 2.0*CDSF*CDSP*CS*HS/COSGS*Q
      RETURN
      END


      SUBROUTINE SPRAY (H1,B1,TANG,CS1,CS2,TC1,TC2,SL,Q,DSS)
      HS = H1 • B1*TANG*0.5
      WCS = CS2 • (CS1-CS2) ● ■••♍
      TCS = TC2 • (TC1-TC2)*HS/SL
      DSS = (0.011*WCS**2*TCS + 0.08*(WCS*TCS)**2)*Q
      RETURN
      END


      SUBROUTINE FENCE (CS1,CS2,FL,SL,TC1,TC2,Q,FD)
      CF = CS2 + (CS1-CS2)*FL/SL
      TCF = TC2 + (TC1-TC2)*FL/SL
      FD = 0.009*Q*TCF*CF**2
      RETURN
      END


      SUBROUTINE BUOY (H1,B1,DPH,TANG,COSG,CS1,CS2,TC1,TC2,SL,S,C,TC,
     1PL,PD,FBO,SBO,PBO)
      HS = H1 • 0.5*B1*TANG - DPH
      CS = CS2 + 0.5*(CS1-CS2)*HS/SL
      TCS = TC2 + 0.5*(TC1-TC2)*HS/SL
      FBO = 0.7*C*TC*S
      SBO = 0.7*CS*HS/COSG*CS*TCS
      PBO = 0.55*PD**2*PL
      RETURN
      END
```

```
 SUBROUTINE POD (PL,PD,U,DELCF,Q,DPP)
 COMMON RHO,PI,G
 PLD = PL/PD
 CDPP = 3.0*PLD . 4.5/PLD**0.5 + 21.0/PLD**2
 R = U*PL/1.28E-5
 CDFP = 0.075/(ALOG10(R)-2.0)**2 + DELCF
 DPP = Q*PI/4.0*CDFP*CDPP*PD**2
 RETURN
 END


 SUBROUTINE FOIL (DEL,U,C,DELCF,TC,CLO,CLA2D,S,COSG,Q,FB,ALFD,CLA,
1TRIM,AO,DNW,AI,DPA,DPB,DI)
 R = U*C/1.28E-5
 CDFF = 0.075/(ALOG10(R)-2.0)**2 + DELCF
 CDPF = 1.0 . 1.2*TC + 120.0*TC**4 + 60.0*(TC + 0.2*(CLO . 0.5*
1CLA2D*ALFD*DEL))**4
 DPB = 0.005*(CLA2D*ABS(TRIM + [illegible] + DNW . 0.5*ALFD*DEL))**1.9*S/
1COSG*Q
 DPA = 2.0*CDFF*CDPF*S/COSG*Q
 DI = FB*Q*S*(ALFD*CLA*DEL + CLA*(TRIM-AO+DNW+AI))**2
 RETURN
 END
```

INPUT DATA

UK	EM	EL	FRA	
25.0000	360.0000	97.5000	.9000	22.00::

B1M	B2M	C1M	C2M	H1M	TCM	DELCF
29.0000	18.5000	11.4000	3.8000	14.5000	.0650	. [illegible]
88	C1B	C2B	HB	TCB	DELM	AIMD
19.5000	6.3000	2.1000	2.4700	.0650	3.5000	0.0030
GMD	GSD	CLIM	CLIB	AIBD		
0.0000	14.0000	.3300	.3300	0.0000		
BF1M	BF2M	BF2B	FM	FB	PLB	PDB
10.0000	14.0000	8.7500	.2000	.3000	10.0000	1.5000
CDA	HUB	HKD	PLM	PDM		
.6000	32.0000	24.0000	19.2500	3.5000		
CS1M	CS2M	TC1M	TC2M	SLM	FLM1	FLM2
14.5000	12.5000	.1600	.0800	21.5000	6.5000	1 1.5090
CS1B	CS2B	TC1B	TC2B	SLB	FLB1	FLB2
cr.0000	6.5000	.1600	.0800	13.0000	2.5000	7.0000
DPHM	DPHB					
3.2500	.7500					

OUTPUT DATA

ZERO LIFT ANGLES		LIFT CURVE SLOPES		LIFT COEFFTS		BOW FRACTION
AUM	AUB	CLAM	CLAB	CLM	CLB	WB
-2.8831	-3.0248	3.7955	2.0095	.6604	.5867	01062

TRIM	FLAP ANGLES		DOWNWASH	FLAP EFFECTIVENESS	
TRIM	DELB	DELW	DNW	ALFDM	ALFDB
4.9999	6.9598	5.6919	.0022	.3439	.5660

MAIN FOIL STRUTS AND TOTAL STRUT DRAGS

DPSM	DSSM	FDM	TDSM
1849.	809.	568.	6453.

MAIN FOIL POD DRAGS

DPPM	TDPM
991.	1982.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAM	DPBM	DIM	TDFM	DMF
7769.	2077.	35439.	45285.	53721.

BOW FOIL STRUT DRAG

DPSB	DSSB	FDB	TDSB
153.	14s.	to.	369.

BOW FOIL POD, MISCELLANEOUS AND HULL DRAGS

DPPB	DMIS	DRAGH
228.	1246.	978.

BOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
1178.	274.	5533.	6986.	7583.

TOTAL DRAG AND THRUST HORSEPOWER

Of	THP	UK	EM
63527.	4877.	25.00	360.0

INPUT DATA

UK	EM	EL	FRA	HG
27.5000	360.6060	97.5000	.9000	22.0000

B1M	B2M	C1M	C2M	H1M	TCM	DELCF
29.0000	18.5000	11.4000	3.8000	13.8000	.0650	.0008

BB	C1B	C2B	HB	TCB	DELM	AIMD
19.5000	6.3000	2.1000	3.4800	.0650	3.5000	0.0000

GMD	GSD	CLIM	CLIB	AIBD
0.0000	14.0000	.3300	.3300	0.0000

BF1M	BF2M	BF2B	FM	FB	PLB	PDB
10.0000	14.0000	8.7500	.2000	.3000	10.0000	1.5000

CDA	HUB	HKD	PLM	PDM
.bOOO	32.0000	24.0600	19.2500	3.5000

CS1M	CS2M	TC1M	TC2M	SLM	FLM1	FLM2
12.5000	12.5000	.1600	.0800	21.5000	6.5000	11.5001,

CS1B	CS2B	TC1B	TC2B	SLB	FLB1	FLB2
8.0000	6.5000	.1600	.0800	13.0000	2.5000	7.0000

DPHM	DPHB
3.2500	.7500

OUTPUT DATA

ZERO LIFT ANGLES — LIFT CURVE SLOPES — LIFT COEFFTS BOY FRACTION

AOM	AOB	CLAM	CLAB	CLW	CAY	WB
-2.8628	-2.9802	3.8633	3.4136	.3347	.3165	.1123

TRIM — FLAP ANGLES — DOWNWASH — FLAP EFFECTIVENESS

TRIM	DELB	DELM	DNC	ALFDM	ALFDB
1.9972	.6068	.9268	-.0038	.3451	.5526

MAIN FOIL STRUTS AND TOTAL STRUT DRAGS

DPSM	DSSM	FDM	TDSM
2666.	1419.	1114.	10397.

MAIN FOIL POD DRAGS

DPPM	TDPM
1673.	3746.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAM	DPBM	DIM	TDFM	DMF
14613.	461.	16293.	31367.	45510.

BOW FOIL STRUT DRAG

DPSB	DSSB	FDB	TDSB
734.	384.	138.	1256.

BOW FOIL POD, MISCELLANEOUS AND HULL DRAGS

DPPB	DMIS	DRAGH
430.	1078.	1916.

BOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
2178.	70.	2515.	4763.	6449.

TOTAL DRAG AND THRUST HORSEPOWER

DT	THP	UK	EM
54953.	5906.	35.09	360.0

INPUT DATA

UK	EM	EL	FRA	HG		
30.0000	360.0000	97.5000	.9000	22.0000		
B1M	**B2M**	**C1M**	**C2M**	**H1M**	**TCM**	**DELCF**
29.0900	18.5000	11.4000	3.8000	13.2500	.0650	.0006
BB	**C1B**	**C2B**	**HB**	**TCB**	**DELM**	**AIMD**
19.5000	6.3000	2.1000	4.3000	.0650	3.5000	0.0000
GMD	**GSD**	**CLIM**	**CLIB**	**AIBD**		
0.0000	14.0000	.3300	.3300	0.0000		
BF1M	**BF2M**	**BF2B**	**FM**	**FB**	**PLB**	**PDB**
10.0000	14.0000	8.7500	.2000	.3000	10.0000	1.5000
CDA	**HUB**	**HKD**	**PLM**	**PDM**		
.6000	32.0090	24.0000	19.2500	3.5000		
CS1M	**CS2M**	**TC1M**	**TC2M**	**SLM**	**FLM1**	**FLM2**
12.5000	12.5000	.1600	.0800	21.5000	6.5000	11.5000
CS1B	**CS2B**	**TC1B**	**TC2B**	**SLB**	**FLB1**	**FLB2**
4.0000	6.5000	.1600	.0800	13.0000	2.5~00	1.0000
DPMM	**DPMB**					
3.2500	.7500					

OUTPUT DATA

ZERO LIFT ANGLES		LIFT CURVE SLOPES		LIFT COEFFTS BOY FRACTION		
AOW	AOB	CLAM	CLAB	CLM	CLB	WB
-2.8714	-2.9919	3.8572	3.3000	.4572	• 4A64	.1090

TRIM	FLAP ANGLES		DOWNWASH	FLAP EFFECTIVENESS	
TRIM	DELB	DELM	DNW	ALFDM	ALFDB
3.1994	1.9230	2.5430	-.0027	.3444	.5545

MAIN FOIL STRUTS AND TOTAL STRUT DRAGS

DPSM	DSSW	FDM	TDSM
2311.	1105.	818.	8470.

MAIN FOIL POD DRAGS

DPPM	TDPM
1399.	2798.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAM	DPBM	DIM	TDFM	DMF
10935.	1030.	22897.	34062.	46130.

BOW FOIL STRUT DRAG

DPSB	DSSB	FDB	TDSB
455.	261.	101.	817.

BOW FOIL POD, MISCELLANEOUS AND HULL CRAGS

DPPB	DMIS	DRAGH
321.	1077.	1408.

BOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
1637.	140.	3397.	5174.	6313.

TOTAL DRAG AND THRUST HORSEPOWER

DT	THP	UK	EM
54928.	5060.	30.00	360.0

INPUT DATA

UK	EM	EL	FRA	HG		
35.0000	360.0000	97.5000	.9000	22.0000		
B1M	B2M	C1M	C2M	H1M	TCM	VELCF
29.0000	18.5000	11.~000	3.8000	11.9000	.0650	.0008
BB	C1B	C2B	HB	TCB	DELM	AIMD
19.5000	6.3000	2.1000	5.0000	.0650	3.5000	0.0000
GMD	GSD	CL1M	CL1B	AIBD		
0.0000	14.0000	.3300	.3300	0.0000		
BF1M	BF2M	BF2B	FM	FB	PLY	PDB
10.0000	14.0000	a.7500	.2000	.3000	10.0000	[illegible]
CDA	MU0	HKD	PLM	PDM		
.6000	32.0000	24.0000	19.2500	3.5000		
CS1M	CS2M	TC1M	TC2M	SLM	FLM1	FLM2
12.5000	12.5000	.1600	.0800	21.5000	6.5000	11.5000
CS1B	CS2B	TC1B	TC2B	SLB	FLB1	FLB2
8.0000	6.5000	.1600	.0800	13.0000	2.5000	7.0000
DPHM	DPHB					
3.2500	.7500					

OUTPUT DATA

ZERO LIFT ANGLES | LIFT CURVE SLOPES | LIFT COEFFTS BOW FRACTION

AOM	AOB	CLAM	CLAB	CLM	CLB	Lb
-2.8770	-3.0126	3.8311	3.1349	.5450	.4911	.1075

TRIM | FLAP ANGLES | DOWNWASH | FLAP EFFECTIVENESS

TRIM	DELB	DELM	DNW	ALFDM	ALFDB
4.0013	3.5162	3.8789	-.0011	.3442	.5580

MAIN FOIL STRUTS AND TOTAL STRUT DRAGS

DPSM	DSSM	FDM	TDSM
2072.	951.	688.	7421.

MAIN FOIL POD DRAGS

DPPM	TDPM
1187.	2373.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAW	DPBM	DIM	TDFM	DMF
9287.	1472.	28131.	38890.	48684.

BOW FOIL STRUT DRAG

DPSB	DSSB	FDB	TDSB
294.	155.	85.	579.

BOW FOIL POD, MISCELLANEOUS AND HULL DRAGS

DPPB	DMIS	DRAGH
273.	1130.	1183.

BOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
1396.	195.	4202.	5793.	6645.

TOTAL DRAG AND THRUST HORSEPOWER

DT	THP	UK	EM
57642.	4866.	27.50	360.0

INPUT DATA

UK	EM	EL	FRA	HG		
40.0000	360.0000	97.5000	.9000	22.0000		
B1M	B2M	C1M	C2M	H1M	TCM	DELCF
29.0000	18.5000	11.4000	3.6000	10.2000	.0650	.0008
BB	C1B	C2B	HB	TCB	DELH	AIMD
10.5000	6.3000	2.1000	5.0000	.0650	3.5000	0.0000
GMD	GSO	CLIM	CLIB	AIBD		
0.0000	14.0000	.3300	.3300	0.0000		
BF1M	BF2M	BF2B	FM	FB	PLB	PDB
10.0000	14.0000	8.7500	.2000	.3000	10.0000	1.5000
CDA	HUB	HKD	PLM	PDM		
.6000	32.0000	24.0000	19.2500	3.5000		
CS1M	CS2M	TC1M	TC2M	SLM	FLM1	FLM2
12.5000	12.5000	.1600	.0800	21.5000	6.5000	11.5000
CS1B	CS2B	TC1B	TC2B	SLB	FLB1	FLB2
8.0000	6.5000	.1600	.0800	13.0000	2.5000	7.[illegible]
DPHM	DPHB					
3.2500	.7500					

OUTPUT DATA

ZERO LIFT ANGLES		LIFT CURVE SLOPES		LIFT COEFFTS	BOW FRICTION	
AOM	AOB	CLAM	CLAB	CLM	CLB	WB
-2.8577	-2.9692	3.6090	3.4333	.2553	.2499	.1158

TRIM	FLAP ANGLES		DOWNWASH	FLAP EFFECTIVENESS	
TRIM	DELB	DELM	DNW	ALFDM	ALFDB
.9989	.3662	.5717	-.0038	.3464	.5526

MAIN FOIL STRUTS AND TOTAL STRUT DRAGS

DPSM	DSSM	FDM	TDSM
2746.	1717.	668.	10260.

MAIN FOIL POD DRAGS

DPPM	TDPM
2412.	4825.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAM	DPBM	DIM	TDFM	DMF
18795.	133.	12469.	31398.	46483.

BOW FOIL STRUT DRAG

DPSB	DSSB	FDB	TDSB
943.	502.	180.	1626.

BOW FOIL POD, MISCELLANEOUS AND HULL DRAGS

DPPB	DMIS	DRAGH
553.	1120.	2503.

BOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
2191.	25.	2026.	4848.	7026.

TOTAL DRAG AND THRUST HORSEPOWER

DT	THP	UK	EM
57132.	7019.	40.00	360.0

INPUT DATA

UK	EM	EL	FRA	HG
45.0000	360.0000	97.5000	.9000	22.0000

B1M	B2M	C1M	C2M	H1M	TCM	DELCF
2Y.0000	18.5000	11.4000	3.0000	8.9300	.0650	.0008

BB	C1B	C2B	HB	TCB	DELM	AIMD
19.5000	6.3000	2.1000	5.0000	.0650	3.5000	0.0000

GMD	GSD	CL1M	CL1B	AIBD
0.0000	14.0000	.3300	.3300	0.0000

BF1M	BF2M	BF2B	FM	FB	PLB	PDB
10.0000	14.0000	8.7500	.2000	.3000	10.0000	1.5000

CDA	HUB	HKD	PLW	PDM
.6000	32.0000	24.0000	19.2500	3.5000

CS1M	CS2M	TC1M	TC2M	SLM	FLM1	FLM2
12.5000	12.5000	.1600	.0800	21.5000	6.5000	11.5000

CS1B	CS2B	TC1B	TC2B	SLB	FLB1	FLB2
8.0000	6.5000	.1600	.0800	13.0000	2.5000	7.0000

DPHM	DPHB
3.2500	.7500

ZERO LIFT ANGLES LIFT CURVE SLOWS LIFT COEFFTS BOW FRACTION

AOM	AOB	CLAM	CLAB	CLM	CLB	WB
-2.8536	-2.9597	3.7474	3.4493	.2008	.2040	.1196

TRIM FLAP ANGLES DOWNWASH CLAP EFFECTIVENESS

TRIM	DELB	DELM	DNW	ALFDM	ALFDB
.2527	.3211	.4603	-.0034	.3478	.5526

MAIN FOIL STRUTS AND TOTAL STRUT DRAGS

DPSM	DSSM	FDM	TDSM
2196.	2047.	845.	11375.

MAIN FOIL POD CRAGS

DPPM	TDPM
3016.	6032.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAM	DPBM	DIM	TDFM	DMF
23474.	5.	9851.	33329.	50737.

BOW FOIL STRUT WAG

DPSB	DSSB	FOB	TDSB
1177.	636.	228.	2041.

BOW FOIL PCD,MISCELLANEOUS AND HULL DRAGS

DPPB	DMIS	DRAGH
691.	1236.	3168.

BOW FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
3488.	3.	1697.	5188.	7920.

TOTAL DRAG AND THRUST HORSEPOWER

DT	THP	UK	EM
63061.	8714.	45.00	360.0

INPUT DATA

UK	EM	EL	FRA	HG		
SO .OOOO	360.0000	97.5000	.9000	22.0000		
B1M	B2M	C1M	C2M	H1M	TCM	DELCF
29.0000	18.5000	11.4000	3.8000	8.3300	.0650	.0006
BB	C1B	C28	HB	TCB	DELH	AIMD
19.5000	6.3000	2.1000	5.0000	.0650	3.5000	0.0000
GMD	GSD	CLIM	CLIB	AIBD		
0.0000	14.0000	• 3300	.3300	0.0000		
BF1M	BF2M	BF2B	FM	FB	-- PLB	PDB
IU.OOOO	14.0000	6.7500	.2000	.3000	10.0000	1.5000
CDA	HUB	HUD	PLM	PDM		
.6000	32.0000	24.0000	19.2500	3.5000		
CS1M	CS2M	TC1M	TC2M	SLM	FLM1	FLM2
12.5000	12.5000	.1600	.0800	21.5000	6.5000	11.5000
CS1B	CS2B	TC1B	TC2B	SLB	FLB1	FLB2
8.0000	6.5000	.1600	.0800	A3.0000	2.5000	7.0000
DPHM	DPHB					
3.2500	.7500					

OUTPUT UATA

ZERO LIFT ANGLES   LIFT CURVE SLOPES   LIFT COEFFTS B O Y FRACTION

AOM	AOB	CLAM	CLAB	CLM	CLB	WB
-2.8486	-2.9513	3.7139	3.461 1	.1619	.1713	.1240

TRIM   FLAP ANGLES   DOYNYASH   FLAP EFFECT IVENESS

TRIM	DELB	DELM	DNY	ALFDW	ALFDB
-.0999	-.0297	a.2219	-.0030	.3486	.5526

MAIN FUIL STRUTS AND TOTAL STWUT DRAGS

DPSM	DSSM	FDM	TDSM
3048.	2455.	1043.	13092.

MAIN F O I L POD DRAGS

DPPM	TDPM
3684.	7367.

MAIN FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAM	DPBM	DIM	TDFM	DMF
28638.	28.	7923.	36590.	57049.

BOW F O I L STRUT DRAG

DPSB	DSSB	FDB	TDSB
1436.	785.	282.	2502.

BOW FOIL POD,MISCELLANEOUS AND HULL DRAGS

DPPB	DMIS	DRAGH
843.	1400.	3911.

BOY FOIL PROFILE, INDUCED AND TOTAL ASSEMBLY DRAGS

DPAB	DPBB	DIB	TDFB	DBF
4248.	0.	1468.	5716.	9061.

TOTAL ORAG AND THRUST HORSEPOWER

DT	THP	UK	EM
71422.	1096b.	50.00	360.0

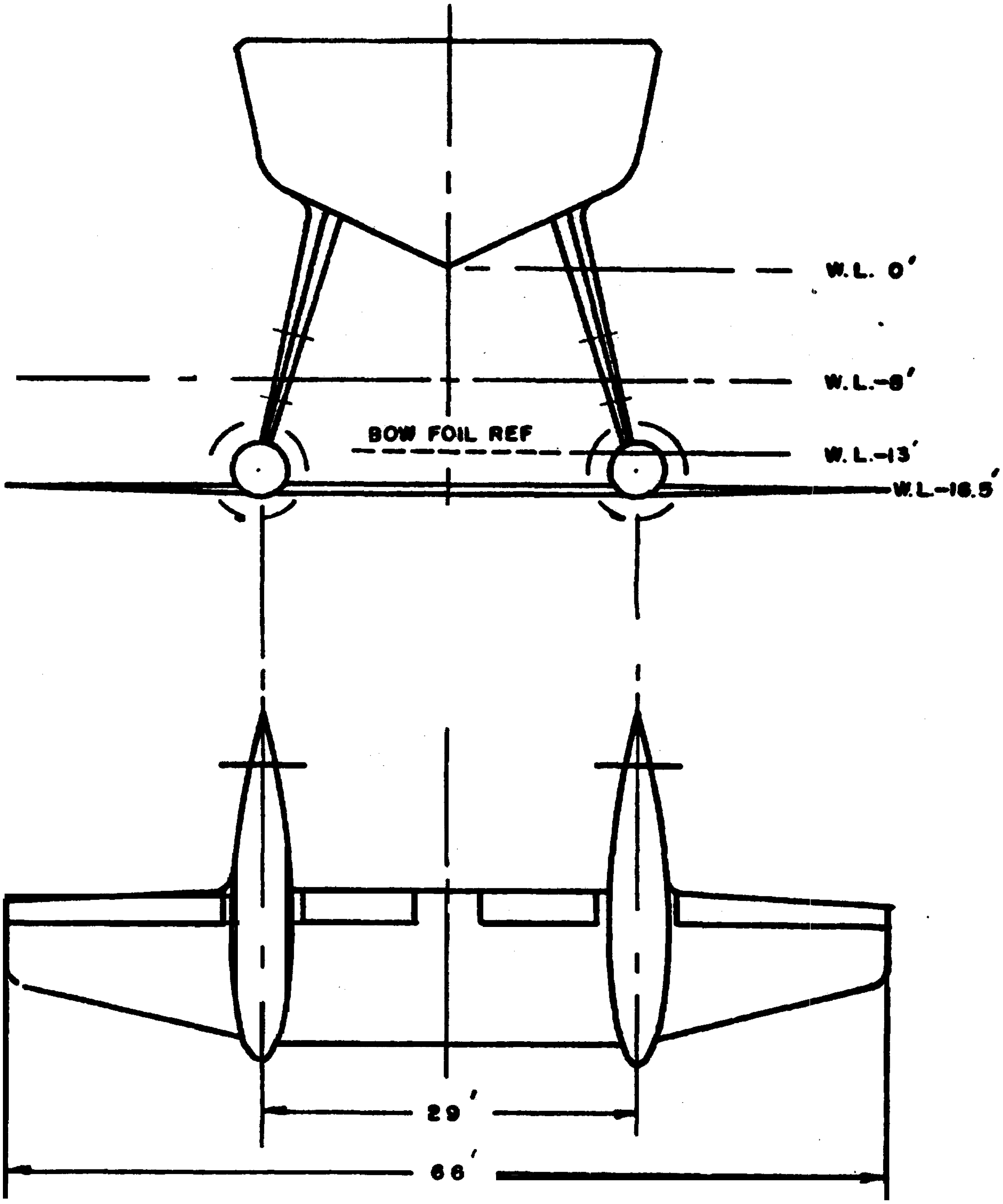

FIG IA TYPE 64 MAIN FOIL GEOMETRY

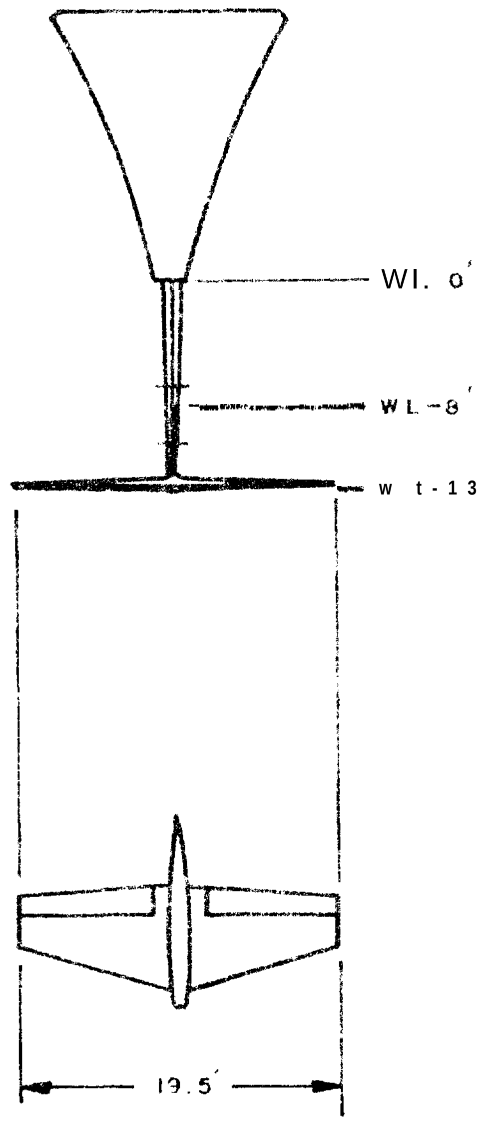

FIG 2A TYPE 64 BOW FOIL GEOMETRY

UNCLASSIFIED

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13. ABSTRACT

A method is presented for prediction of the steady state performance characteristics of craft with hydrofoil systems of the fully-submerged type. The principles have fairly general application but the emphasis is on a canard hydrofoil system of type and size suitable for open ocean operation. Considerable use is made of empirical expressions, with some discussion of their underlying physical basis. Limited comparison is made with experimental data.

DSIS
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KEY WORDS

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