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This supercedes the "Old" Version

DRAFT

HYDROFOIL DESIGN CRITERIA AND SPECIFICATIONS

Volume II
Hydrofoil Ship Hydrodynamic
Specifications and Criteria

10-U16203

VOLUME II

SPECIFICATIONS

Sections 3.3.1 through 3.3.9 of this volume were published in 1980 and 1981 and the masters are in a file cabinet in the Naval Ship Systems area. The art work should be checked because the glue is old.

Sections 3.4 through 3.7 were published in 1983 without benefit of the associated Substantiation and, as expected, preparation of that Substantiation in 1984 required changes in Volume II. Without benefit of publications assistance those changes were made in the most expeditious manner possible, preserving the original pages as far as possible.

Sections 3.8 through 6.2 were written and typed in 1984, again under severe time constraints. No art work was done and time did not permit typing the tables. The masters for Sections 3.8 through 6.2 and portions of 3.4 through 3.7 are the typed. pages and had drawn figures stored with the printed masters in the Naval Ship Systems area.

DRAFT
HYDROFOIL DESIGN CRITERIA AND SPECIFICATIONS

Volume II
Hydrofoil Ship Hydrodynamic
Specifications and Criteria

Contract N00600-76-C-0246, Task 010

Grumman Aerospace Corporation
Bethpage, New York 11714

CONTENTS

CONTENTS (contd.

CONTENTS (contd.)

CONTENTS (contd)

CONTENTS (contd.)

ILLUSTRATIONS

TABLES

1. SCOPE

This specification establishes the component and total craft hydrodynamic performance prediction and quality assurance requirements for hydrofoil ships and is intended to insure that those predictions are well defined, state of the art, and directly comparable for distinct design agencies. This specification is limited to craft having hydrofoils of conventional (thin trailing edge) section and maximum speeds of 60 knots.

Sections 3.1 and 3.2 of this specification define the hull characteristics; Section 3.3 defines the hydrofoil section characteristics, and sections 3.4 through 3.10 assemble various characteristics of the craft and its components from preceding sections. Section: 4 specifies test requirements in support of those performance predictions for which the state of the art confidence level is inadequate and for which the state of the art test procedures are effective. Section 5 specifies the content and format for summaries of predicted craft performance characteristics.

2. APPLICABLE DOCUMENTS

The following companion Design Criteria and specifications for U.S. Navy Hydrofoil Ships form a part of this specification:

Volume I	General Information Manual
Volume IA	General Information Manual - Technical Substantiation
Volumes IIA,B	Hydrodynamic and Performance Prediction Criteria - Technical Substantiation
Volume III	Hydrofoil Ship Control and Dynamics Specifications and Criteria
Volume IIIA	Hydrofoil Ship Control and Dynamics Specifications and Criteria - Technical Substantiation
Volume IV	Structural Design Criteria
Volume IVA	Structural Design Criteria - Technical Substantiation
Volume V	Propulsion System Design Criteria
Volume V	Propulsion System Design Criteria - Technical Substantiation

3. REOUIREMENTS

3.1 Hull Hydrostatics (to be supplied)

3.2 Hull Hydrodynamic (to be supplied)

3.3 Section Characteristics.

3.3.1 Section Lift.

3.3.1.1 Reynolds Number and Mach Number Effects. Smooth surface section lift curve slopes measured at Reynolds Numbers less than 3 x 10^6 shall be corrected by the factor:

$$\frac{c_{\ell_{\alpha RN}}}{c_{\ell_\alpha}} = .874 + .042 \text{ RN} \times 10^{-6} \qquad 3.3.1.1\text{-}1$$

Where NACA standard roughness transition is employed the correction factor shall be:

$$\frac{c_{\ell_{\alpha RN}}}{c_{\ell_\alpha}} = .79 + .07 \text{ RN} \times 10^{-6} \qquad 3.3.1.1\text{-}2$$

Aerodynamic section lift curve slopes measured at Mach Numbers of .3 or more shall be corrected by the factor:

$$\frac{c_{\ell_\alpha}}{c_{\ell_{\alpha M}}} = \sqrt{1 - M^2} \qquad 3.3.1.1\text{-}3$$

The nominal precision associated with the measurement of section lift curve slope is ±5%.

Measured section zero lift angles shall not be corrected for Reynolds Number or Mach Number.

The nominal precision associated with the measurement of section zero lift angle is ±1/3°. Model zero lift angle shifts of –1/2 degree or more shall be considered indicative of scale effect.

3.3.1.2 Section Lift Curve Slope. The section lift curve slope shall be predicted by:

$$\kappa = 1 + c_{1_\kappa} \frac{t}{c} + c_{2_\kappa} \left(\frac{t}{c}\right)^2 \qquad 3.3.1.2\text{-}1$$

where: $c_{1_\kappa} = .77 - \mathring{m}_\phi \, \mathring{c}_\phi$

$c_{2_\kappa} = .77 \, \mathring{m}_\phi \, \mathring{c}_\phi$

$\mathring{m}_\phi$ = 0.00715 for 4 & 5 digit sections, for l&series sections,, for 63-series sections, and generally for sections of $(x/c)_{t/c_{max}} \leq 35\%$

= .01059 for sections of $(x/c)_{t/c_{max}} > 35\%$ except 16-series sections

$\mathring{c}_\phi = \mathring{\phi}_{5\%} / t/c$

The nominal precision associated with the prediction of the lift curve slope is ±5%.

3.3.1.3 Section Zero Lift Angle. The section zero lift angle shall be predicted by:

$$\alpha_{0\ell} = \kappa_0 \alpha_{0\ell_{pot}} + a \qquad 3.3.1.3\text{-}1$$

$$= \kappa_0 (\alpha_i - c_{\ell_i}/2\pi) \pm \sigma$$

where: κ_0 = .74 for 16- and 6-series sections on a = 1.0 mean line

= .93 for 4 digit sections and 6A series sections on a = 1.0 mean line

= 1.08 for 5 digit sections

= 1.15 for 6-series sections on a < 1.0 mean line

σ = 1/3 deg.

For other sections, substantiation satisfactory to the procuring agency shall be supplied for the value of κ_0 employed in Equation 3.3.1.3-k

3.3.1.4 Section Effective Design Lift Coefficient. The section effective design lift coefficient shall be predicted by:

$$c_{\ell_{i_{eff}}} = \left[2\pi \frac{\alpha_i}{c_{\ell_i}} (1 - \kappa_0) + \kappa_0\right] \kappa\, c_{\ell_i} \pm \sigma \qquad 3.3.1.4\text{-}1$$

$$= \kappa_0 \kappa\, c_{\ell_i} \pm \sigma \text{ for a = 1.0 mean line}$$

where: κ is from Equation 3.3.1.2-1

κ_0 is from Equation 3.3.1.3-I

σ = .03

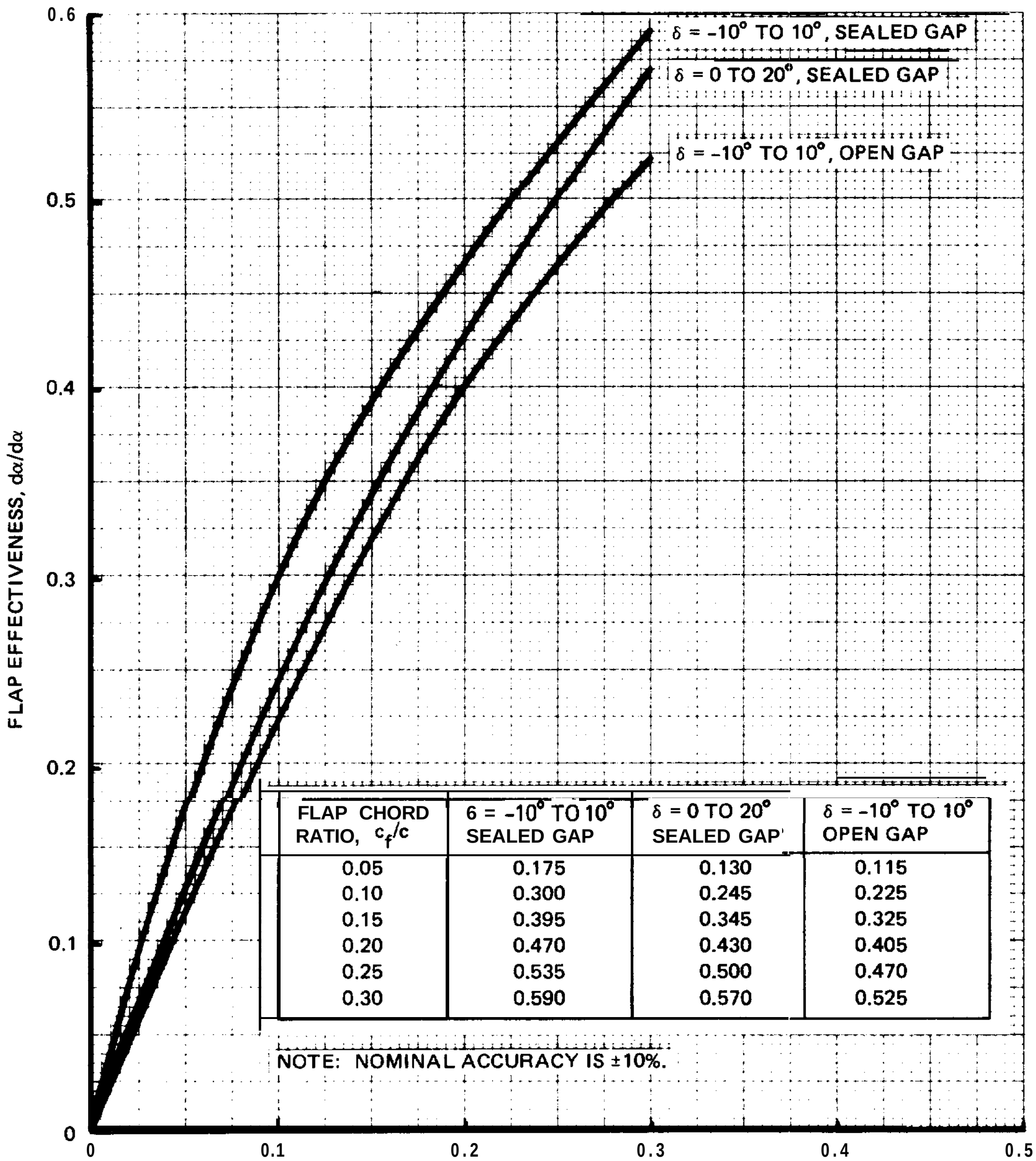
3.3.1.5 Flap Effectiveness.

3.3.1.5.1 Trailing Edge Flap. The effectiveness of Figure 3.3.1-1 shall be employed.

3.3.1.5.2 Other Flap Configurations. For flap configurations other than the trailing edge flap, substantiation satisfactory to the procuring agency shall be provided for the predicted effectiveness.

3.3.1.6 Section Lift Curve. Predicted section lift curves shall be provided in the form:

$$c_\ell = c_{\ell_0} + c_{\ell_\alpha} (\alpha + \frac{d\alpha}{d\delta} \delta) \qquad 3.3.1.6\text{-}1$$



FLAP CHORD RATIO, c_f/c	δ = -10° TO 10° SEALED GAP	δ = 0 TO 20° SEALED GAP	δ = -10° TO 10° OPEN GAP
0.05	0.175	0.130	0.115
0.10	0.300	0.245	0.225
0.15	0.395	0.345	0.325
0.20	0.470	0.430	0.405
0.25	0.535	0.500	0.470
0.30	0.590	0.570	0.525

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Figure 3.3.1-1 Toll Flap Effectiveness

1

3.3.2 Section Lift Distribution.

3.3.2.1 Additional Lift Distribution. For section thickness distributions not included in Reference 1 the thick airfoil potential theory relative lift distribution, c_{ℓ_x}/c_ℓ, and corresponding aerodynamic center shall be presented.

3.3.2.2 Viscous Effect. For 16-series thickness distributions, thickness distributions not included in Reference 1, and for all sections of thickness ratio greater than 15%; the additional lift distribution of Section 3.3.2.1 shall be adjusted by the increment:

$$\frac{A\, c_{\ell_{xb}}}{c_\ell} = P_{ac}\, A\ a.c. \qquad 3.3.2.2\text{-}1$$

where: $A\ a.c. = a.c._{pot} - a.c.$

$a.c._{pot}$ = aerodynamic center of Section 3.3.2.1

a.c. = aerodynamic center of Section 3.3.3.1

and where Pope's P_{ac} function is defined by

$$P_{ac} = 366.717\ \frac{x}{c} - 12{,}079.49\left(\frac{x}{c}\right)^2 + 217{,}528\left(\frac{x}{c}\right)^3 - 1{,}933{,}922\left(\frac{x}{c}\right)^4 + 6{,}546{,}669\left(\frac{x}{c}\right)^5 \qquad 0 \leq \frac{x}{c} \leq .1 \qquad 3.3.2.2\text{-}2$$

$$P_{ac} = 6.84921 \quad -13.6984: \qquad .1 \leq \frac{x}{c} \leq .9$$

$$P_{ac} = - P_{ac_{L.E.}} \qquad .9 \leq \frac{x}{c} \leq 1$$

3.3.2.3 Basic Lift Distribution. For camber lines not included in Reference 1 the thin airfoil potential theory relative lift distribution, relative ideal angle of attack, and relative quarter-chord moment; c_{ℓ_x}/c_{ℓ_i}, α_i/c_{ℓ_i}, and $c_{m_{c/4}}/c_{\ell_i}$; shall be presented.

The lift distribution of thin airfoil potential theory shall be employed for all the camber lines of Reference 1 except for a > .94 camber lines for which the a = .94 lift distribution shall be employed at the nominal ideal angle of attack.

Substantiation satisfactory to the procuring agency shall be supplied for the lift distribution employed for camber lines not included in Reference 1.

3.3.2.4 Flap Lift Distribution. Flap lift distribution shall be predicted by:

$$\frac{(c_{\ell_x})_\delta}{(c_\ell)_\delta} = (1-\zeta)\left(\frac{c_{\ell_x}}{c_\ell}\right)_a + \zeta \frac{(c_{\ell_{xb}})_\delta}{(c_{\ell_b})_\delta} \qquad 3.3.2.2\text{-}3$$

where: $\zeta = \sqrt{\frac{h}{c}\left(1-\frac{h}{c}\right)} \Big/ \left[\frac{1}{2}\cos^{-1}\left(2\frac{h}{c}-1\right) + \sqrt{\frac{h}{c}\left(1-\frac{h}{c}\right)}\right]$

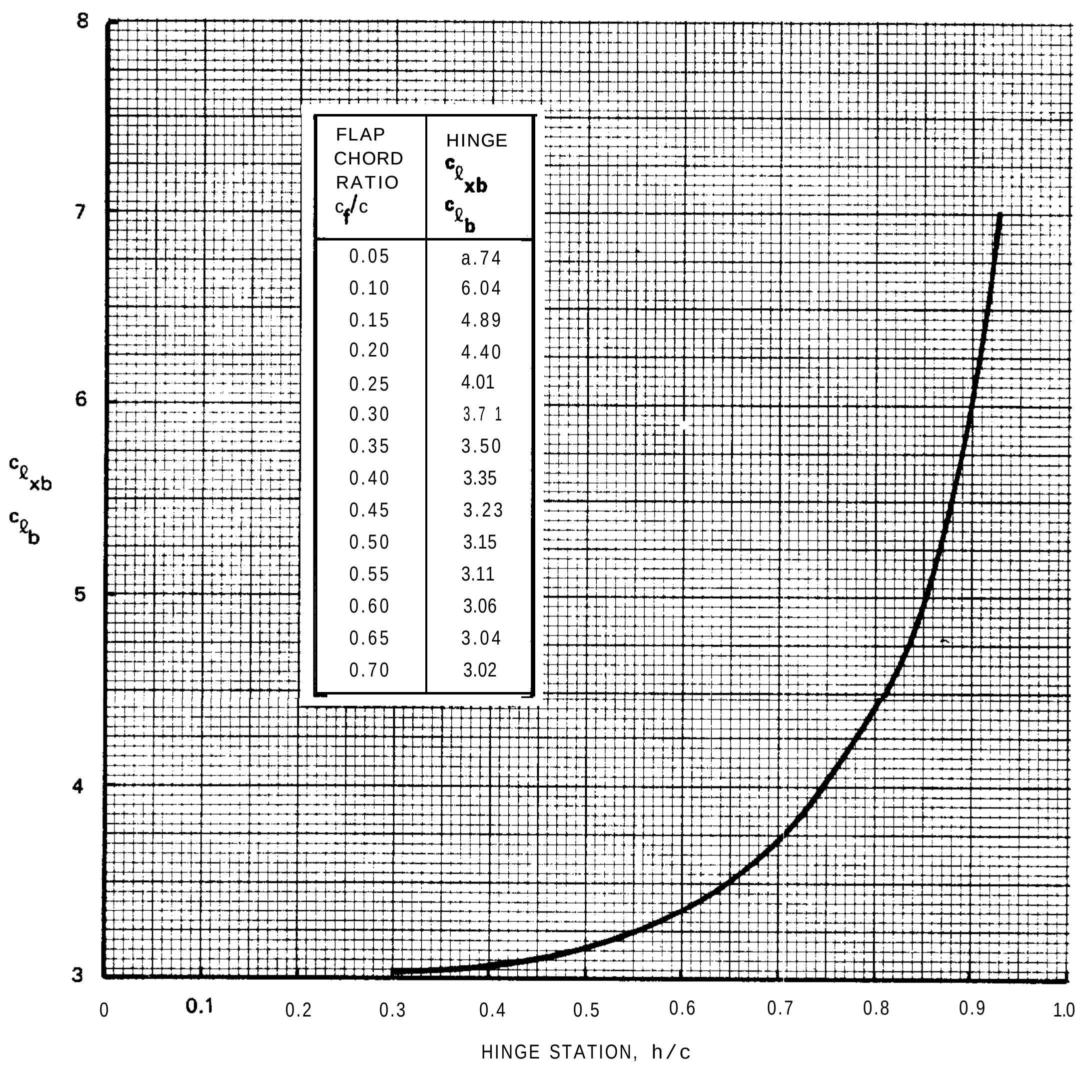
$\left(\frac{c_{\ell_x}}{c_\ell}\right)_a$ is the additional lift distribution of Sections 3.3.2.1 and 3.3.2.2

$$\frac{(c_{\ell_{xb}})_\delta}{(c_{\ell_b})_\delta} = \frac{1}{\pi\sqrt{\frac{h}{c}\left(1-\frac{h}{c}\right)}} \ln \frac{\left(\sqrt{\frac{h}{c}}\sqrt{1-\frac{x}{c}} + \sqrt{1-\frac{h}{c}}\sqrt{\frac{x}{c}}\right)^2}{\left|\frac{h}{c}-\frac{x}{c}\right|} \qquad \frac{x}{c} \neq \frac{h}{c}$$

$\frac{(c_{\ell_{xb}})_\delta}{(c_{\ell_b})_\delta}$ is from Figure 3.3.2-l for $\frac{x}{c} = \frac{h}{c}$

REFERENCES

1. Abbott, Ira H. and vonDoenhoff, Albert E.: Theory of Wing Sections. Dover, 1959.



FLAP CHORD RATIO c_f/c	HINGE $\frac{c_{\ell_{xb}}}{c_{\ell_b}}$
0.05	a.74
0.10	6.04
0.15	4.89
0.20	4.40
0.25	4.01
0.30	3.7 1
0.35	3.50
0.40	3.35
0.45	3.23
0.50	3.15
0.55	3.11
0.60	3.06
0.65	3.04
0.70	3.02

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Fig. 3.3.2-1 Flap Hinge Line Lift Coefficient

1

3.3.3 Section Pitching Moment

3.3.3.1 Section Pitching Moment. The aerodynamic centers of Figure 3.3.3-l shall be employed for 4- and 5-digit, 16-series, and 6-series sections.

For the same sections, the moment about the aerodynamic center shall be predicted by:

$$c_{m_{ac}} = -c_{\ell_{i_{eff}}} (c.p._c - a.c.) + \sigma \qquad 3.3.3\text{-}1$$

where: $c_{\ell_{i_{eff}}}$ is from Equation 3.3.1.4-1

a.c. is from Figure 3.3.3-l

$c.p._c$ is the thin airfoil potential value except for a $\geqslant .94$ mean lines for which it is ,485

σ = 0 to .012 for 4 digit sections

= .006 to .020 for 5 digit sections

= ± .006 for all other sections

3.3.3.2 Flap Lift Pitching Moment Slope. The flap lift pitching moment slope shall be predicted by:

$$dc_{m_{ac}}/d(c_\ell)_\delta = -\zeta(c.p._\delta - a.c.) \qquad 3.3.3\text{-}2$$

$$dc_{m_{ac}}/d\delta = -\zeta(c.p._\delta - a.c.)\, c_{\ell_\delta}$$

where: ζ is from Equation 3.3.2.2-3

$c.p._\delta = \frac{1}{4} + \frac{1}{2}\frac{h}{c}$

a.c. is from Figure 3.3.3-l

$c_{\ell_\delta} = c_{\ell_\alpha} d\alpha/d\delta$

c_{ℓ_α} is from Equation 3.3.1.2-1

$d\alpha/d\delta$ is from Figure 3.3.1-l

3.3.3.3 Section Moment Curve. Presentations of the total section pitching moment shall be in the form:

$$c_{m_{ac\ total}} = c_{m_{ac}} + (c_\ell)_\delta\, dc_{m_{ac}}/d(c_\ell)_\delta \qquad 3.3.3\text{-}3$$

where: $c_{m_{ac}}$ is from Equation 3.3.3-l

$dc_{m_{ac}}/d(c_\ell)_\delta$ is from Equation 3.3.3-2

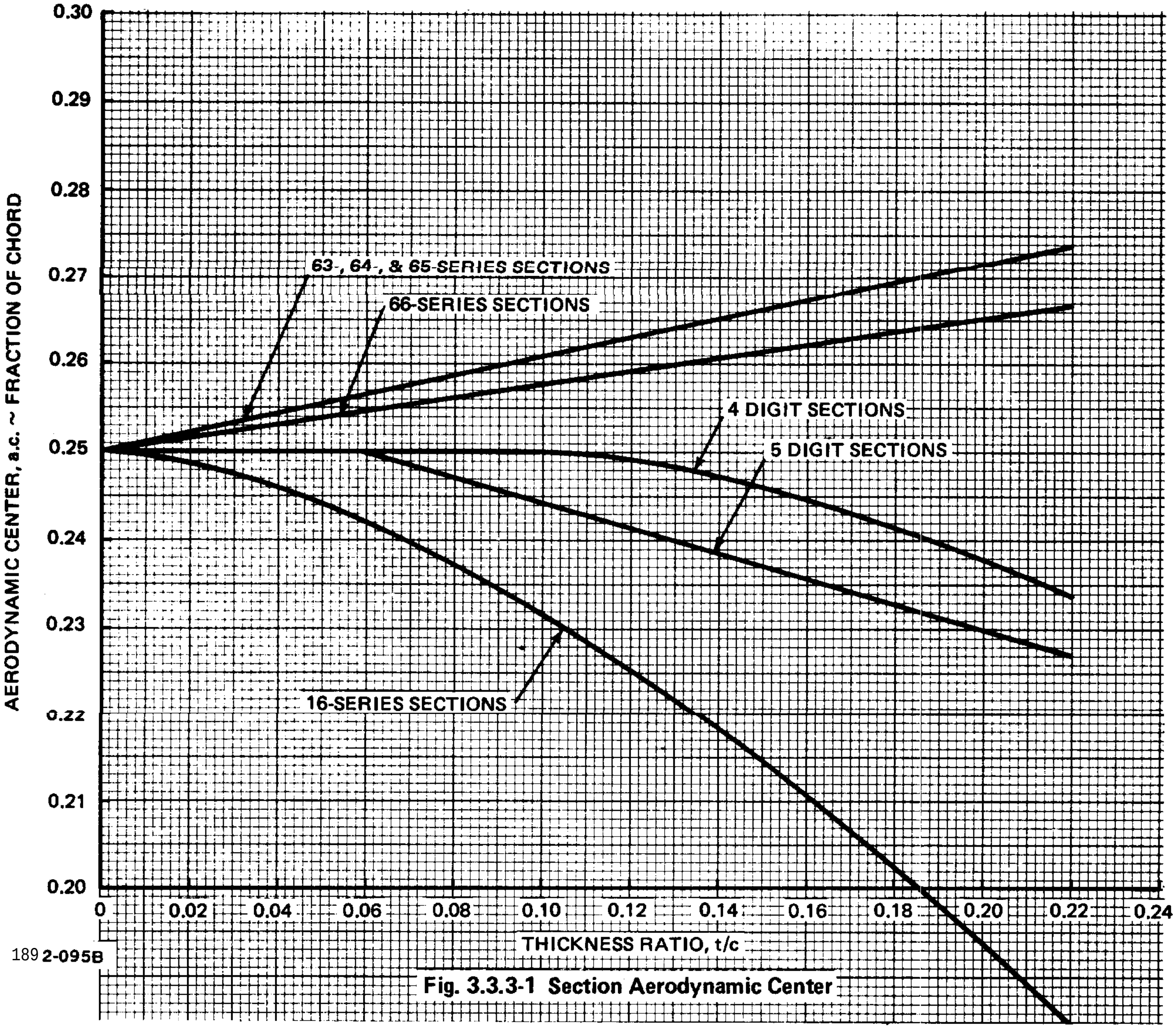


Fig. 3.3.3-1 Section Aerodynamic Center

3.3.4 Section Flap Hinge Moment.

3.3.4.1 Residual Flap Hinge Moment. The residual flap hinge moment shall be predicted by:

$$\frac{c_{h_0}}{c_{\ell_{i_{eff}}}} = -\left(\frac{c}{c_f}\right)^2 \int_{h/c}^{1} \left(\frac{x}{c} - \frac{h}{c}\right) \frac{c_{\ell_x}}{c_{\ell_{i_{eff}}}} \, d\frac{x}{c} \qquad 3.3.4\text{-}1$$

where: $c_{\ell_{i_{eff}}}$ is from Equation 3.3.1.4-1

$c_{\ell_x}/c_{\ell_{i_{eff}}}$ is the basic lift distribution of Section 3.3.2.3

3.3.4.2 Flap Hinge Moment Due to Angle of Attack. The flap hinge moment due to angle of attack shall be predicted by:

$$c_{h_{c_{\ell\alpha}}} \equiv (c_h)_\alpha/(c_\ell)_\alpha \qquad 3.3.4\text{-}2$$

$$= c_{h_{c_{\ell\alpha 0}}} + .183\, t/c + \Delta\, a.c.\left(\frac{c}{c_f}\right)^2 \int_{h/c}^{1} \left(\frac{h}{c} - \frac{x}{c}\right) P_{ac}\, d\frac{x}{c} + \Delta\, c_{h_{c_{\ell\alpha}}}$$

where: $$c_{h_{c_{\ell\alpha 0}}} = -\frac{1}{\pi}\left(\frac{c}{c_f}\right)^2 \left[\left(\frac{h}{c} + \frac{1}{2}\right)\sqrt{\frac{h}{c}\left(1 - \frac{h}{c}\right)} - \left(\frac{h}{c} - \frac{1}{4}\right)\cos^{-1}\left(2\frac{h}{c} - 1\right)\right]$$

$\Delta\, a.c. = a.c._{pot} - a.c.$

$a.c._{pot}$ = aerodynamic center of Section 3.3.2.1

$a.c.$ = aerodynamic center of Section 3.3.3.1

P_{ac} is from Equation 3.3.2.2-2

$\Delta\, c_{h_{c_{\ell\alpha}}} = .0055\, \Delta\phi^\circ$

$\Delta\phi$ = trailing edge bevel angle $- \phi_{5\%}$

Nominal accuracy is ± .01 for the true contour flap and ± .04 for the beveled trailing edge flap.

3.3.4.3 Flap Hinge Moment Due to Flap Deflection. The flap hinge moment due to flap deflection shall be predicted by:

$$c_{h_{c_{\ell\delta}}} \equiv (c_h)_\delta/(c_\ell)_\delta \qquad 3.3.4\text{-}3$$

$$= (1 - \zeta)\, c_{h_{c_{\ell\alpha}}} + \zeta\, c_{h_{c_{\ell b\delta}}} + \Delta\, c_{h_{c_{\ell\delta}}}$$

where: ζ is from Equation ~~3.3.2-3~~

$c_{h_{c_{\ell\alpha}}}$ is from Equation 3.3.4-2

$c_{h_{c_{\ell b \delta}}} = c_{h_{c_{\ell b \delta 0}}} + .1557 \frac{t/c}{c_f/c}$

$c_{h_{c_{\ell b \delta 0}}}$ is from Figure 3.3.4-l

$\Delta c_{h_{c_{\ell\delta}}} = .0055 \, A\phi^\circ$

$A\phi$ = trailing edge bevel angle $- \phi_{5\%}$

Nominal accuracy is ± .02 for the true contour flap and ± .04 for the beveled trailing edge flap.

3.3.4.4 Section Flap Hinge Moment. The total flap hinge moment shah be predicted by:

$$c_h = c_{h_0} + c_{h_{c_{\ell\alpha}}} (c_\ell)_\alpha + c_{h_{c_{\ell\delta}}} (c_\ell)_\delta \qquad 3.3.4\text{-}4$$

where: c_{h_0} is from Equation 3.3.4-l

$c_{h_{c_{\ell\alpha}}}$ is from Equation 3.3.4-2

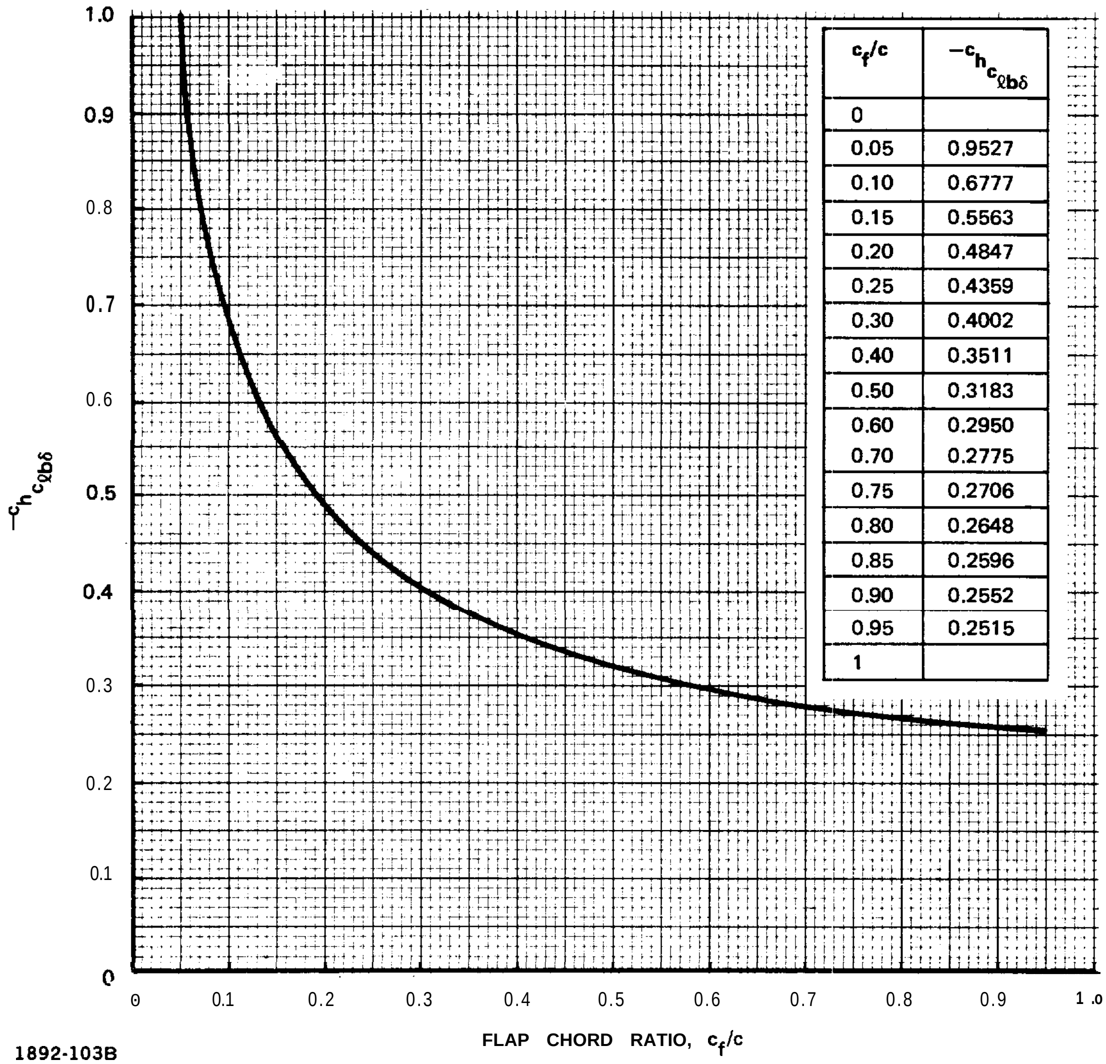
$c_{h_{c_{\ell\delta}}}$ is from Equation 3.3.4-3

Section flap hinge moment data shah be presented in the form:

$$c_h = c_{h_0} + c_{h_{c_{\ell\alpha}}} c_{\ell_\alpha} \left(\alpha + \frac{c_{h_{c_{\ell\delta}}}}{c_{h_{c_{\ell\alpha}}}} \frac{d\alpha}{d\delta} \delta \right) \qquad 3.3.4\text{-}5$$

where : c_{ℓ_α} is from Equation 3.3.1.2-1

$\frac{d\alpha}{d\delta}$ is from Figure 3.3.1-1



c_f/c	$-c_{h_{c_{\ell b\delta}}}$
0	
0.05	0.9527
0.10	0.6777
0.15	0.5563
0.20	0.4847
0.25	0.4359
0.30	0.4002
0.40	0.3511
0.50	0.3183
0.60	0.2950
0.70	0.2775
0.75	0.2706
0.80	0.2648
0.85	0.2596
0.90	0.2552
0.95	0.2515
1	

Fig. 3.3.4-l Flap Hinge Moment Parameter, $c_{h_{c_{\ell b\delta}}}$

3.3.5 Linear Lift Range. The section and flap lift curves shall be assumed to be linear between the upper and lower surface lift effect boundaries of Section 3.8.

3.3.6 Section Maximum Lift. A requirement for the estimation of the foil section aerodynamic maximum lift coefficient is defined in Section 3.8.

3.3.7 Free Surface Effect.

3.3.7.1 Lift Curve Slope. The hydrodynamic lift curve slope shall be predicted by:

$$c_{\ell_\alpha} = c_{\ell_{\alpha_\infty}} \Big/ \left[1 + \frac{\Omega}{(4\,h/c)^2 + 1} + \frac{f(F_h)}{h/c}\right] \qquad 3.3.7.1\text{-}1$$

where: $c_{\ell_{\alpha_\infty}}$ is the aerodynamic section lift curve slope of Equation 3.3.1.2-l

$$\Omega = 1 - 8\, f\,(Fh)\, Ei\,(2/F_h^2)$$

$$f(Fh) = e^{-2/F_h^2} / 2\, F_h^2$$

$$F_h = V/\sqrt{gh}$$

3.3.7.2 Zero Lift Angle. The aerodynamic section zero lift angle of Equation 3.3.1.3-1 shall be employed for all depths greater than 1/2 chord and for all depth Froude numbers greater than $\sqrt{2}$.

3.3.7.3 Free Surface Effect. Predicted hydrodynamic lift curves shall be provided in the form:

$$c_\ell = \frac{c_{\ell_\alpha}}{c_{\ell_{\alpha_\infty}}}\, c_{\ell_\infty}$$

where: c_{ℓ_∞} is the aerodynamic lift coefficient of Equation 3.3.1.6-1

$c_{\ell_\alpha}/c_{\ell_{\alpha_\infty}}$ is from Equation 3.3.7.1-1

The aerodynamic lift distribution of Section 3.3.2 shall be employed for the hydrodynamic case.

3.3.8 Section Cavitation Characteristics. The cavitation boundary for any chord station shall be predicted by :

$$\sqrt{S} = \frac{v}{V} \pm \frac{\Delta v/V}{c_{\ell_{i_{ref}}}} c_{\ell_{i_{eff}}} \pm \frac{\Delta v_a{}'}{V} (c_\ell)_\alpha \pm \left(\frac{\Delta v_a{}'}{V} + \zeta\,\Omega\right)(c_\ell)_\delta \qquad 3.3.8\text{-}1$$

where: $S = 1 + \sigma_c$

σ_c = cavitation number for incipient cavitation

$\pm$ is for $\frac{\text{upper}}{\text{lower}}$ surface

$c_{\ell_{i_{eff}}}$ is from Equation 3.3.1.4-1

$(c_\ell)_\alpha$ is the lift coefficient due to angle of attack, $c_{\ell_\alpha}\alpha$

$(c_\ell)_\delta$ is the lift coefficient due to flap angle, $c_{\ell_\alpha}\frac{d\alpha}{d\delta}\delta$

c_{ℓ_α} is the section lift curve slope, $2\pi\kappa$

κ is from Equation 3.3.1.2-1

$\frac{d\alpha}{d\delta}$ is from Figure 3.3.1-1

$\frac{v}{V}$ is the inviscid relative velocity due to thickness distribution, from Appendix I of Reference 1 or equivalent

$\Delta v/V/c_{\ell_{i_{ref}}}$ is the inviscid thin airfoil incremental relative velocity due to camber, from Appendix II of Reference 1 or equivalent

$$\frac{\Delta v_a{}'}{V} = \frac{\Delta v_a}{V} + \frac{P_{ac}\,\Delta a.c.}{4\,v/V}$$

$\frac{\Delta v_a}{V}$ is the inviscid incremental relative velocity due to angle of attack for the thickness distribution, from Appendix I of Reference 1 or equivalent

P_{ac} is from Equation 3.3.2.2-2

$\Delta a.c. = a.c._{pot} - a.c.$

$a.c._{pot}$ = aerodynamic center of Section 3.3.2.1

a.c. = aerodynamic center of Section 3.3.3.1

ζ is from Equation 3.3.2-3

$$\Omega = \frac{(\Delta v/V)_F}{c_{\ell_{b\delta}}} - \frac{\Delta v_a'}{V}$$

$$\frac{(\Delta v/V)_F}{c_{\ell_{b\delta}}} = \frac{1}{4\pi\sqrt{\frac{h}{c}(1-\frac{h}{c})}} \ln \frac{\left(\sqrt{\frac{h}{c}}\sqrt{1-\frac{x}{c}}+\sqrt{1-\frac{h}{c}}\sqrt{\frac{x}{c}}\right)^2}{\left|\frac{h}{c}-\frac{x}{c}\right|} \quad \text{for } \frac{x}{c} \neq \frac{h}{c}$$

$$= 1.3\left[\frac{1}{2} + 0.175\,(c_f/c)^{-3/4}\right] \text{ for } \frac{x}{c} = \frac{h}{c} \text{ and } \delta \leqslant 15^\circ$$

Except for **16-Series** sections for which;

$$\frac{(\Delta v/V)_F}{c_{\ell_{b\delta}}} = 1.5\left[\frac{1}{2} + 0.175\,(c_f/c)^{-3/4}\right] \text{ for } \frac{x}{c} = \frac{h}{c} \text{ and } \delta \leqslant 15^\circ$$

The cavitation bucket for the unflapped section **shall** be defined in the speed-loading plane by the lower surface **1/2%** chord station, the most restrictive upper surface mid-chord station, and the section loading at the intersection of the upper surface **1-1/4%** chord and most restrictive mid-chord stations.

The cavitation bucket for the flapped section **shall** be defined in the flap and pitch angle plane by the upper surface chord station 5% of the chord forward of the flap hinge, the most restrictive upper surface mid-chord station, the flap angle at the intersection of the upper surface l-1/4% chord and most restrictive mid-chord stations, and/or the lower surface **1/2%** chord station.

REFERENCES

1. Abbott, Ira H. and Von Doenhoff, Albert E.: Theory of Wing Sections. Dover Publications, 1959.

3.3.9 Section Drag Characteristics. The section drag shall be predicted by:

$$c_d = c_{d_{min}} + K_{wake_b}(c_{\ell_b})_\delta^2 + K_{wake}[(c_\ell)_\alpha + (c_{\ell_a})_\delta]^2 \qquad 3.3.9\text{-}1$$

where: $c_{d_{min}} = Rc_{d_{ft}}$

$R = 1 + 1.2\ t/c + 100(t/c)^4$ for sections having maximum thickness at 40% or more of chord. For other sections a value for R must be supplied and documented.

$$c_{d_{ft}} = .16957[\log(RN \times 10^{-6}) + 4.3815]^{-2}$$

or

$$= .59875(\log c + 6.6895)^{-2.5} \text{ for c in meters}$$

$$= .59875(\log c + 6.1735)^{-2.5} \text{ for c in ft.}$$

whichever is greater

$K_{wake} = .005$

$K_{wake_b} = .12$ for $\delta > 0$

$= .01$ for $\delta < 0$

$$(c_{\ell_b})_\delta = \zeta(c_\ell)_\delta$$

$$(c_{\ell_a})_\delta = (c_\ell)_\delta - (c_{\ell_b})_\delta = (1 - \zeta)(c_\ell)_\delta$$

ζ is from Equation 3.3.2.2-3

$$(c_\ell)_\delta = c_{\ell_\alpha} \frac{d\alpha}{d\delta} \delta$$

$d\alpha/d\delta$ is from Figure 3.3.1-1

$$c_{\ell_\alpha} = 2\pi\kappa$$

κ is from Equation 3.3.1.2-1

$$(c_\ell)_\alpha = c_{\ell_\alpha} \alpha = c_\ell - c_{\ell_{i_{eff}}}$$

$c_{\ell_{i_{eff}}}$ is from Equation 3.3.1.4-1

No confidence level has been established for this equation, and no **hydrodynamic** data can be offered in its support. The hydrodynamic model data available demonstrates Reynolds Number distortions which preclude model measurement of prototype drag for the general case for current experimental practice.

3.4 Circulation Distribution

3.4.1 Foil Circulation Distribution

3.4.1.1 Definitions "Picth Lift", $(C_L)_\alpha$, is that lift which results when the foil and pod(s) experience the same angle of attack. All lift is pitch lift when the foil is rigidly attached to the pod. Craft and orbital motions produce pitch lift for any foil configuration.

"Incidence Lift", $(C_L)_i$, is that lift produced by foil angular deflection relative to the pod.

"Full Chord Flap Lift" is that lift produced by deflection of a full chord flap located over the spanwise extent of a lift control flap.

"Foil Twist" refers to a spanwise variation in section zero lift angle, relative to that for the section at the plane of 'Symmetry, produced by mean line twist and/or by section geometry variation on the span. Discontinuites in the section zero lift angle distribution over the span shall be treated as full chord flap lift cases.

"Basic" foil lift distribution is the spanwise lift distribution for zero pod angle of attack, zero flap deflection, and zero incidence lift. The untwisted foil presents no basic lift.

"Additional" foil lift is that lift due to pitch angle of attack, incidence angle realtive to the zero lift incidence angle, and/or flap deflection.

All circulation distributions shall be estimated for the aerodynamic (infinite depth) case, for a 2π section lift curve slope, and for zero Mach number.

3.4.1.2 Symmetric Lift Distribution - The estimated distribution of circulation over one semi-span of each foil shall be presented graphically in the non-dimensional form:

$$\frac{G}{\delta_1} = \frac{\Gamma}{bV\delta_1} = \frac{c_l c}{2b\delta_1} \text{ vs. } \eta \text{ for additional lift} \qquad 3.4.1.2\text{-}1$$

$$G_0 = \frac{\Gamma_0}{bC} = \frac{c_{l_o}}{2b} \text{ vs. } \eta \text{ for basic lift}$$

For each foil the basic circulation distribution and the additional circulation distribution for pitch, incidence, and full chord flap lift (as appropriate) shall be presented on a single plot. Each additional circulation distribution shall be labeled by a lift curve slope defined by:

$$C_{L_{\delta_1}} = 2A\int_0^1 \frac{G}{\delta_1}\, d\eta \qquad 3.4.1.2\text{-}2$$

For twisted foils the basic circulation shall be labeled by the incidence angle at the plane of symmetry, if exposed, or by the incidence angle at the pod/foil intersection.

3.4.1.3 Antisymmetric Lift Distribution - For foils provided with antisymmetric flap control (ailerons), the estimated additional circulation over one semi-span due to asymmetric flap deflection shall be added to the plot of Section 3.4.1.2-2 and labeled by the lift curve slope defined by:

$$C_{L_\delta}' = 2A\int_0^1 \frac{G}{\delta}\, d\eta \qquad 3.4.1.3\text{-}1$$

3.4.2 Foil Loading Distributinn

3.4.2.1 Lift Coefficient Distribution - For each foil the distribution of pitch, incidence, and flap lift coefficient over one semi-span shall be presented on one plot in the form:

$$\left(\frac{c_l}{C_L}\right)_{\delta_1} = \frac{2A}{C_{L_{\delta_1}}} \frac{c_{avg}}{c} \frac{G}{\delta_1} \text{ vs. } \eta \qquad 3.4.2.1\text{-}1$$

where the lift curve slopes, $C_{L_{\delta_1}}$, shall be those of Equations 3.4.1.2-2 and 3.4.1.3-1. For each distribution the maximum and minimum C_l/C_L ratios on the exposed semi-span shall be noted.

3.4.2.2 Shear Distribution - For each foil the shear distribution over one semi-span for pitch, incidence, and flap lift shall be presented on one plot in the form:

$$\frac{V_{\delta_1}}{L'/2} = \frac{2A}{C_{L_{\delta_1}}} \int_{\eta}^{1} \frac{G}{\delta_1} d\eta \qquad 3.4.2.2\text{-}1$$

where the lift curve slopes, $C_{L_{\delta_1}}$, shall be those of Equations 3.4.1.2-2 and 3.4.1.3-1 and where the lift, L', includes the foil lift carry-over onto the pod but does not include the pod lift. For each distribution the ratio of the shear at the pod to the semi-lift shall be noted.

3.4.2.3 Moment Distribution - For each foil the bending moment distribution over one semi-span for pitch, incidence, and flap lift shall be presented on one plot in the form:

$$\frac{M_{\eta}}{\frac{L'}{2}\,\frac{b}{2}} = \frac{2A}{C_{L_{\delta_1}}} \int_{\eta}^{1} \int_{\eta}^{1} \frac{G}{\delta_1} d\eta\, d\eta \quad vs.\ \eta \qquad 3.4.2.3\text{-}1$$

where the lift curve slopes, $C_{L_{\delta_1}}$, shall be those of Equations 3.4.1-2 and 3.4.1-3. For each distribution the spanwise centers of pressure for the exposed and total semi-span shall be noted:

$$\eta_{c.p._e} = \eta_{pod} + \frac{M_{pod}}{\frac{L'}{2}\,\frac{b}{2}} \Big/ \frac{V_{pod}}{L'/2} \qquad 3.4.2.3\text{-}1$$

$$\eta_{c.p.} = \frac{2A}{C_{L_{\delta_1}}} \int_{0}^{1} \int_{\eta}^{1} \frac{G}{\delta_1} d\eta\, d\eta \qquad 3.4.2.3\text{-}2$$

3.4.3 Foil Aerodynamic Centers

For pitch and incidence lift for foils of constant section, the foil aerodynamic center shall be defined as the section aerodynamic center at the spanwise center of pressure and shall be expressed as a fraction of the chord at the foil plane of symmetry. The section aerodynamic center shall be taken from Figure 3.3.3-1.

For flap lift for foils of constant section and fixed flap chord ratios, the flap lift center of pressure shall be defined as the section flap lift center of pressure at the spanwise flap lift center of pressure and shall be expressed as a fraction of the chord at the foil plane of symmetry. The section flap lift center of pressure shall be defined by:

$$c.p._F = a.c. + \frac{1}{2} \zeta \frac{h}{c} \qquad 3.4.3\text{-}1$$

where: a.c. = section aerodynamic center from Figure 3.3.3-1

ζ = flap basic lift parameter of Equation 3.3.2.2-3

h/c = flap hinge station expressed as fraction of chord.

The appropriate craft trim and lift control system parameters of Table 3.4.3-I shall be evaluated and tabulated.

3.4.4 Strut Circulation Distribution and Side Force

Pending model test, the strut side force slope shall be estimated by:

$$C_{Y_\beta} = \frac{Y}{q S_S \beta} = \frac{2\pi A}{AE + K_S K_E} + \frac{S}{S_S} C_{L_\alpha} \sin^2\Gamma \qquad 3.4.4\text{-}1$$

where: Y = side force

β = sideslip angle

q = dynamic pressure, $\rho V^2/2$

S_S = wetted strut area, hC_{avg}

h = foil depth

C_{avg} = average chord for strut leading and trailing edge extended to chord plane

A = strut aspect ratio, h/C_{avg}

E = emperical factor $\approx 1 + \frac{1}{A}$

K_S = emperical factor ≈ 2.12

$K_E = \frac{1+b/h}{1+2b/h}$

b = foil span

S = foil area

C_{L_α} = foil pitch lift curve slope

Γ = foil dihedral angle

The strut side force and closure angle shall be measured in accordance with Section 4.1 prior to completion of the craft detail design. Values of the emperical factors, E and K_S, approriate to the measured side force slope shall be noted.

The strut side force of Equation 3.4.4-1 shall be assumed uniformly distributed on the strut quarter-chord line.

TABLE 3.4.3-I

AERODYNAMIC CENTER PARAMETERS

	SYMBOL	INTEGRATION RANGE INBD.	INTEGRATION RANGE OUTBD.	CIRCULATION DISTRIBUTION	NOTE
CRAFT TRIM AND FIXED FOIL/POD INCIDENCE LIFT CONTROL	a.c.$_\alpha$	FULL SEMI-SPAN		G/α	
	a.c.$_i$			G/i	
	c.p.$_\delta$			G/δ	FLAP LIFT CONTROL SYSTEMS ONLY
INCIDENCE LIFT CONTROL WITH FOIL/POD MOTION	a.c.$_{\alpha_i}$	POD	TIP	G/α	INCIDENCE LIFT CONTROL SYSTEMS ONLY
	a.c.$_{i_i}$			G/i	
	c.p.$_{\delta_i}$			G/δ	INCIDENCE + FLAP LIFT CONTROL SYSTEMS ONLY
FLAP LIFT CONTROL	a.c.$_{\alpha_\delta}$	FLAPPED SPAN EXTREMITIES		G/α	FLAP LIFT CONTROL SYSTEMS ONLY
	a.c.$_{i_\delta}$			G/i	
	c.p.$_{\delta_\delta}$			G/δ	

Note: Nominal aerodynamic center uncertainty is %, -1% of MAC

3.5 Foilborne Lift.

3.5.1 Pod Lift. The pod lift curve slope increment shah be evaluated by:

$$\Delta C_{L_{\alpha_{pod}}} = 2 S_{0_{pod}} / S \qquad 3.5.1\text{-}1$$

where $S_{0_{pod}}$ = pod frontal area

3.5.2 Pod Pitching Moment. The pod aerodynamic center shall be assumed to lie one-third of the **forebody** length aft of station zero and shall be specified as a station on the foil chord at the foil plane of symmetry, i.e.:

$$a.c._{pod} = -\left(x_N - \frac{1}{3}\ell_{forebody}\right) \Big/ c_r \qquad 3.5.2\text{-}1$$

where: c_r = foil chord at foil plane of symmetry

x_N = longitudinal distance between leading edges for c_r and pod

$\ell_{forebody}$ = pod **forebody** length

3.5.3 Foil Lift.

Note: The foil lift components of sections 3.5.3.1-3.5.3.4 are for a 2π section lift curve slope. Corrections for section geometry, depth, Reynolds Number, and Mach Number are incorporated in Section 3.5.3.5.

3.5.3.1 Foil Pitch Lift curve Slope. The foil pitch lift **curve** slope shah be evaluated by:

$$C_{L_\alpha} = C_{L_{\alpha_{foil}}} + \Delta C_{L_{\alpha_{pod}}} \qquad 3.5.3.1\text{-}1$$

where: $C_{L_{\alpha_{foil}}}$ = the foil-only pitch lift curve slope of Equation 3.4.1.2-2

$\Delta C_{L_{\alpha_{pod}}}$ = the pod lift curve slope increment of Equation 3.5.1-l

3.5.3.2 Foil Incidence Lift Curve Slope. The foil incidence lift curve slope of Equation 3.4.1.2-2 shall be employed.

3.5.3.3 Flap Lift Curve Slope. The flap lift curve slope shah be evaluated by:

$$C_{L_\delta} = \frac{d\alpha}{d\delta} C_{L'_\delta} \qquad 3.5.3.3\text{-}1$$

where: $\frac{da}{d\delta}$ = the flap effectiveness of Figure 3.3.1-1

$C_{L'_\delta}$ = the full chord flap lift curve slope of Equation 3.4.1.2-2

3.5.3.4 Foil Residual Lift. The reference line for the foil angle of attack shall be the pod axis. The reference line for the foil incidence angle shall be the foil chord at the pod/foil intersection. The residual lift shall be evaluated by:

$$C_{L_0} = C_L \text{ for } \alpha = i = \delta = 0 \qquad 3.5.3.4\text{-}1$$

$$= - C_{L_i} i_{0L}$$

where: C_{L_i} = the incidence lift curve slope of Equation 3.4.1.2-2

i_{0L} = the incidence angle for the foil section at the pod/foil intersection for the basic circulation distribution of Equation 3.4.1.2-1

= the section zero lift angle, $\alpha_{0\ell}$, of Equation 3.3.1.3-1 for untwisted foils

3.5.3.5 Foil Lift Equation. The foil lift shall be corrected for section lift curve slope by the factor:

$$K = \frac{c_{\ell_{\alpha RN}} / c_{\ell_\alpha}}{c_{\ell_\alpha} / c_{\ell_{\alpha M}}} \kappa \frac{c_{\ell_\alpha}}{c_{\ell_{\alpha_\infty}}} \qquad 3.5.3.5\text{-}1$$

where: $c_{\ell_\alpha RN}/c_{\ell_\alpha}$ = Reynolds Number correction of Equation 3.3.1.1-1 or 3.3.1.1-2, for Reynolds Numbers less than 3×10^6 referenced to the average exposed chord

$c_{\ell_\alpha}/c_{\ell_{\alpha M}}$ = Mach Number correction of Equation 3.3.1.1-3, for Mach Numbers greater than .3

κ = Section geometry correction of Equation 3.3.1.2-1 for section at average exposed chord

$c_{\ell_\alpha}/c_{\ell_{\alpha_\infty}}$ = Depth correction of Equation 3.3.7.1-1 evaluated at mean foil depth and referenced to average exposed chord

Predicted foil lift curves shall be provided in the form:

$$C_L = K\left(C_{L_{0_\infty}} + C_{L_{\alpha_\infty}}\alpha + C_{L_{i_\infty}'} i + C_{L_{\delta_\infty}}\delta\right) \qquad 3.5.3.5\text{-}2$$

$$= C_{L_0} + C_{L_\alpha}\alpha + C_{L_i'} i + C_{L_\delta}\delta$$

$$= C_{L_0} + C_{L_\alpha}\left(\alpha + \frac{C_{L_i'}}{C_{L_\alpha}} i + \frac{C_{L_\delta}'}{C_{L_\alpha}}\frac{d\alpha}{d\delta}\delta\right)$$

$$= C_{L_0} + (C_L)_\alpha + (C_L)_i + (C_L)_\delta$$

$$= C_{L_{ref}} + (C_L)_\alpha + (C_L)_\delta$$

for rigid foil/pod intersection

where

K = section lift curve slope correction of Equation 3.5.3.5-l

$C_{L_{0_\infty}}$ = the residual lift of Equation 3.5.3.4-l

$C_{L_{\alpha_\infty}}$ = the foil pitch lift curve slope of Equation 3.5.3.1-1

$C_{L_{i_\infty}'}$ = the foil incidence lift curve slope of Equation 3.4.1.2-2

$C_{L_{\delta_\infty}}$ = the flap lift curve slope of Equation 3.5.3.3-l

α, i, δ = pitch, incidence, and flap angles

C_{L_δ}' = full chord flap lift curve slope of Equation 3.4.1.2-2

$d\alpha/d\delta$ = flap effectiveness of Figure 3.3.1-1

$C_{L_{ref}}$ = $C_{L_0} + (C_L)_i$

The nominal precision associated with the prediction of the foil lift curve is:

+15%, -0 for slope

+0, -1.5° for zero lift angle

3.6 Foilborne Moments

3.6.1 Mean Aerodynamic Chord

The foil mean aerodynamic chord shall be defined by:

$$MAC = \sqrt{\frac{A}{S}}\int_0^1 c^2 d\eta \qquad 3.6.1\text{-}1$$

$$= \frac{4}{3}\sqrt{\frac{S}{A}}\left[1 - \frac{\lambda}{(1+\lambda)^2}\right]$$

for semi-spans having straight leading and trailing edges.

3.6.2 Moment About Aerodynamic Center, C_{MAC}

The foil moment about the aerodynamic center shall be estimated by:

$$C_{M_{ac_{sect}}} = \frac{\sqrt{A/S}}{MAC}\int_{pod}^1 c^2 c_{m_{ac}} d\eta \qquad 3.6.2\text{-}1$$

$$= \frac{MAC'}{MAC} c_{m_{ac}}$$

for foil of fixed section on span

where: $c_{m_{ac}}$ = the section $c_{m_{ac}}$ of Equation 3.3.3-1

MAC' is the MAC for a foil consisting of the two exposed semi-spans

3.6.3 Incidence Hinge Moment

The incidence hinge moment shall be estimated in the dimensional form:

$$\frac{H}{SMAC} = C_{H_{C_L}} \frac{L}{S} + H_q q \qquad 3.6.3\text{-}1$$

where: H = incidence hinge moment

S = foil area

MAC = mean aerodynamic chord, Equation 3.6.1-1

L/S = foil loading

q = hydrodynamic pressure

$C_{H_{CL}}$ and H_q are defined in Table 3.6.3-I

The hinge moment envelope defined in Table 3.6.3-11 shall be presented graphically for each incidence lift control system. If applicable, the flap deflection schedule shall be specified as a function of hydrodynamic pressure. The entire hinge moment envelope shall present negative moments. Model measurements instead of the moments of Equation 3.6.3-l shall not be accepted.

TABLE 3.6.3-I

INCIDENCE HINGE MOMENT EQUATION

COEFFICIENT	RIGID INTERACTION: FOIL/POD	RIGID INTERACTION: POD/STRUT
$C_{H_{C_L}}$	$\frac{c_r}{MAC}\left(\frac{H}{c_r} - c.p._\alpha\right)^{+.01}_{-.05}$	$\left(\frac{V}{L'/2}\right)_i \left[\frac{c_r}{MAC}\left(\frac{H}{c_r} - a.c._{i_i}\right)^{+.01}_{-.05}\right]$
$C_{H_{C_{L\alpha}}}$	Not applicable	$\frac{c_r}{MAC}\left[\frac{C_{L_{\alpha foil}}}{C_{L_\alpha}}\left(\frac{V}{L'/2}\right)_\alpha\left(\frac{H}{c_r} - a.c._{\alpha_i}\right) - \left(\frac{V}{L'/2}\right)_i\left(\frac{H}{c_r} - a.c._{i_i}\right)\right]$
$C_{H_{C_{L\delta}}}$	$\frac{c_r}{MAC}\left(c.p._\alpha - c.p._\delta\right)$	$\frac{c_r}{MAC}\left[\left(\frac{V}{L'/2}\right)_\delta\left(\frac{H}{c_r} - c.p._{\delta_i}\right) - \left(\frac{V}{L'/2}\right)_i\left(\frac{H}{c_r} - a.c._{i_i}\right)\right]$
$C_{H_{ref}}$	$C_{M_{a.c.}} + \frac{c_r}{MAC}\left(c.p._\alpha - a.c._i\right) C_{L_{ref}} + \sigma C_{M_{a.c.}}$	$C_{M_{a.c.}} + \sigma C_{M_{a.c.}}$

$$\frac{H}{S\,MAC} = C_{H_{C_L}} \frac{L}{S} + 1q\,\mathfrak{z}$$

where the symbols are defined on the next page

TABLE 3.6.3-I (cont.)

H = incidence hinge moment

H/C_r = incidence hinge position expressed as fraction of the foil chord at the foil plane of symmetry

S = foil area

MAC = mean aerodynamic chord, Equation 3.6.1-1

$H_q = (1 \pm .05)(C_{H_{C_{L\alpha}}} C_{L_\alpha} \alpha + C_{H_{C_{L\delta}}} C_{L_\delta} \delta + C_{H_{ref}})$

a.c.'s and c.p.'s are from Table 3.4.3-I where they are expressed as fractions of the foil chord at the foil plane of symmetry

$C_{L_{\alpha_{foil}}}/C_{L_\alpha} = C_{L_{\alpha_{foil}}}/(C_{L_{\alpha_{foil}}} + \Delta C_{L_{\alpha_{pod}}})$ of Equation 3.5.3.1-1

C_{L_α} = foil pitch lift curve slope, Equation 3.5.3.5-2

C_{L_δ} = foil flap lift curve slope, Equation 3.5.3.5-2

$(V/L'/2)_{S_1}$ = ratio of shear at pod to the semi-lift, Equation 3.4.2.2-l

C_r = foil chord at foil plane of symmetry

L/S = foil loading

$C_{M_{ac}}$ = KX coefficient for moment about aerodynamic center, Equations 3.5.3.5-l and 3.6.2-l

$\sigma\, C_{M_{ac}}$ = uncertainty range for CMAC

= 0 to .12 for 4 digit sections

= ,006 to .020 for 5 digit sections

= ±.006 for all other sections

$C_{L_{ref}}$ = rigid foil/pod intersection reference lift coefficient of Equation 3.5.3.5-2

q = hydrody namic pressure, $\rho V^2/2$

α = pitch angle

δ = flap angle

TABLE 3.6.3-II

INCIDENCE HINGE MOMENT ENVELOPE

CONDITION	PURPOSE	$C_{H_{C_L}}$ σ	FOIL LOADING, L/S	C_{L_α} PRECISION FACTOR	SECTION LIFT CURVE SLOPE FACTOR, K	H_q VALUE IN UNCERTAINTY RANGE
1	CROSS-OVER MARGIN	+.01	$C_{H_{C_L}} > 0$: 1.25 X MAXIMUM L/S IN OPERATING W-LCG ENVELOPE $C_{H_{C_L}} \leq 0$: .75 X MINIMUM L/S IN OPERATING W-LCG ENVELOPE	.95	MIN. VALUE IN SPEED-FOIL DEPTH ENVELOPE	HIGHEST ALGEBRAIC
2	POSSIBLE	+.01	L/S FOR NOMINAL FULL LOAD DISPLACEMENT AND LCG	1.0	CRUISE SPEED AND FOIL DEPTH	HIGHEST ALGEBRAIC
3	OPERATING	0	L/S FOR NOMINAL FULL LOAD DISPLACEMENT AND LCG	1.0	CRUISE SPEED AND FOIL DEPTH	NOMINAL
4	RANGE	-.05	L/S FOR NOMINAL FULL LOAD DISPLACEMENT AND LCG	1.0	CRUISE SPEED AND FOIL DEPTH	LOWEST ALGEBRAIC
5	DESIGN LOADS	-.05	$C_{H_{C_L}} > 0$: .75 X MINIMUM L/S IN OPERATING W-LCG ENVELOPE $C_{H_{C_L}} \leq 0$: 1.25 X MAXIMUM L/S IN OPERATING W-LCG ENVELOPE	1.05	MAX. VALUE IN SPEED-FOIL DEPTH ENVELOPE	LOWEST ALGEBRAIC

Note: Hydrodynamic pressure, q, range is take off speed for minimum operating condition to maximum speed.

3.6.4 [redacted] Flap Hinge Moment. The flap hinge moment shah be evaluated in the form:

$$C_h = h/q\, S_f\, c_{f_{avg}}$$

where: h = flap hinge moment

q = hydrodynamic pressure, $\rho V^2/2$

S_f = flap area

$c_{f_{avg}}$ = average flap chord, S_f/b_f

3.6.4.1 [redacted] Pitch And Incidence Lift Flap Hinge Moment. The flap hinge moment due to pitch and incidence lift shah be evaluated in the form:

$$C_{h_{C_{L\alpha}}} \equiv (C_h)_\alpha \big/ (C_L)_\alpha = c_{h_{c_{\ell\alpha}}} \frac{S}{S'} \frac{2A}{C_{L_\alpha}} \int_{\eta_i}^{\eta_0} \frac{c}{c_{avg}} \frac{G}{\alpha}\, d\eta$$

3.6.4.1-1 [redacted]

$$C_{h_{C_{Li}}} \equiv (C_h)_i \big/ (C_L)_i = c_{h_{c_{\ell\alpha}}} \frac{S}{S'} \frac{2A}{C_{L_i}} \int_{\eta_i}^{\eta_0} \frac{c}{c_{avg}} \frac{G}{i}\, d\eta$$

where: $C_{h_{c_{\ell\alpha}}}$ = the section flap hinge moment due to angle of attack of **Equation** 3.3.4-2

S' = the flapped foil area

C_{L_α}, C_{L_i} = the pitch and incidence lift **curve** slopes of Equation 3.4.11.2-2

$G/\alpha, G/i$ = the pitch and incidence lift circulation distributions of Equation 3.4.1.2-1

η_i, η_0 = the inboard and outboard span stations for the flap extremities.

3.6.4.2 [redacted] Flap Lift Flap Hinge Moment. The flap hinge moment due to flap lift shall be evaluated in the form:

$$C_{h_{C_{L\delta}}} \equiv (C_h)_\delta \big/ (C_L)_\delta = c_{h_{c_{\ell\delta}}} \frac{S}{S'} \frac{2A}{C_{L'_\delta}} \int_{\eta_i}^{\eta_0} \frac{c}{c_{avg}} \frac{G}{\delta}\, d\eta \qquad \text{3.6.4.2-1}$$

[redacted]

where: $C_{h_{c_{\ell\delta}}}$ = the section flap hinge moment due to flap deflection of Equation 3.3.4-3

S' = the flapped foil area

$C_{L'_{\delta}}$ = the full chord flap lift curve slope of Equation 3.4.1.2-2

G/6 = the flap **lift** circulation distribution of Equation 3.4.1.2-1

η_i, η_0 = the inboard and outboard span stations for the flap extremities

3.6.4.3
[redacted] Residual Flap Hinge Moment. The residual flap hinge moment shall be evaluated in the form:

$$C_{h_0} = \frac{C_{h_0}}{c_{\ell_{i_{eff}}}} c_{\ell_{i_{eff}}} + 2A \frac{S}{S'} \int_{\eta_i}^{\eta_0} c_{h_{c_{\ell\alpha}}} \frac{c}{c_{avg}} G_0 \, d\eta \qquad \text{3.6.4.3-1 [redacted]}$$

where: $C_{h_0}/C_{\ell_{i_{eff}}}$ is from Equation 3.3.4-l

S' = the flapped foil area

$C_{h_{c_{\ell\alpha}}}$ = the section flap hinge moment due to angle of attack of Equation 3.3.4-2

G_0 = the basic circulation distribution of Equation 3.4.1.2-1

3.6.4.4
- Flap Hinge Moment Equation. The flap hinge moment shall be evaluated in the form:

$$C_h = C_{h_0} + (C_h)_\alpha + (C_h)_i + (C_h)_\delta$$

$$= KC_{h_{0_\infty}} + C_{h_{C_{L\alpha}}} (C_L)_\alpha + C_{h_{C_{Li}}} (C_L)_i + C_{h_{C_{L\delta}}} (C_L)_\delta \qquad \text{3.6.4.4-1 [redacted]-1}$$

$$= K\left(C_{h_{0_\infty}} + C_{h_{C_{L\alpha}}} C_{L_{\alpha_\infty}} \alpha + C_{h_{C_{Li}}} C_{L_{i_\infty}} i + C_{h_{C_{L\delta}}} C_{L_{\delta_\infty}} \delta\right)$$

where: K = the section lift curve slope correction factor of Equation 3.5.3.5-l

$C_{h_{0_\infty}}$ = the residual moment of Equation [redacted] 3.6.4.3-1

$C_{h_{C_{L\alpha}}}$ = the pitch lift flap hinge moment slope of Equation [redacted] 3.6.4.1-1

$C_{h_{C_{Li}}}$ = the incidence lift flap hinge moment slope of Equation [redacted] 3.6.4.1-1

$C_{h_{C_{L\delta}}}$ = the flap lift flap hinge moment slope of Equation [redacted] 3.6.4.2 -1

$C_{L_{\alpha_\infty}}$ = the pitch lift curve slope of Equation 3.5.3.1-1

$C_{L_{i_\alpha}}$ = the incidence lift curve slope of Equation 3.4.1.2-2

$C_{L_{\delta_\infty}}$ = the flap lift curve slope of Equation 3.5.3.3-l

Experience does not provide a significant test for this characteristic, and there is evidence of substantial scale effect in model measurements.

3.6.5 Craft Weight Distribution

The craft net weight, L, shall be distributed to the incidence hinge for incidence lift control systems and to the pitch lift aerodynamic center, a.c.$_\alpha$, for flap lift control systems.

3.7 Drag.

3.7.1 Parasite Drag.

3.7.1.1 Foil Profile Drag. The foil profile drag coefficient shall be estimated by:

$$C_{D_F} = \frac{S_1'}{S} c_{d_{min_1}} + \frac{S_2'}{S} c_{d_{min2}} \qquad 3.7.1.1\text{-}1$$

where: Sl' and S2' = the total forward and aft exposed foil area

S = the total foil area, Sl + S2

$c_{d_{m\,m}}$ = the section minimum drag coefficient of Equation 3.3.9-l for a Reynolds Number based upon the average exposed foil chord.

3.7.1.2 Pod Profile Drag. The pod profile drag coefficient shall be estimated by:

$$C_{D_{pod}} = \frac{1}{2} \frac{S_{wet_1}}{S} R_1 c_{d_{ft_1}} + \frac{1}{2} \frac{S_{wet_2}}{S} R_2 c_{d_{ft_2}} \qquad 3.7.1.2\text{-}1$$

where: S_{wet_1} and S_{wet_2} = the total forward and aft pod wetted area

S = the total foil area, Sl + S_2

R = $1 + 1.5\,(d/\ell)^{3/2} + 7(d/\ell)^3$

d = effective pod diameter $= (4S_0/\pi)^{1/2}$

S_0 = pod frontal area

ℓ = pod length

$c_{d_{ft}}$ = the turbulent friction drag coefficient of Equation 3.3.9-l for a Reynolds Number based upon the pod length

3.7.1.3 Strut Profile Drag. The strut profile drag coefficient shah be estimated by:

$$C_{D_S} = \frac{S_{S_1}}{S} c_{d_{min_1}} + \frac{S_{S_2}}{S} c_{d_{min_2}} \qquad 3.7.1.3\text{-}I$$

where: S_{S_1} and S_{S_2} = the total forward and aft wetted strut area

S = the total foil area, Sl + S_2

$c_{d_{min}}$ = the section minimum drag coefficient of Equation 3.3.9-l for a Reynolds Number based upon the average wetted strut chord and for the average wetted strut thickness ratio.

Strut ventilation fence drag coefficients **shall** be estimated by:

$$C_{D_{fence}} = 1.25 \frac{S_{fence}}{S} c_{d_{ft}} \qquad 3.7.1.3\text{-}2$$

where: S_{fence} = the exposed fence area

S = the total **foil** area, Sl + S2

$c_{d_{ft}}$ = the turbulent friction drag coefficient of Equation 3.3.9-l for a Reynolds Number based upon the average fence chord

3.7.1.4 Interference Drag. The interference drag coefficient shah be estimated by:

$$C_{D_{int}} = 0.2(C_{D_F} + C_{D_{Pod}} + C_{D_S} + C_{D_{fence}}) \qquad 3.7.1.4\text{-}1$$

where: C_{D_F} = the total **foil** profile drag coefficient of Equation 3.7.1.1-l

$C_{D_{pod}}$ = the **total** pod profile drag coefficient of Equation 3.7.1.2-l

C_{D_S} = the total strut profile drag coefficient of Equation **3.7.1.3-1**

$C_{D_{fence}}$ = the total fence drag coefficient of Equation 3.7.1.3-2

3.7.1.5 Spray Drag. The spray drag coefficient **shall** be estimated by:

$$C_{D_{spray}} = .24 n_1 \frac{t^2_{surf_1}}{S} + .24 n_2 \frac{t^2_{surf_2}}{S} \qquad 3.7.1.5\text{-}1$$

n_1 and n_2 = number of forward and aft struts

where: t_{surf_1} and t_{surf2} = the forward and aft strut maximum thickness at the surface

S = the total **foil** area, Sl + S_2

3.7.1.6 Air Drag. ~~Pending model test~~ A .5 air drag coefficient referenced to frontal area **shall** be assumed and the air drag coefficient **shall** be expressed **hydrodynamically** in the form:

$$C_{D_{air}} = \frac{S_{air}}{S} \Big/ 1674.1 \qquad 3.7.1.6\text{-}1$$

where: S_{air} = the craft frontal area

S = the total **foil** area, Sl + S_2

~~This drag coefficient shall be increased, but not reduced, as required by the appropriate model tests of Section 4.1~~.

3.7.1.7 Total Parasite Drag. The total parasite drag coefficient, CD_p, shah be the sum of the following coefficients:

TABLE 3.7.1.7-l PARASITE DRAG COEFFICIENT COMPONENTS

COMPONENT	SYMBOL	EQUATION
FOIL PROFILE DRAG	C_{D_F}	3.7.1 .1-1
POD PROFILE DRAG	$C_{D_{pod}}$	3.7.1.2-l
STRUT PROFILE DRAG	C_{D_S}	3.7.1.3-l
FENCE DRAG	$C_{D_{fence}}$	3 7.1.3-Z
INTERFERENCE DRAG	$C_{D_{int}}$	3 7.1.4-1
SPRAY DRAG	$C_{D_{spray}}$	3.7.1.5-1
AIR DRAG	$C_{D_{air}}$	3.7.1.6-1

R83-1412-003B

A cumulative parasite drag coefficient vs. speed plot shah be presented for the speed range from one-half maximum speed to maximum speed at the cruise foil depth. For the minimum, cruise, and keel-kissing foil depths total parasite drag coefficient vs l/q plots shall be presented for the same speed range comparing the computed drag coefficients with quadratic curve fits in l/q.

3.7.2 Drag Due To Lift.

3.7.2.1 Craft Lift Coefficient. Craft steady state performance shall be defined in terms of the craft lift coefficient, CL:

$$C_L = \frac{W_{net}}{qS} = \frac{W-B}{qS} \qquad 3.7.2.1\text{-}1$$

where: W_{net} = net craft weight, W-B

W = craft weight

B = total buoyancy

q = dynamic pressure, $\rho V^2/2$

S = total foil area

The forward and aft **foil** lift coefficients **shall** be defined in terms of the craft lift coefficient by:

$$C_{L_1} = \frac{\ell_2/\ell}{S_1/S} C_L, \quad C_{L2} = \frac{\ell_1/\ell}{S_2/S} C_L \qquad 3.7.2.1\text{-}2$$

where: ℓ_1 = the longitudinal distance between the craft c.g. and the forward **foil** reference point

ℓ_2 = the longitudinal distance between the craft c.g. and the aft **foil** reference point

ℓ = the **foil** base, $\ell_1 + \ell_2$

S_1 = the total forward **foil** area

S_2 = the total aft **foil** area

S = the **total foil** area, $S_1 + S_2$

The longitudinal reference point for the foils **shall** be the incidence hinge for incidence lift control systems and the pitch lift aerodynamic center for flap **lift** control systems.

3.7.2.2 Induced Drag. For each **foil** the induced drag coefficient **shall** be estimated by:

$$\pi A C_{Di_1} / (C_L)^2_{\delta 1} = 1 \text{ for pitch lift} \qquad 3.7.2.2\text{-}1$$

$$= 32I/J^2 \text{ for incidence or flap lift}$$

$$\text{where: } I = \left(\frac{G_1}{\delta_1}\right)^2 + \left(\frac{G_2}{\delta_1}\right)^2 + \left(\frac{G_3}{\delta_1}\right)^2 + \frac{1}{2}\left(\frac{G_4}{\delta_1}\right)$$

$$- \frac{G_4}{\delta_1}\left(.056 \frac{G_1}{\delta_1} + .789 \frac{G_3}{\delta_1}\right) - \frac{G_2}{\delta_1}\left(.733 \frac{G_1}{\delta_1} + .845 \frac{G_3}{\delta_1}\right)$$

$$J = .765 \frac{G_1}{\delta_1} + 1.414 \frac{G_2}{\delta_1} + 1.848 \frac{G_3}{\delta_1} + \frac{G_4}{\delta_1}$$

G_n / δ_1 = the non-dimensional circulations of Equation 3.4.1.2-1 for span stations defined by:

$\eta = \cos n\pi/8$

The total induced drag coefficient **shall** be estimated by:

$$C_{D_i} / C_L^2 = \frac{(\ell_2/\ell)^2}{S_1/S}\left(\frac{C_{D_i}}{C_L^2}\right)_1 + \frac{(\ell_1/\ell)^2}{S_2/S}\left(\frac{C_{D_i}}{C_L^2}\right)_2 \qquad 3.7.2.2\text{-}2$$

as defined by Equation 3.7.2.1-2.

3.7.2.3 Wake Drag. The total wake drag coefficient variation with lift shall be estimated by:

$$C_{D_{wake}} = \frac{S_1}{S} C_{D_{wake1}} + \frac{S2}{S} C_{D_{wake_2}} \qquad 3.7.2.3\text{-}1$$

where: $C_{D_{wake_n}} = K_{wake} \left[C_{L_n} - C_{\ell_{i_{eff}}} - \zeta (C_L)_\delta\right]^2_n + K_{wake_b} \left[\zeta (C_L)_\delta\right]^2_n$

S_1, S_2 = total forward and aft foil areas

S = total foil area, $S1 + S2$

K_{wake}, K_{wake_b} = the wake drag factors of Equation 3.3.9-l

C_{L_n} = forward or aft foil lift coefficient, C_{L_1} or C_{L_2}

$(C_L)_\delta$ = flap lift coefficient, $C_{L_\delta} \delta$

C_{L_δ} = flap lift curve slope of Equation 3.5.3.3-l

$C_{\ell_{i_{eff}}}$ = the section effective design lift coefficient of Equation **3.3.1.4-1**

ζ = the flap lift distribution parameter of Equation 3.3.2.2-3

3.7.2.4 Surface Image Drag. For each foil the surface image component of the free surface drag coefficient shall be related to the induced drag coefficient by:

$$C_{D_{surf}} / C_{D_i} = \cancel{.7868\, e^{5.105\, h/b}}\ \sigma'_i \qquad 3.7.2.4\text{-}1$$

where: $C_{D_{surf}}$ = foil surface image drag coefficient

C_{D_i} = foil induced drag coefficient

σ'_i is from Table 3.7.2.4-I, Page 3.7-10

~~h = foil depth~~

~~b = foil span~~

to estimate the total surface image drag coefficient by:

$$C_{D_{surf}} / C_L^2 = \frac{(\ell_2/\ell)^2}{S_1/S} \cancel{\left(\frac{C_{D_{surf}}}{C_{D_i}}\right)_1} \sigma'_{i_1} \left(\frac{C_{D_i}}{C_L^2}\right)_1 + \frac{(\ell_1/\ell)^2}{S_2/S} \cancel{\left(\frac{C_{D_{surf}}}{C_{D_i}}\right)_2} \sigma'_{i_2} \left(\frac{C_{D_i}}{C_L^2}\right)_2 \qquad 3.7.2.4\text{-}2$$

as defined by Equation 3.7.2.2-2

3.7.2.5 Wave Drag. For each foil the wave drag component of the free surface **drag** coefficient shall be estimated by:

$$C_{D_{wave}} \Big/ C_L^2 = \frac{K_W\, c_{avg}\ (\text{~~MAC~~})}{h}\, e^{-2/F_h^2} \Big/ 2\,F_h \qquad 3.7.2.5\text{-}1$$

where: $C_{D_{wave}}$ = foil wave drag coefficient

C_L = foil lift coefficient

c_{avg} ~~MAC~~ = foil average ~~mean aerodynamic~~ chord, ~~Equation 3.4.3.5.1~~

h = foil depth

F_h = depth Froude Number, $V/\sqrt{gh}$

V = craft speed

K_W = 1.0 in flight, σ_i for take off (Table 3.7.2.4 - I)

to estimate the total wave drag by:

$$C_{D_{wave}} \Big/ C_L^2 = \frac{(\ell_2/\ell)^2}{S_1/S}\left(\frac{C_{D_{wave}}}{C_L^2}\right)_1 + \frac{(\ell_1/\ell)^2}{S_2/S}\left(\frac{C_{D_{wave}}}{C_L^2}\right)_2 \qquad 3.7.2.5\text{-}2$$

as defined by equation 3.7.2.1-2.

Wave drag coefficient vs. lift coefficient plots comparing the computed drag coefficients with quadratic curve fits in C_L shall be presented for the minimum, cruise, and keel-kissing foil depths at maximum gross weight over the speed range from one-half maximum speed to maximum speed.

3.7.2.6 Total Drag Due to Lift.

The total coefficient for drag due to lift, C_{D_L}, shah be the sum of the following coefficients:

TABLE 3.7.2.6-i COMPONENTS FOR COEFFICIENT OF DRAG DUE TO LIFT

COMPONENT	SYMBOL	EQUATION
INDUCED DRAG	C_{D_i}	3.7.2.2-2
WAKE DRAG	$C_{D_{wake}}$	3.7.2.3-I
SURFACE IMAGE DRAG	$C_{D_{surf}}$	3.7.2.4-2
WAVE DRAG	$C_{D_{wave}}$	3.7.2.5-2

R83-1412-004B

A cumulative drag-due-to-lift coefficient vs. speed plot **shall** be presented for the speed range from one-half maximum speed to maximum speed at the cruise **foil** depth and maximum gross weight.

3.7.3 Craft Drag.

3.7.3.1 **Total** Craft Drag. The **total** craft drag coefficient **shall** be estimated by:

$$C_D = 1.15\, C_{D_P} + C_{D_L} \qquad 3.7.3.1\text{-}1$$

where: C_{D_P} = the total parasite drag coefficient of Table 3.7.1.7-I

C_{D_L} = the total drag-due-to **lift** coefficient of Table 3.7.2.6-I

A cumulative craft drag curve distinguishing parasite drag less interference drag, parasite drag, 1.15 X parasite drag, and **total** drag shah be presented for the speed range from **one-half** maximum speed to maximum speed at the cruise **foil** depth and maximum gross weight. For the cruise and minimum foil depth at maximum, maximum less one-half useful fuel load, and minimum gross weight, craft drag curves **shall** be presented for the same speed range comparing the computed drag **with** that derived from the drag polar approximations of Section 3.7.3.2.

3.7.3.2 Craft Drag Polar. The parasite drag coefficient quadratics in l/q of Section 3.7.1.7 shall be converted to quadratics in craft lift coefficient by substituting $(S/W_{net})\, C_L$ for l/q:

$$\begin{aligned} C_{D_P} &= C_{0_P} + C_{1'_P}(1/q) + C_{2'_P}(1/q)^2 \\ &= C_{0_P} + (S/W_{net})\, C_{1'_P}\, C_L + (S/W_{net})^2\, C_{2'_P}\, C_L^2 \qquad 3.7.3.2\text{-}1 \\ &= C_{0_P} + C_{1_P} C_L + C_{2_P} C_L^2 \end{aligned}$$

The wave drag coefficient quadratics in lift coefficient of Section 3.7.2.6 shah be generalized in craft weight in the form:

$$\begin{aligned} C_{D_{wave}} &= \left(\frac{W_{net}}{W_{net_{max}}}\right)^2 C_{0'_{wave}} + \frac{W_{net}}{W_{net_{max}}}\, C_{1'_{wave}}\, C_L + C_{2_{wave}}\, C_L^2 \qquad 3.7.3.2\text{-}2 \\ &= C_{0_{wave}} + C_{1_{wave}}\, C_L + C_{2_{wave}}\, C_L^2 \end{aligned}$$

The remaining drag coefficient components are in drag polar form as derived and **shall** be added to Equations 3.7.3.2-l and 3.7.3.2-2 in accordance with Equation 3.7.3.1-1 to produce the craft drag polar:

$$C_D = C_0 + C_1 C_L + C_2 C_L^2 \qquad 3.7.3.2\text{-}3$$

The cumulative drag curve and drag curve comparisons of Section 3.7.3.1 shall be repeated in drag polar form, and the corresponding drag polar parameters of Table 3.7.3.2-I shall be evaluated. The variation of C_L/C_D and $C_L^{1/2}/C_D^{2/3}$ with speed shall be presented for the two depths and three gross weights of Section 3.7.3.1 and over the same speed range.

TABLE 3.7.3.2-I DRAG POLAR CHARACTERISTICS

SPECIFIC RANGE PARAMETER	C_L	$-\frac{1}{10}\frac{C_1}{C_2}\left(\sqrt{1+60\frac{C_0\,C_2}{C_1^2}}+1\right)$
$C_L^{1/2} / C_D^{2/3}$	$\left(C_L^{1/2} / C_D^{2/3}\right)_{max}$ Note 1	Substitute C_L above into drag polar
MINIMUM DRAG PARAMETER	C_L	$\sqrt{C_0/C_2}$
C_L/C_D	$(D/L)_{min}$ Note 2	$2\sqrt{C_0\,C_2}+C_1$
MINIMUM POWER, MINIMUM FLIGHT SPEED, SPECIFIC ENDURANCE PARAMETERS	C_L	$-\frac{1}{2}\frac{C_1}{C_2}\left(\sqrt{1+12\frac{C_0\,C_2}{C_1^2}}-1\right)$
$C_L^{3/2} / C_D$	$\left(C_L^{3/2} / C_D\right)_{max}$ Note 3	Substitute C_L above into drag polar

R83-1412-005B

Notes: 1. Multiply drag polar value by $(W/W_{net})^{1/2}$ for actual value.

2. Multiply drag polar value of C_L/C_D by W/W_{net} for actual value.

3. Muiripiy drag poiar vaiue by $(W/W_{net})^{3/2}$ for acruai vaiue.

TABLE 3.7.2.4-I

BIPLANE FACTOR σ_i

h/b	σ_i	h/b	σ_i
0	1	.325	.17095
.005	.9364	.35	.1555
.01	.8905	.375	.1418
.015	.8513	.4	.1298
.02	.8163	.425	.1191
.025	.7845	.45	.1096
.03	.7553	.475	.1011
.04	.7027	.5	.09351
.05	.6565	.6	.06999
.075	.5604	.7	.05706
.1	.4842	.8	.04255
.125	.4221	.9	.03472
.15	.3705	1	.02565
.175	.3273	1.25	.01889
.2	.2905	1.5	.01334
.225	.2592	1.75	.009904
.25	.2322	2	.007635
.275	.2089	2.25	.006061
.3	.1886	2.5	.004937

$$\sigma_i = 1 - \frac{8}{\pi}\frac{h}{b}\sqrt{1+4\left(\frac{h}{b}\right)^2}\left[.38629 - .35104 m_1 - .035251 m_1^2 + \left(.5 - .12392 m_1 - .012377 m_1^2\right)\ln\frac{1}{m_1}\right]$$

where: $$m_1 = \frac{1}{1 + \frac{1}{4(h/b)^2}}$$

3.8 Cavitation

3.8.1 Foil Cavitation, Incidence Lift Control Systems

Incipient cavitation boundaries shall be predicted by one of the following equations:

For rigid foil/pod intersections 3.8.1-1

$$\frac{W}{S} = q\cos^2\Lambda\left\{\pm\frac{1}{(C_l/C_L)_\alpha}\,\frac{\sqrt{S}-\psi}{\Delta V_a'/V} + \left[1-\frac{(C_l/C_L)_i}{(C_l/C_L)_\alpha}\right]C_{L_{ref}} + \left[1-\left(1+\frac{3\Omega}{\Delta V_a'/V}\right)\frac{(C_l/C_L)_\delta}{(C_l/C_L)_\alpha}\right](C_L)_\delta\right\}$$

For rigid strut/pod intersections 3.8.1-2

$$\frac{W}{S} = q\cos^2\Lambda\left\{\pm\frac{1}{(C_l/C_L)_i}\,\frac{\sqrt{S}-\psi}{\Delta V_a'/V} + \left[1-\frac{(C_l/C_L)_\alpha}{(C_l/C_L)_i}\right](C_L)_\alpha + \left[1-\left(1+\frac{3\Omega}{\Delta V_a'/V}\right)\frac{(C_l/C_L)_\delta}{(C_l/C_L)_i}\right](C_L)_\delta\right\}$$

where:

W/S = hydrodynamic foil loading for incipient cavitation

q = dynamic pressure, $\rho V^2/2$

ρ = mass density, 1025.9 Kg/M^3 (1.9905 $slugs/ft^3$)

V = craft speed

Λ = foil quarter-chord sweep angle

S = J t $\sigma_c/\cos^2\Lambda$

σ_c = cavitation number for incipient cavitation = $(P_S - P_V)/q$

P_S = static pressure at foil depth, $P_a + \rho g h$

P_V = vapor pressure, 3.5 K P_a (1/2 psi)

P_a = atmospheric pressure, 101.3 K P_a (2116 psf)

g = acceleration of gravity, 9.8066 M/S^2 (32.174 ft/sec^2)

h = foil depth

ν' = a section velocity distribution parameter

$= \frac{v}{V} \pm \left(\frac{\Delta v/V}{C_{l_{iref}}} - \frac{\Delta v_a'}{V} \right) C_{l_{i_{eff}}}$

v/V $\mathfrak{S}$, $\frac{\Delta v}{V}/C_{l_{iref}}$ Ω, $\Delta v_a'/V$ } section velocity distribution parameters of Equation 3.3.8-l

$C_{L_{ref}} = C_{L_0} + (C_L)_i$

C_{L_0} = the residual lift coefficient of Equation 3.5.3.4-l

$(C_L)_\alpha, (C_L)_i, (C_L)_\delta$ = the foil pitch, incidence, and flap lift coefficients of Equation 3.5.3.5-Z

$C_{l_{i_{eff}}}$ = section effective design lift coefficient of Equation 3.3.1.4-1

$(C_l/C_L)_\alpha, (C_l/C_L)_i, (C_l/C_L)_\delta$ = the maximum (for upper surface) or mimimum (for lower survface) C_l /CL ratios of Section 3.4.3.1 for pitch, incidence, and flap lift respectively. For foils of varying section the C_l /CL ratios for that span station presenting the most restricted boundary shall be employed.

The cavitation bucket shall be defined for the cruise foil depth.

The predicted cavitation bucket shall be defined in the speed-loading plane by the lower surface ½% chord station, the most restrictive upper surface mid-chord station, and the upper surface 15% chord station from the mid-chord boundary to the maximum foil loading for the 15% chord station. The foil loading range from the minimum value to 1 1/8 times the maximum value in the W-LCG envelope shall be contained within this bucket to 105% of the craft maximum speed. Boundaries for the lower surface 1.25% chord station, the upper surface 20% chord station, and the most restrictive of the upper surface 1.25% and 2.5% chord stations shall be shown for reference.

The predicted cavitation bucket shall be superseded by the experimental cavitation bucket of Section 4.1 before detail design of the foil system.1

3.8.2 Foil Cavitation, Flap Lift Control Systems

Incipient cavitation boundaries shall be predicted by:

$$\frac{w}{s} = q\cos^2\Delta\left\{\pm\frac{1}{(c_l/C_L)_\delta}\,\frac{\sqrt{s}-\psi}{\sqrt{s}+\Delta v_a'/V} + \left[1-\frac{\Delta v_a'/V}{\sqrt{s}+\Delta v_a'/V}\,\frac{(c_l/C_L)_i}{(c_l/C_L)_\delta}\right]C_{L_{ref}} \right. \qquad 3.8.5.4\text{-}4$$

$$\left. + \left[1-\frac{\Delta v_a'/V}{\sqrt{s}+\Delta v_a'/V}\,\frac{(c_l/C_L)_\alpha}{(c_l/C_L)_\delta}\right](C_L)_\alpha\right\}$$

where: w/s = hydrodynamic foil loading for incipient cavitation

q = dynamic pressure, $\rho V^2/2$

ρ = mass density, 1025.9 Kg/M^3 (1.9905 $slugs/ft^3$)

V = craft speed

A = foil quarter-chord sweep angle

s $= 1+\sigma_c/\cos^2\Delta$

σ_c = cavitation number for incipient cavitation

$= (P_S-P_V)/q$

P_S = static pressure at foil depth, $P_a+\rho gh$

P_V = vapor pressure, 3.5 K Pa (1/2 psi)

P_a = atmospheric pressure, 101.3 K Pa (2116 psf)

g = acceleration of gravity, 9.8066 M/S^2 (32.174 ft/sec^2)

h = foil mean depth

$= 3\,(\ell_S+h_{min})$

a_S = strut length, keel-foil clearance

h_{min} = minimum foil depth

ψ = a section velocity distribution parameter

$$= \frac{v}{V} \pm \left(\frac{\Delta v/V}{c_{l_{i\,ref}}} - \frac{\Delta v_a'}{V}\right)c_{l_{i\,eff}}$$

v/V, $\frac{\Delta v}{V}/C_{\ell iref}$, $\Delta v_a'/V$, ζ, Ω } section velocity distribution parameters of Equation 3.3.8-1

$C_{Lref} = C_{L0} + (C_L)_i$

C_{L0} = the residual lift coefficient of Equation 3.5.3.4-1

$(C_L)_i$ = the incidence lift coefficient of Equation 3.5.3.5-2.

$(C_L)_\alpha = C_{L\alpha}\,(\alpha + |u|/V)$

$C_{L\alpha}$ = the pitch lift curve slope of Equation 3.5.3.5-2

α = foil pitch angle

$|u|$ = absolute value of orbital velocity

$= .7\sqrt{\ell_{su}}\ (.582)^{h\,min/\ell\,su}$

ℓ_{su} = useful strut length, $\ell_s - h_{min}$

$C_{\ell ieff}$ = section effective design lift coefficient of Equation 3.3.1.4-1

$(C_\ell/C_L)_\alpha, (C_\ell/C_L)_i, (C_\ell/C_L)_\delta$ = the maximum (for upper surface) or minimum (for lower surface) C_ℓ/C_L ratios of Section 3.4.3.1 for pitch, incidence, and flap lift respectively. For foils of varying section the C_ℓ/C_L ratios for that span station presenting the most restricted boundary shall be employed.

The predicted cavitation bucket shall be defined in the speed-loading plane by the incipient cavitation boundaries for the lower surface ½% chord station, the most restrictive of the upper surface mid-chord stations, and the upper surface station 5% of the chord forward of the flap hinge, all for negative orbital velocity. The incipient cavitation boundaries for the lower surface 1.25% chord station for negative orbital velocity and for the upper surface 1.25/2.5% chord stations and upper surface flap hinge station for positive and negative orbital velocity shall be shown for reference. The foil loading range from the minimum value to 1 1/8 times the maximum value in the W-LCG envelope shall be contained within this bucket to 105% of the craft maximum speed.

There is no requirement for experimental measurement of the flap lift control system cavitation bucket in model scale.

3.8.3 Pod Cavitation

Unless of prismatic cross-section throughout the length of the foil and strut intersections, the pods shall be demonstrated in model scale to be free of cavitation at 5 degrees pitch and 5 degrees yaw at 105% of the craft top speed.

3.8.4 Strut Cavitation

The strut section at the pod intersection shall satisfy the following relationship:

$$4.7437\left[\frac{h + 31.917}{(v/V)^2 - 1}\right]^{1/2}_{3} \geq \text{craft top speed in knots} \qquad 3.8.4\text{-}1$$

where: h = depth of strut/pod intersections for foil at minimum depth

v/V = the maximum inviscid relative velocity due to the section thickness distribution, from Appendix I of Reference 1 or equivalent

REFERENCES

1. Abbott, Ira H. and Von Doenhoff, Albert E.; Theory of Wing Sections. Dover Publications, 1959

3.9 Ventilation

3.9.1 Strut Ventilation

The nominal closure angles for the forward and aft struts shall be demonstrated for plus and minus yaw angles with the mean water line at the mid-point of the useful strut length, ℓ_{su}, by one of two procedures:

A. The strut shall be operated at the nominal closure angle in a wave system of significant wave height equal to or greater than the useful strut length for a period of at least three minutes with no instances of strut ventilation which are not closed within one second.

or

B. The strut shall be operated at a yaw angle equal to or greater than the nominal closure angle for a period of at least three minutes in a surface sufficiently disturbed to produce an average of one strut ventilation per minute with no instances in which the strut ventilation is not closed withon one second.

The demonstration shall be conducted at full scale design speed cavitation and Froude Number and at the cavitation or Froude scaled speed. If the Froude scaled speed is less than the cavitation scaled speed, the Reynolds Number referenced to the average strut chord shall exceed $2x10^6$.

For the strut closure angle demonstration the pod, incidence, and flap, angles shall be set at their predicted values for the maximum rate flat turn at 1.125 times the full-load displacement. For a split foil system those angles shall be the angles for the outboard foil in the turn.

The demonstrated strut closure angle shall be at least 4.5 degrees.

Any foil/pod/strut configuration design changes, except those which alter the foil aspect ratio and/or taper ratio by less than 10%, shall invalidate the strut closure angle demonstration.

3.9.2 Foil Ventilation.

3.9.2.1 Nominal Minimum Foil Depth. - The nominal minimum foil depth for each foil shall be at least one-half the foil average chord and shall be demonstrated to be ventilation free at design speed and 1 1/8 times the maximum foil loading in the craft W-LCG envelope. The demonstration shall be conducted at full scale cavitation and Froude Number and at Froude scaled speed in smooth or rough water.

3.9.2.2 Broach and Plunging Ventilation Control - Aft Foil systems of conentional area distrubtion or split foil configuration which are not mounted on pods containing propulsion elements and all forward split foil configurations shall employ incidence lift control incorporating a system which commands full-down incidence when the foil depth is less than the nominal minimum foil depth.

3.10 Area Distribution

3.10.1 Foil Area Distribution - For the most aft C.G. in the W-LCG envelope and at minimum foil depth, the static pitch stablity shall be:

$$C_{M_\alpha} = \frac{l_1}{l}\frac{S_1}{S}C_{L_{\alpha_1}} - \frac{l_2}{l}\frac{S_2}{S}C_{L_{\alpha_2}} \leq -.14/\text{radian} \qquad 3.10.1\text{-}1$$

where: $C_{L_{\alpha_1}}$, $C_{L_{\alpha_2}}$ = The forward and aft pitch lift curve slopes of Equation 3.5.3.5-2. All other symbols are defined in Equation 3.7.2.1-2

3.10.2 Lateral Area Distribution

For the most aft C.G. in the W-LCG envelope and for the normal pitch attitude in smooth water at any water line from minimum foil depth to keel the static directional stability shall be:

$$C_{M_\beta} = \frac{l_{s_1}}{l}\frac{S_{s_1}}{S}C_{Y_{\beta_1}} - \frac{l_{s_2}}{l}\frac{S_{s_2}}{S}C_{Y_{\beta_2}} \leq -.085/\text{radian} \qquad 3.10.2\text{-}1$$

where: $C_{Y_{\beta_1}}$, $C_{Y_{\beta_2}}$ = the forward and aft side force slopes of Equation 3.4.4-1

l_{s1}, and l_{s2} are the longitudinal distances between the C.G. and the point on the forward and aft strut quarter-chord lines midway between the surface and the respective foils.

S_{s_1}, S_{s_2} = the forward and aft strut areas of Equation 3.4.4-1

l, S = the foil base and total foil area of Equation 3.7.2.1-2

4 OUALITY ASSURANCE

4.1 Model Test Program

4.1.1 Foil Test Program

4.1.1.1 Incidence Lift Control - The foil model test program for incidence lift control foil systems shall be conducted in accordance with Table 4.1.1.1-I and the data shall be presented in the following format:

- For each depth, angle of attack and drag coefficient shall be plotted against a common lift coefficient ordinate. The equation for a linear regression analysis for the linear lift data shall be shown and the line drawn on the lift plot. The predicted lift curve equation, Equation 3.5.9-1, and corresponding line shall also be shown on the lift plot. The equation fitting the effectively wetted drag coefficients to a quandratic in lift coefficient shall be shown and the curve drawn on the drag plot. The predicted drag polar, Equation 3.7.3.2-3, and corresponding curve shall also be shown on the drag plot.
- For each depth, the initation of the lift and drag effect and the lift plateau shall be shown on the predicted cavitation bucket of section 3.8.1. For the mid-useful strut length water line the foil loading range from the minimum value to 1 1/8 times the maximum value in the W-LCG envelope shall be contained within the load plateau boundary (ies) to the maximum speed.
- Tabulated lift and drag coefficients, Reynolds Numbers, and cavitation numbers.

TABLE 4.1.1.1-I

FOIL MODEL TEST PROGRAM

INCIDENCE LIFT CONTROL

Facility:	Any free Surface facility
Model:	Complete foil/pod/strut configuration. Foil motion relative to pod shall be simulated. Pod motion relative to strut(s) may be simulated by pitching strut(s). No fixed transition shall be employed.
Foil Depth:	Keel-Kissing, mid-useful strut length, and nominal minimum foil depth.
Speed:	Cavitation scaled speeds at intervals of 5 knots f.s. or less from 1/2 to 1.0 x design speed and at intervals of 2.5 knots or less from design speed to 1.1 x maximum speed.
Angle of Attack:	Zero lift angle to $C_{L MAX}$ for 1/2 design speed at 1° ± .2° increments except 1/2° ± .1° increments between -2" and +2°. Angle of attack shall be varied from zero lift angle to maximum angle to zero lift angle.
Data:	Lift and Drag.

4.1.1.2 Flap Lift Control

For the flap lift control system there are no model test requirements for the deflected flap and the model shall not incorporate a simulated flap. The model test program shall be conducted in accordance with Section 4.1.1.1, employing strut pitch to pitch the foil.

4.1.2.1 Strut Test Program - The strut test program shall be conducted in accordance with Table 4.1.2.1-I and the data shall be presented in the following format:

- For each depth; yaw angle, drag coefficient, and moment coefficient referenced to the aerodynamic center shall be plotted on separate abscissas against a common side force coefficient ordinate. For each depth the equation fitting the effectively wetted drag coefficients to a quadratic in side force coefficient shall be shown and the curve drawn on the drag plot. For each depth the equation for a linear regression analysis on the effectively wetted moment coefficients shall be shown and the line drawn on the moment plot.
- The effectively wetted side force slope, neglecting non-linearities in the vicinity of the orgin, shall be plotted against the parameter:

  $$\frac{h+b}{h+2b} \; \frac{C_{avg}}{h}$$

  where: h = foil depth

  b = foil span

  C_{avg} = strut reference chord

  The equation for a linear regression analysis on these data points, identifying the slope as K_s and the intercept as E, shall be shown and the line drawn on the plot. For these values of K_s and E the slopes of Equation 3.4.4-l shall be drawn on the side force coefficient vs. yaw angle plots.
- Tabulated lift, drag, and moment coefficient; Reynolds, Froude, and cavitation numbers.

TABLE 4.1.2.1-I

STRUT MODEL TEST PROGRAM

Facility:	Any free surface facility
Model:	Complete foil/pod/strut configuration except that strut dihedral shall not be simulated. Incidence and/or flap control deflections shall be zero. No fixed transition shall be employed.
Foil Depth:	Nominal minimum foil depth and nominal minimum foil depth plus 1/4, 1/2, 3/4, and 1.0 times useful strut length.
Speed:	Cavitation scaled maximum speed, design speed, and 1/2 design speed.
Yaw Angle:	Minus ventilation angle to plus ventilation angle at 1/2°±.1° increments except 1/4°± .05° increments between -1" and +1°. Yaw angle shall be varied from zero to plus ventilation angle to minus ventilation angle to zero.
Data:	Side Force, Drag, and Yawing Moment.
Coefficient References:	The strut area shall be defined by the nominal water line, the foil chord plane, and the strut leading and trailing edges, extended through the pod. For this reference area the reference chord shall be the mean chord and the aerodynamic center shall be assumed to be the quarter-chord point on the mean chord.

5 STANDARD HYDROFOIL CRAFT CHARACTERISTICS (SHC) CHARTS

The SHC sheets shall be 81/2" x 11", oriented to read from the 11" edge and stapled on the left. The format for the individual pages follows.

5.1 Cover

The cover shall contain an artist's rendering or photograph of the craft, the words "STANDARD HYDROFOIL CRAFT CHARACTERISTICS", the Navy designation for the craft, the design agencie's name, and the date of the latest revision incorporated.

5.2 Drawings

Page 2 shall present a three-view and a general arrangements drawing. The three-view drawing shall present the craft in the normal flight attitude with water line at mid-useful strut length and shall show the full load displacement and the principle dimensions including, but not limited to, the following:

Distance from forward perpendicular to forward foil reference (incidence hinge or pitch lift aerodynamic center)

Foil base (distance between foil references)

Longitudinal distance between forward foil reference and center of gravity

Vertical distance between center of gravity and forwward foil chord plane

Vertical distance between forward and aft chord planes

Minimum vertical distance between keel and forward foil plane

Lateral distance between foil mid-spans (for split foil systems)

Foil dihedral

Strut dihedral

Frontal area, excluding foils/struts/pods (by note)

The front view shall show the water line for the maximum roll angle.

5.3 Component Drawings

Page 3 shall present separate planforms for the forward and aft foils and forward and aft struts and separate side views for the forward and aft pods.

The foil planforms shall show the pod outline, flap hinge, and foil reference (incidence hinge or pitch lift aerodynamic center) but shall not be dimensioned. The following dimensions shall be tabulated:

Aspect Ratio, A	Area, s
Taper Ratio, λ	Span, b
C/4 sweep, Λ	Root chord, Cr
L.E. Sweep,&, E.	Tip Chord, CT
Flap Hinge Sweep, Λ_F	Average Chord, C_{avg}
T.E. Sweep, $\Lambda_{T.E.}$	Mean Aerodynamic Chord, MAC
Pod Dia/Span	Exposed Root Chord, Cr'
Reference as fraction of Cr	Exposted Average Chord, C_{avg}'
Section	Buoyancy

The pod side views shall show the foil root chord (or foil chord at outboard intersection if the pod is not at foil plane of symmetry), the strut intersection, and propeller plane and shall show the following longitudinal dimensions:

pod nose to beginning of prismatic section (or maximum cross section area)

length of prismatic section

afterbody length (or to propeller plane)

over-all length

Pod nose to strut leading edge

Pod nose to foil root chord leading edge

Pod nose to foil reference

The pod side views shall be accompanied by sectional views at the prismatic section or at the section of maximum area showing the foil chord plane, thrust line, and incidence hinge line and the following dimensions:

As required to define the cross section

Foil chord plane to bottom of pod, thrust line, incidence hinge line, and top of pod.

The following dimensions and ratios shall be tabulated for each pod:

Maximum cross section area, So

Maximum perimeter

Effective diameter, $(4S_0/\pi)^{\frac{1}{2}}$

Wetted Area, S_{wet}

Length/Effective Diameter

Wetted Area/(Max. perimeter x pod length)

Buoyancy

The strut planforms shall show the pod and foil root chord with the strut leading and traling edges extended to the foil chord plane in outline. The following dimensions shall be shown:

Streamwise chord and section at pod/strut intersection, top of strut, and at intermediate stations as required to define strut taper in chord and thickness.

Vertical dimensions from top of pod to dimensioned sections.

Strut lateral area housed in strut (by note)

Buoyancy/ft at dimensioned sections

5.4 Description

Page 4 shall present a brief verbal description of the principle features of the design , standard gross and net weights, and specifications for the fuel, oil, ordance, power plant, propulsor, and electronics.

5.5 Weight and Balance

Page 5 shall present the W-LCG envelope and a plot of buoyancy vs forward foil depth for the normal flight attitude for water lines from the upper foil tip or top of the highest pod, whichever is highest, to the Keel. Page 5 shall also present a table of the maximum and minimum pitch and yaw static stabilities , as defined by Equations 3.10.1-1 and 3.10.2-1, for waterlines at the minimum foil depth, mid-useful strut length, and keel. Page 5 shall also present the mid-useful strut length waterline cavitation buckets, as defined by Sections 3.8.1 and 3.8.2, for the forward and aft foil systems.

5.6 Drag Polar

Page 6 shall present the cumulative parasite drag coefficient vs. speed plot of Section 3.7.1.7 for the mid-useful strut length waterline and the cumulative drag-due-to-lift coefficient vs speed plot of Section 3.7.2.6 for the mid-useful strut length waterline and full-load displacement. Page 6 shall also present the drag polars of Equation 317.3.2-3 for the mid-useful strut length water line at full load displacement, full load displacement less half-fuel load, and minimum operating condition and for the water line at the keel for the full load displacement condition. The four drag polars shall be presented on a single plot and their coefficients shall be presented in a table.

5.7 Engine Performance

Page 7 shall present the engine power chart with specific fuel consumption contours in the form, SHP vs. RPM^3.

5.8 Propulsor Performance

Page 8 shall present the propulsor characteristics on separate advance ratio,3 , and thrust coefficient, CT, ordinates plotted against a common power coefficient, C_p, abscissa. For controllable pitch propellers, four pitch ratios bracketing the pitch ratio variation from half design speed to maximum speed shall be presented, "Free Stream" or "Wake" characteristics shall be specified and the source for the characteristics shall be noted. Propeller thrust coefficients shall not incorporate thrust deduction factors.

5.9 Power Required and Available

Page 9 shall present the rated continuous and intermittent powers and the power required curves for the four drag polars of Page 6 on a single plot. The minimum, design, and maximum speeds shall be tabulated.

5.10 Propulsor Performance vs. Speed

Page 10 shall present the variation of engine output RPM, propulsive coefficient, and pitch (for propellers) for the six power curves of Page 9. The SHP-RPM relationships for these power curves shall be superimposed on the engine power chart of page 7.

5.11 Range and Endurance

Page 11 shall present the variation of specific endurance, specific range, endurance, and range with speed for the three mid-useful strut length water line power required curves of Page 9. The speeds for best range and endurance shall be tabulated. The range and endurance shall be noted to be for 90% of the useable fuel load and the total and useable foil loads shall be noted.

5.12 Turn Performance

Page 12 shall present the turn radius in foil base lengths, R/ℓ, vs. the craft speed in knots and the turn rate in degrees/sec. vs. the craft speed in knots for the fully coordinated and/or flat turn, as supplied by the lateral control system. The foil base length, ℓ, shall be noted on the turn radius plot. The coordinated turn performance shall be for the limit roll angle shown on the front view of Page 2 which shall be noted on the turn radius plot. The flat turn performance shall be for the mid-useful strut length water line. Any constraints imposed by the steerable strut or forward strut closure angle or by the cavitation bucket for the outboard foil or outboard semi-span in a flat turn shall be identified on the turn radius curves.

6 NOTES

6.1 Definitions

Maximum Speed - speed for which the power required for the minimum operating condition and mid-useful strut length water line is the maximum intermittent power. See Page 9 of the SHC charts.

Design Speed - Speed for which the power required for the full load displacement and mid-useful strut length water line is the continuous rated power. See Page 9 of the SHC charts.

Minimum Speed - speed for minimum power required, a function of displacement and water line. See Page 9 of the SHC charts.

Cruise Speed - speed for maximum specific range for half-fuel load displacement and mid-useful strut length water line.

Full-load Displacement Displacement limits for

Minimum Operating Condition I unrestricted craft operation.

Half-fuel Load Displacement - full-load displacement less 45% of the unsable fuel.

Minimum Foil Depth - forward foil depth, measured at upper tips for dihedral foils, when forward or aft foil system, whichever is most restrictive for the normal flight attitude, is at the nominal minimum foil depth of Section 3.9.2.1.

Keel Kissing Water Line - water line tangent to the keel in the normal flight attitude.

Useful Strut Length - difference between the keel kissing and minimum foil depth water lines.

Mid-useful Strut Length Waterline - normal flight attitude water line through mid-point of useful strut length.

6.2 Symbols.

Note: Except for standard deviation, σ, $\pm$ and $\mp$ refer to $\begin{matrix}\text{upper}\\\text{lower}\end{matrix}$ surface.

6.2.1 Section Characteristics, Paragraphs 3.3.1-3.3.9.

SYMBOL	DEFINITION
a.c.	aerodynamic center expressed as fraction of chord
Δ a.c.	aerodynamic center movement due to viscous redistribution of lift; $\Delta\, a.c. = a.c._{pot} - a.c.$
$a.c._{pot}$	thick airfoil potential aerodynamic center
b	wetted span; has unit value for section
b_f	wetted flap span; has unit value for section
c	chord
c_d	section drag coefficient, D/qcb
c_{d_f}	flat plate section friction drag coefficient
$c_{d_{ft}}$	flat plate section turbulent flow friction drag coefficient
$c_{d_{min}}$	section minimum drag coefficient
c_f	flap chord
c_h	section flap hinge moment coefficient, flap hinge moment/$qc_f^2\, b_f$
c_{h_0}	section residual flap hinge moment coefficient; coefficient for $\alpha = \delta = 0$
$(c_h)_\alpha$	section flap hinge moment coefficient due to pitch lift
$(c_h)_\delta$	section flap hinge moment coefficient due to flap lift
$c_{h_{c_{\ell\alpha}}}$	section flap hinge moment-pitch lift slope, $dc_h/d(c_\ell)_\alpha$
$\Delta c_{h_{c_{\ell\alpha}}}$	incremental $c_{h_{c_{\ell\alpha}}}$ due to trailing edge bevel
$c_{h_{c_{\ell\alpha 0}}}$	thin airfoil potential value for $c_{h_{c_{\ell\alpha}}}$
$c_{h_{c_{\ell\delta}}}$	section flap hinge moment-flap lift slope, $dc_h/d(c_\ell)_\delta$

SYMBOL	DEFINITION
$\Delta c_{h_{c_{\ell\delta}}}$	$c_{h_{c_{\ell\delta}}}$ increment due to trailing edge bevel
$c_{h_{c_{\ell b\delta}}}$	section flap hinge moment-flap basic lift slope, $dc_h/d(c_{\ell_b})_\delta$
$c_{h_{c_{\ell b\delta 0}}}$	thin airfoil potential $c_{h_{c_{\ell b\delta}}}$
c_ℓ	section lift coefficient, L/qcb
c_{ℓ_a}	additional type component of section lift coefficient
$(c_{\ell_a})_\delta$	additional type section lift coefficient due to flap deflection
$(c_{\ell_b})_\delta$	flap basic section lift coefficient component
c_{ℓ_i}	section design (ideal) lift coefficient
$c_{\ell_{i_{eff}}}$	effective value of section design lift coefficient; i.e. viscous section lift coefficient at ideal angle of attack
$c_{\ell_{i_{ref}}}$	c_{ℓ_i} for which the thin airfoil potential lift distribution over a mean line is derived
c_{ℓ_0}	section residual lift coefficient, c_ℓ for $\alpha = \delta = 0$
c_{ℓ_α}	section lift curve slope, $dc_\ell/d\alpha$
$c_{\ell_{\alpha_M}}$	section lift curve slope for $M > .17$
$c_{\ell_{\alpha_{pot}}}$	thick airfoil potential value for section lift curve slope
$c_{\ell_{\alpha_{RN}}}$	section lift curve slope for $RN < 3 \times 10^6$
$(c_\ell)_\alpha$	section pitch lift coefficient, $c_{\ell_\alpha}\alpha$
c_{ℓ_δ}	section flap lift curve slope, $dc_\ell/d\delta = \frac{d\alpha}{d\delta} c_{\ell_\alpha}$

SYMBOL	DEFINITION
c_{ℓ_x}	local lift coefficient at chord station x
$\Delta c_{\ell_{xb}}$	incremental local basic section lift coefficient clue to viscosity
$(c_{\ell_{xb}})_\delta$	local basic section lift coefficient due to flap lift
$(c_\ell)_\delta$	section lift coefficient due to flap deflection, $c_{\ell_\delta}\,\delta$
$(c_{\ell_x})_\delta$	local section lift coefficient due to flap lift at chord station x
$c_{m_{ac}}$	moment coefficient about aerodynamic center, moment/qc^2b
$c_{m_{ac\ total}}$	sum of section and flap moments about aerodynamic center
$c_{m_{c/4}}$	section moment coefficient about quarter-chord station
C_P	pressure coefficient, $(P_\ell - P_S)/q$
$c.p._c$	camber lift center of pressure
$c.p._\delta$	center of pressure for basic component of section flap lift
c_ϕ	$\phi_{5\%}/(t/c)$
$c_{1_\kappa}, c_{2_\kappa}$	coefficients describing section viscous lift curve slope, $\kappa = 1 + c_{1_\kappa}\, t/c + c_{2_\kappa}\,(t/c)^2$
D	drag
$d\alpha/d\delta$	section flap effectiveness, $c_{\ell_\delta}/c_{\ell_\alpha}$
Ei	exponential integral, $Ei = \int_{-\infty}^{x} \frac{e^t}{t}dt$
F_h	depth Froude Number, $V/\sqrt{gh}$
$f(F_h)$	$e^{-2/F_h^2}/2F_h^2$

SYMBOL	DEFINITION
g	acceleration of gravity. Nominal value is 9.8066 m/s^2 (32.174 $ft./S^2$).
h, h/c	1. flap hinge station, generally expressed as fraction of section chord 2. section depth, generally normalized by section chord
K_{wake}	slope of cd vs. $c_{\ell_a}^2$ curve, $dc_d/dc_{\ell_a}^2$, measured outside of drag bucket
K_{wake_b}	wake drag factor for flap basic lift component
L	lift
ln	natural logarithm
log	logarithm to base 10
M	Mach Number, V/V_S
m_ϕ	empirical coefficient relating viscous and potential section lift curve slopes, $c_{\ell_\alpha}/c_{\ell_{\alpha_{pot}}} = 1 - m_\phi \phi_{5\%}$
P_a	atmospheric pressure. Nominal value is 101.3 k Pa (760 mm Hg) = 2116 $lb./ft.^2$ (29.92 in. Hg)
P_{ac}	Pope's function for basic section lift distribution for viscous effect
P_ℓ	local pressure on section surface
P_S	static pressure at depth of section, $P_a + \rho gh$
PV	vapor pressure.. Nominal value is 3.5 k Pa(½ psi)
q	dynamic pressure, $\rho V^2/2$
R	$c_{d_{min}}/c_{d_f}$
RN	Reynolds Number, $V\ell/\nu$ for reference length, ℓ
S	$1 - c_p = \left(\frac{\text{local velocity on section surface}}{\text{free stream velocity}}\right)^2$
t	thickness
V	speed
V_S	speed of sound

SYMBOL	DEFINITION
$v, v/V$	local velocity distribution on symmetric section, generally normalized by free stream velocity
$\Delta v, \Delta v/V$	local velocity increment on section due to camber, generally normalized by free stream velocity
$\Delta v_a, \Delta v_a/V$	local velocity increment due to angle of attack, generally normalized by free stream velocity
$\Delta v_a'/V$	additional lift velocity distribution adjusted for viscosity; $\frac{\Delta v_a}{v} + \frac{P_{ac} \Delta a.c.}{4\, v/V}$
$(\Delta v/V)_F$	velocity distribution for basic component of flap lift
$x, x/c$	chord station, generally expressed as fraction of chord
α	angle of attack
α_i	ideal (design) angle of attack for mean line
$\alpha_{0\ell}$	zero lift angle of attack
$\alpha_{0\ell_{pot}}$	potential value for $\alpha_{0\ell}$
δ	flap angle
ζ	flap lift distribution parameter, $(c_{\ell_b})_\delta / (c_\ell)_\delta$
κ	relative section lift curve slope (relative to thin airfoil potential theory), $c_{\ell_a}/2\pi$
κ_0	empirical relationship between viscous and potential section zero lift angles, $\kappa_0 = \alpha_{0\ell}/\alpha_{0\ell_{pot}}$
ν	kinematic viscosity. Nominal value is 1.1883 x 10^{-6} m^2/S (12.791 x 10^{-6} ft.^{2}/s) for sea water at 15° C (59° F)
	mass density. Nominal value is 1025.9 kg/m^3 (Ns^2/m^4) = 1.9905 slugs/ft.^{3} (lb. s^2/ft.^{4}) at 15°C (59° F)

SYMBOL	DEFINITION
σ	1. cavitation number, $(P_S - P_V)/q$ 2. standard deviation
σ_C	cavitation number for incipient cavitation; $\sigma_C = - C_P = S - 1$
$\Delta\phi$	trailing edge bevel angle $- \phi_{5\%}$
95%	trailing edge angle defined by 95% and 100% chord stations: $= 2 \tan^{-1} \frac{(t/c)_{.95c} - (t/c)_{T.E.}}{.1}$
Ω	1. a section velocity distribution parameter, $\frac{v}{V} \pm \left(\frac{\Delta v/V}{c_{\ell_{i_{ref}}}} - \frac{\Delta v_a'}{V} \right) c_{\ell_{i_{eff}}}$ 2. Gibbs & Cox Ω function, $1-8\, f(F_h)\, Ei \left(\frac{2}{F_h^2} \right)$
	SUBSCRIPTS
L.E.	at leading edge
T.E.	at trailing edge
t/c_{max}	at maximum thickness
x/c	at chord station x/c
∞	aerodynamic (infinite depth) characteristic. Note: this subscript is employed **only** in sub-sections which include free surface considerations.

6.2.2 Three Dimensional Characteristics, Paragraphs 3.4 through 5

SYMBOL	DEFINITION
A	Aspect ratio, b^2/S or H/C_{avg} for strut
a.c.	Foil aerodynamic center expressed as fraction of chord at foil plain of symmetry. The general case presents nine aerodynamic centers depending upon type of lift loading and foil span segments appropriate as specified in Table 3.4.3-I. See definitions for aerodynamic center and center of pressure.
$a.c._{pod}$	Pod aerodynamic center, actually a center of pressure because CMAC is assumed to be zero.
B	buoyancy for a component or total for craft depending on context.
b	Foil span
b_F	Wetted flap span
C_D	Drag coefficient, D/qs, total for craft unless otherwise noted.
$C_{D\ air}$	Air drag coefficient
C_{D_F}	Foil profile drag coefficient
$C_{D\ Fence}$	Ventilation fence drag coefficient
$C_{D\ i}$	Induced drag coefficient
$C_{D\ int}$	Interference drag coefficient, presumed to include a parasite drag margin.
$C_{D\ L}$	Drag-due-to-lift coefficient
$C_{D\ P}$	Parasite drag coefficient
$C_{D\ pod}$	Pod drag coefficient
$C_{D\ S}$	Strut drag coefficient
$C_{D\ Spray}$	Spray drag coefficient

SYMBOL	DEFINITION
$C_{D\ Surf}$	Surface image drag coefficient
$C_{D\ Wake}$	Wake drag coefficient
$C_{D\ Wave}$	Wave drag coefficient
C_H	Incidence hinge moment coefficient, H/q S MAC
$C_{H\ ref}$	Incidence hinge moment coefficient for $\alpha = \delta = 0$
$C_{H\ CL}$	Incidence hinge moment slope for total foil lift coefficient, dC_H/dC_L
$C_{HC_{L\alpha}}$, $C_{HC_{L\delta}}$	Incidence hinge moment slope for pitch and flap lift
C_h	Flap hinge moment coefficient, h/qS_fC_{favg}
C_{h_0}	residual flap hinge moment coefficient, C_h for $\alpha = i = \delta = 0$
$C_{h_{C_{L\alpha}}}$, $C_{h_{C_{Li}}}$, $C_{h_{C_{L\delta}}}$	Flap hinge moment coefficient slope for pitch, incidence and flap lift; distances between the flap hinge and the respective aerodynamic centers, normalized by the average flap chord and the respective lift coefficient proportions carred on the flap.
$(C_h)_\alpha$, $(C_h)_i$, $(C_h)_\delta$	Flap hinge moment coefficient due to pitch, incidence, and flap lift.

SYMBOL	DEFINITION
C_L	Lift coefficient, L/qS; for foil, foil system, or craft depending on context
$C_{L\,ref}$	C_L for01 = 6 = 0 for rigid foil/pod intersection C_{L0} + $(C_L)_i$
C_{L0}	Residual lift coefficient, C_L for α = i = 6 = 0
$C_{L\alpha}$, C_{Li}, $C_{L\delta}$	Lift coefficient slope for pitch, incidence, and flap deflection
$C_{L\alpha}$ Foil	Pitch lift curve slope for foil alone, i.e., neglecting pod.
$\Delta C_{L\alpha\,pod}$	Pitch lift curve slope increment for pod
$C_{L\delta 1}$	Lift curve slope for general type deflection, δ_1
$C_{L\delta}^{1}$	Lift coefficient slope for deflection of full chord flap, i.e., for unit flap effectiveness
$C_{L\delta}^{11}$	antisymmetric flap (aileron) lift curve slope (for semi-span)
$(C_L)_\alpha$, $(C_L)_i$, $(C)_\delta$	Foil lift coefficient due to pitch, incidence, and flap defflection
C_{Mac}	Hydrodynamic foil moment coefficient about the aerodynamic center due to section camber, presumably = K $C_{Mac\,sect}$'
$C_{Mac\,sect.}$	Aerodynamic foil moment about the aerodynamic center due to section camber

SYMBOL	DEFINITION
$C_{M\alpha}$	Static pitch stability, slope of craft pitching moment coefficient vs. pitch curve
$C_{M\beta}$	Static directional (yaw) stability (wind vane stability), slope of craft yawing moment coefficient vs. yaw curve
C_Y	Side force coefficient, Y/qS for reference area depending on context
$C_{Y\beta}$	Side force coefficient slope, $dC_Y/d\beta$
C	Chord, usually foil
C_r	Foil root chord, i.e., chord at foil plane.of symmetry
C_{avg}	Average foil chord, S/b
C^1_{avg}	Average exposed foil chord, $S'/\eta_{pod} b$
C_{Favg}	Average flap chord, S_F/b_F
C_{dFT}	Flat plate section turbulent flow friction drag coefficient
C_{dmin}	Section minimum drag coefficient
C_l	Section lift coefficient, L/qcb for unit b
$C_{l\,ieff}$	Effective value of section design lift coefficient,, i.e., viscous section lift coefficient at ideal angle of attack
$C_{l\,iref}$	C_{l_i} for which the thin airfoil potential lift distribution over a mean line is derived
$(C_l/C_L)_{\delta_1}$	Ratio of section/foil lift coefficient for general type loading, δ_1
$C_{l\alpha}$	Section lift curve slope
$C_{l\alpha\infty}$	Section lift curve slope at infinite depth
$C_{l\alpha}$ M	Section lift curve slope for M 7.17
$C_{l\alpha}$ RN	Section lift curve slope for $RN < 3 \times 10^6$
C_{Mac}	Section moment coefficient about aerodynamic center

C.P.	Center of pressure for a lift distribution, see a.c. and see Table 3.4.3-I for c.p.'s of primary interest
C.P.F	Section center of pressure for flap lift. Note that section center of pressure for basic component of flap lift is $C.P._\delta$ which is same symbol employed for 3-dimensional flap lift center of pressure in Table 3.4.3-I
$C_o, C_1, C_2,$	Coefficients of drag polar, $C_D = C_o + C_1 C_L + C_2 - C_2 C_L^2$
$C'_{0p}, C'_{1p}, C'_{2p}$	Coefficients of parasite drag coefficient fit to quadratic in 1/q; $C_{DP} = C_{0P} + C_{1p}1(1/q) + C_{2}1_{p}(1/q)^2$
C_{0P}, C_{1p}, C_{2p}	Coefficients of parasite drag polar, $C_{DP} = C_{op} + C_{1p} C_L + C_{2p} C_L 2.$ These coefficients are function of L
C'_0 wave, C'_1 wave, C_2 wave	Coefficients of wave drag polar for some reference L, C_D wave $= C'_o$ wave $+ C'_1$ wave $C_L + C_2$ wave C_L^2 for $L = L_{ref}$
$CO_{wave}, C1_{wave}, C2_{wave}$	Coefficients of wave drag polar, $CD_{wave} = CO_{wave} + C_{1wave} C_L + C_2$ wave-C_L^2 for any L, derived from wave drag polar for L_{ref}
D	Drag, total for craft unless otherwise identified
d	Effective pod diameter, $(4 S_0/\pi)^{\frac{1}{2}}$
d/ℓ	Pod diameter/length ratio
dα /dδ	Section flap effectiveness, $C_{\ell_\delta} / C_{\ell_\alpha}$
E	Emperical factor for strut side force slope $\simeq 1 + \frac{1}{A}$
F_h	Depth Froude Number, $V/\sqrt{gh}$
G	Non-dimensional circulation parameter, $\Gamma/bV = C_\ell$ c /2b
G_o	G for basic lift distribution on span, i.e., for effective foil twist
G/α , G/i	Pitch and incidence lift circulation distributions

SYMBOL	DEFINITION
G_n/δ_1	Non-dimensional circulation parameter for general deflection δ_1 and span station defined by $\eta = \cos n\pi/8$
g	Acceleration of gravity, 9.8066 M/S^2 (32.174 ft/sec^2)
H	Incidence hinge moment, positive nose up; also incidence hinge location but only in ratio H/C_r
H_q	Slope of H/SMAC vs. q curve
H/C_r	Incidence hinge position expressed as fraction of foil root chord
h	depth of flap hinge moment or flap hinge position in ratio h/c
h_{min}	Nominal minimum foil depth
h/c	Flap hinge position expressed as fraction of chord
I, J	Incidence or flap lift induced drag parameters defined in Equation 3.7.2.2-1
i	Incidence angle, positive nose up
i_{OL}	Zero lift incidence angle
K	Section (and foil) lift curve slope correction factor for Reynolds Number, Mach Number, and depth; defined by Equation 3.5.3.5-l
K_E	Strut side force slope parameter accounting for end plate effect of foil, (1+b/h)/(1+2b/h)
K_S	Emperical factor for strut side force slope $\approx$ 2.12
K_W	Wave drag approximation factor defined in Equation 3.7.2.5-l
K_{wake}, K_{wakeb}	Wake drag factors defined by Equation 3.3.9-l
L	Hydrodynamic lift, W-B
L^1	Foil lift less pod lift
L/S	Hydrodynamic foil loading

SYMBOL	DEFINITION
$\ell_{forebody}$	Pod forebody length, nose to shoulder
ℓ_s	Strut length, vertical distance between foil chord plane at strut/foil intersection and keel
ℓ_{su}	Useful strut length, $\ell_s - h_{min}$
ℓ_1, ℓ_2	Longitudinal distance between C.G. and forward and aft foil reference points
M_{pod}	Foil bending moment at foil/pod intersection
M_η	Foil bending moment at span station η,
MAC	Foil mean aerodynamic chord, $\sqrt{A/S}\int_0 c_\eta^2\, d\eta$
MAC^1	MAC for a foil consisting of two exposed semi-spans
n_1, n_2	number of forward and aft struts
P_a	Atmospheric pressure. Nominal value is 101.3 K Pa (760 mm Hg)=2116 lb/ft^2(29.92 in.Hg)
P_S	Static pressure at depth of section, $P_a + \rho g h$
P_V	Vapor pressure, Nominal value is 3.5 K Pa ($\frac{1}{2}$ psi)
q	Dynamic pressure, $\rho V^2/2$
R	$1+1.5(d/\ell)^{3/2}+7(d/\ell)^3$, provides supervelocity and wake drag increments on pod friction drag
S	Foil area, foil system area, or total craft foil area depending on context, or pressure coefficient, $1-C_p=1+\sigma_c/\cos^2\Lambda = \left(\frac{\text{local velocity on section surface}}{\text{free stream velocity}}\right)^2$.
S^1	Exposed foil area or flapped foil area
S_{air}	Craft frontal area, neglecting foils/struts/pods
S_F	Flap area
S_{fence}	Exposed ventilation fence area

SYMBOL	DEFINITION
S_S	Wetted strut area
S_{wet}	Wetted area
S_O, $S_{O\ pod}$	Pod frontal area
t_{surf}	Strut thickness at surface
$\mathcal{V}$	Orbital velocity at foil depth
V	Speed or spanwise foil shear
V_{pod}	Shear at foil/pod intersection,i.e., lift on exposed semi-span
V_{δ_1}	Shear produced by general deflection δ_1, i.e., by pitch, incidence, or flap deflection
v/V	Local velocity distribution on symmetric section, normalized by free stream velocity
Δ v/V	Local velocity increment on section due to camber, normalized by free stream velocity
Δv_a1/V	Add. lift velocity distribution adjusted for viscosity
W	Craft weight
W_{net}	Craft net weight, weight less buoyancy, Identical with L
W/S	Foil weight loading. Note that it is L/S, not W/S, which determines foil performance but it is more convenient to express performance in terms of W/S, e.g. B/S added to cavitation L/S to present cavitation bucket as W/S vs speed.
X_N	Longitudinal distance between pod nose and C_r leading edge.
Y	Side force
α	Foil angle of attack, measured at pod axis
β	Yaw angle. Note a confusion in terms here. In the wind tunnel and towing tank it is called yaw angle; in free

SYMBOL	DEFINITION
	flight, it is called side slip angle and changes in heading are called yaw angle. In this volume the strut angle of attack in a turn is β ; the heading change is ψ.
Γ	Circulation, M^2/S (Ft^2/sec) or dihedral angle
Γ_o	Circulation due to basic type (twist) span loading
δ	Flap deflection, positive T.E. down
δ_1	A general angle; pitch, incidence, full-chord flap, or flap angle
ζ	Flap lift distribution parameter, basic/total flap lift, given in Equation 3.3.2.2-3
η	Foil span station, expressed as fraction of semi-span
$\eta_{c.P}$	Spanwise center of pressure for semi-span neglecting pod lift
$\eta_{c.p.C}$	Spanwise center of pressure for exposed semi-span
η_i, η_o	Spanwise stations for inboard and outboard flap extremities
η_{pod}	Spanwise station at foil/pod intersection
κ	Relative section lift curve slope (relative to thin airfoil potential theory), $C_{\ell_\alpha}/2\pi$
Λ	Quarter-chord line sweep angle
$\Lambda_{L.E.}$, Λ_F, $\Lambda_{T.E.}$	Leading edge, flap hinge line and trailing edge sweep angles
λ	Taper ratio, C_t/C_r
ρ	Mass density. Nominal value is 1025.9 Kg/M^3 (NS^2/M^4) = 1.9905 $slugs/ft^3$ ($lb\ sec^2/ft^4$) at 15°C (59°F)
σ	Standard deviation, nominal uncertainty for a prediction

SYMBOL	DEFINITION
σ_c	Cavitation number for incipient cavitation; $\sigma_c = -C_p = S-1$
σ_1	Biplane factor, See Table 3.7.2.4 - I, Page 3.7-10
γ	A section velocity distirubiton parameter, $\frac{v}{V} \pm \left(\frac{\Delta v/V}{C_{l_{i_{ref}}}} - \frac{\Delta v_a'}{V} \right) C_{l_{i_{eff}}}$
Ω	A section velocity distribution parameter, $\frac{(\Delta v/V)_F}{C_{l_{\delta S}}} - \frac{\Delta v_a'}{V}$ (see Equation 3.3.8-1)

SUBSCRIPTS

i	For incidence lift
n	1 or 2 or foil span station defined by $\frac{8}{\pi} \cos^{-1} \eta$
α	For pitch lift
δ	For flap lift
∞	Aerodynamic (infinite depth) characteristic. Note that this subscript is employed only in sub-sections which include free surface considerations.
1,2	Forward and aft.