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PREDICTION OF ROLL, SWAY AND YAW MOTIONS OF HULLBORNE HYDROFOIL SHIPS

D.R.E.A. TECHNICAL MEMORANDUM 76/C

RESEARCH AND DEVELOPMENT BRANCH
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PREDICTION OF ROLL, SWAY AND YAW MOTIONS OF HULLBORNE HYDROFOIL SHIPS

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ABSTRACT

To provide further capability for prediction and analysis of hydrofoil hullborne seakeeping, a mathematical model and computer program have been developed to predict roll, sway and yaw motions of hullborne hydrofoil ships in beam seas. Predictions agree well with towing tank data for a 1:20-scale model of the PHM hydrofoil craft.

SOMMAIRE

Afin d'accroître les possibilités de prédiction et d'analyse de la tenue en mer des navires hydroptères en flottaison sur leur coque, on a créé un modèle mathématique et un programme d'ordinateur pour prévoir le roulis, le tangage et l'embardée des navires hydroptères en mers du travers. Les prédictions s'accordent bien avec les données obtenues dans un réservoir de remorquage avec un modèle à l'échelle de 1/20 de l'hydroptère PHM.

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NOTATION

A	subscript and superscript referring to aftermost hull section
A_{jk}	added mass coefficient
B_{jk}	damping coefficient
C_{jk}	stiffness coefficient
C_L	lift coefficient
$C_{L\alpha}$	lift curve slope
C_n	flat plate normal force coefficient
C_w	strut wave-making damping coefficient
$C(k)$	Theodorsen's function
F	superscript denoting foil contribution
F_j	exciting force or moment
$\overline{GM}$	metacentric height
H	superscript denoting hull contribution
I_4	rolling moment of inertia
I_6	yawing moment of inertia
L	foil lift, also length between perpendiculars
N	foil yawing moment
S	foil area
$S_e(k)$	Sear's function
T_i	coefficient dependent on flap-chord ratio
U	ship speed
a_{jk}	sectional added mass
b_{jk}	sectional wave-making damping
b	foil span

c	foil mean chord
e_β	flap effectiveness parameter
f_j	sectional Froude-Kriloff force
g	gravitational acceleration
h	foil mean depth
h_j	sectional diffraction force
k	reduced frequency
k_w	wave number
k_ϕ, k_ψ, etc.	control systems gains
m	ship mass
n_2, n_3	y and z components of unit outward normal to hull
p	distance from flap hinge line to mid chord ÷ semi-chord
s	x - coordinate of foil mid chord
t	time variable
u	wave horizontal orbital velocity
w	wave vertical orbital velocity
$\hat{w}$	component of wave orbital velocity perpendicular to the foil
x, y, z	coordinate system (Fig. 2)
Γ	foil dihedral angle
α	foil angle of attack
β	flap deflection
δ	rudder deflection
ϕ_j	two-dimensional section potential
ζ	wave amplitude
ζ_β	flap control system damping ratio

ζ_{δ}	rudder control system damping ratio
η	wave elevation
η_2	sway displacement
η_4	roll angle
$\hat{\eta}_4$	roll amplitude
η_6	yaw angle
ξ	variable of integration in longitudinal direction
ρ	density of water
ω	frequency of encounter (= wave frequency for beam sea)
ω_{β}	flap control system natural frequency
ω_{δ}	rudder control system natural frequency

1. INTRODUCTION

Although hydrofoil ships will spend some of their operational time in the displacement condition, little attention has been paid to the theoretical analysis of hullborne hydrofoil seakeeping until recently. Indeed, Ref. 1, which treats pitch and heave motions in head seas, appears to be the first published work to address this problem. The present report describes a mathematical model to predict roll, sway and yaw motions of hullborne hydrofoil ships in beam seas; also included is a computer program which applies to craft with fully submerged foil systems arranged in either a canard or airplane configuration. This work is thus a logical extension of Ref.1 and together they furnish computerized procedures for predicting hullborne hydrofoil motions in the five major degrees of freedom. Further, these programs are applicable to a wide range of hull and foil configurations.

As in Ref. 1, hull exciting forces, added mass, and damping are computed by the usual means of strip theory, and upon these are superposed linearized hydrofoil terms. Predictions agree well with towing tank data for a 1:20-scale model of the PHM hydrofoil craft. However, because of the limited scope of the test results, one should not base general conclusions on this comparison.

2. MATHEMATICAL MODEL

The mathematical model is obtained by adding linearized hydrofoil terms to the strip theory of Ref. 2. The most important assumptions and restrictions are:

(1) Ship response is a linear function of wave excitation.
(2) Ship length is much greater than either beam or draft.
(3) The hull does not develop appreciable planing lift.
(4) All viscous effects are negligible except for zero speed foil and strut damping.
(5) Hull-foil interaction is negligible.

In applying strip theory to a displacement hull, (1) to (3) are normally assumed, but (4) is changed to "all viscous effects other than roll damping are negligible", and the effect of viscosity on roll damping is included at all speeds. For hydrofoil ships, however, which do not have bilge keels, hull viscous damping is always negligible compared with foil and strut damping. Assumption (5) makes the problem theoretically tractable by permitting direct superposition of hull and foil terms.

2.1 EQUATIONS OF MOTION

Consider a hydrofoil ship whose length is significantly greater than either its beam or draft and assume that this ship is travelling at constant speed U along a mean course at right angles to the direction of propagation of a train of long-crested regular waves of frequency ω (Fig. 1). Let x, y, z be a right-handed orthogonal coordinate system fixed with respect to the mean position of the ship with the origin at the mean position of the centre of gravity. The positive x-axis points forward in the direction of motion, the positive y-axis to port, and the positive z-axis vertically upward (Fig. 2). Denote sway by η_2, roll by η_4, and yaw by η_6.

The coupled sway, roll and yaw equations are given below, using the same subscript convention as in Ref. 2. Flap (β) and rudder (δ) equations are also given, with notation similar to Ref. 1.

Sway:
$$(A_{22}+m)\ddot{\eta}_2 + B_{22}\dot{\eta}_2 + A_{24}\ddot{\eta}_4 + B_{24}\dot{\eta}_4 + C_{24}\eta_4 + A_{26}\ddot{\eta}_6 + B_{26}\dot{\eta}_6 + C_{26}\eta_6 + A_{2\beta}\ddot{\beta} + B_{2\beta}\dot{\beta} + C_{2\beta}\beta + A_{2\delta}\ddot{\delta} + B_{2\delta}\dot{\delta} + C_{2\delta}\delta = F_2 \quad (1)$$

Roll:
$$A_{42}\ddot{\eta}_2 + B_{42}\dot{\eta}_2 + (A_{44}+I_4)\ddot{\eta}_4 + B_{44}\dot{\eta}_4 + C_{44}\eta_4 + A_{46}\ddot{\eta}_6 + B_{46}\dot{\eta}_6 + C_{46}\eta_6 + A_{4\beta}\ddot{\beta} + B_{4\beta}\dot{\beta} + C_{4\beta}\beta + A_{4\delta}\ddot{\delta} + B_{4\delta}\dot{\delta} + C_{4\delta}\delta = F_4 \quad (2)$$

Yaw:
$$A_{62}\ddot{\eta}_2 + B_{62}\dot{\eta}_2 + A_{64}\ddot{\eta}_4 + B_{64}\dot{\eta}_4 + C_{64}\eta_4 + (A_{66}+I_6)\ddot{\eta}_6 + B_{66}\dot{\eta}_6 + C_{66}\eta_6 + A_{6\beta}\ddot{\beta} + B_{6\beta}\dot{\beta} + C_{6\beta}\beta + A_{6\delta}\ddot{\delta} + B_{6\delta}\dot{\delta} + C_{6\delta}\delta = F_6 \quad (3)$$

Flap:
$$-\omega_\beta^2(k_{\ddot{\phi}}\ddot{\eta}_4 + k_{\dot{\phi}}\dot{\eta}_4 + k_\phi\eta_4) + \ddot{\beta} + 2\zeta_\beta\omega_\beta\dot{\beta} + \omega_\beta^2\beta = 0 \quad (4)$$

Rudder:
$$-\omega_\delta^2(k_{\ddot{\psi}}\ddot{\eta}_6 + k_{\dot{\psi}}\dot{\eta}_6 + k_\psi\eta_6) + \ddot{\delta} + 2\zeta_\delta\omega_\delta\dot{\delta} + \omega_\delta^2\delta = 0 \quad (5)$$

The A_{ij}'s, B_{ij}'s, C_{ij}'s, and F_i's are ascribed the general form

$$A_{ij} = A^H_{ij} + A^F_{ij} \tag{6}$$

where A^H_{ij} and A^F_{ij} denote contributions from the hull and foils, respectively. Interaction between hull and foils has been ignored. Expressions for the A^H_{ij}, A^F_{ij}, etc. are given below.

2.2 HULL COEFFICIENTS

The strip theory used to compute hull coefficients is obtained from Ref. 2. Since an adequate derivation is given therein, only the final results are presented here.

2.2.1 Added Mass and Damping

$$A^H_{22} = \int_L a_{22} d\xi - \frac{U}{\omega^2} b^A_{22} \tag{7}$$

$$B^H_{22} = \int_L b_{22} d\xi + U a^A_{22} \tag{8}$$

$$A^H_{24} = A^H_{42} = \int_L a_{24} d\xi - \frac{U}{\omega^2} b^A_{24} \tag{9}$$

$$B^H_{24} = B^H_{42} = \int_L b_{24} d\xi + U a^A_{24} \tag{10}$$

$$A^H_{26} = \int_L a_{22} \xi d\xi - \frac{U}{\omega^2} [x_A b^A_{22} - \int_L b_{22} d\xi] + \frac{U^2}{\omega^2} a^A_{22} \tag{11}$$

$$B^H_{26} = \int_L b_{22} \xi d\xi + U[x_A a^A_{22} - \int_L a_{22} d\xi] + \frac{U^2}{\omega^2} b^A_{22} \tag{12}$$

$$A^H_{44} = \int_L a_{44} d\xi - \frac{U^2}{\omega^2} b^A_{44} \tag{13}$$

$$B^H_{44} = \int_L b_{44} d\xi + U a^A_{44} \tag{14}$$

$$A^H_{46} = \int_L a_{24} \xi d\xi - \frac{U}{\omega^2} [x_A b^A_{24} - \int_L b_{24} d\xi] + \frac{U^2}{\omega^2} a^A_{24} \tag{15}$$

$$B^H_{46} = \int_L b_{24} \xi d\xi + U[x_A a^A_{24} - \int_L a_{24} d\xi] + \frac{U^2}{\omega^2} b^A_{24} \tag{16}$$

$$A^H_{62} = \int_L a_{22} \xi d\xi - \frac{U}{\omega^2} [x_A b^A_{22} + \int_L b_{22} d\xi] \tag{17}$$

$$B^H_{62} = \int_L b_{22}\xi d\xi + U[x_A a^A_{22} + \int_L a_{22} d\xi] \tag{18}$$

$$A^H_{64} = \int_L a_{24}\xi d\xi - \frac{U}{\omega^2}[x_A b^A_{24} + \int_L b_{24} d\xi] \tag{19}$$

$$B^H_{64} = \int_L b_{24}\xi d\xi + U[x_A a^A_{24} + \int_L a_{24} d\xi] \tag{20}$$

$$A^H_{66} = \int_L a_{22}\xi^2 d\xi - \frac{U}{\omega^2} x^2_A b^A_{22} + \frac{U^2}{\omega^2}[x_A a^A_{22} + \int_L a_{22} d\xi] \tag{21}$$

$$B^H_{66} = \int_L b_{22}\xi^2 d\xi + U x^2_A a^A_{22} + \frac{U^2}{\omega^2}[x_A b^A_{22} + \int_L b_{22} d\xi] \tag{22}$$

The above integrations are over the length of the ship. In practice, the length of ship is divided into ten or more sections and the two-dimensional sectional added mass (a) and wave-making damping (b) computed for each section using, for example, the Frank close-fit method. a_{22} and b_{22} result from sway motions, a_{44} and b_{44} apply to roll, while a_{24} and b_{24} are due to cross-coupling between sway and roll. Subscript and superscript A refer to the aftermost section.

Note that B^H_{44} contains no hull viscous damping term. This simplification has been made since extensive calculations have shown that hull viscous damping is negligible in comparison to the viscous effects of the foils and struts.

2.2.2 Hydrostatic Restoring Coefficient

The only hydrostatic restoring coefficient affecting lateral motions is C_{44}, given by

$$C^H_{44} = \Delta \overline{GM} \tag{23}$$

where Δ is displacement and $\overline{GM}$ the metacentric height.

2.2.3 Exciting Force and Moments

$$F^H_2 = \rho\zeta[\int_L (f_2 + h_2) d\xi - i\frac{U}{\omega} h^A_2] \tag{24}$$

$$F^H_4 = \rho\zeta[\int_L (f_4 + h_4) d\xi - i\frac{U}{\omega} h^A_4] \tag{25}$$

$$F^H_6 = \rho\zeta\{\int_L [\xi(f_2 + h_2) - i\frac{U}{\omega}] d\xi - i\frac{U}{\omega} x_A h^A_2\} \tag{26}$$

where ζ is the amplitude of the incident wave and the integration is over the length of the hull. f_j and h_j are the sectional incident and diffraction forces, respectively, given by

$$f_2(\xi) = g \int_{C_\xi} n_2 \exp(k_w z' + ik_w y)d\ell \tag{27}$$

$$f_4(\zeta) = g \int_{C_\xi} (yn_3 - zn_2)\exp(k_w z' + ik_w y)d\ell \tag{28}$$

$$h_2(\zeta) = \omega \int_{C_\xi} \phi_2(in_3 - n_2)\exp(k_w z' + ik_w y)d\ell \tag{29}$$

$$h_4(\xi) = \omega \int_{C_\xi} \phi_4(in_3 - n_2)\exp(k_w z' + ik_w y)d\ell \tag{30}$$

The integrations are performed over the submerged hull section. n_2 and n_3 are the y and z components of the unit outward normal to the hull at (ξ,y,z). ϕ_2 and ϕ_4 are the two-dimensional section potentials for sway and roll oscillations, respectively. k_w is the wave number, given by

$$k_w = \frac{\omega^2}{g} \tag{31}$$

and $$z' = z+h_{CG} \tag{32}$$

where h_{CG} is the height of the CG above the waterplane. The Frank close-fit method may be used to evaluate ϕ_2 and ϕ_4.

2.3 FOIL COEFFICIENTS

2.3.1 Nonzero Forward Speed

The foil coefficients are derived in much the same way as in Ref. 1. We begin by considering a foil of dihedral angle Γ and resolving its lift force L and moment N into sway, roll and yaw components.

$$\text{sway force} = -L\sin\Gamma \tag{33}$$

$$\text{roll moment} = L(y\cos\Gamma + z\sin\Gamma) \tag{34}$$

$$\text{yaw moment} = N\sin\Gamma \tag{35}$$

Here, no distinction is made between foils and struts. The following sign convention is adopted for dihedral and anhedral angles:

for a port dihedral foil of angle Γ_{DP}, $\Gamma_i = \Gamma_{DP}$

for a starboard dihedral foil of angle Γ_{DS}, $\Gamma_i = -\Gamma_{DS}$

for a port anhedral foil of angle Γ_{AP}, $\Gamma_i = -\Gamma_{AP}$ (36)

for a starboard anhedral foil of angle Γ_{AS}, $\Gamma_i = \Gamma_{AS}$

Denote by L_d and N_d the lift and moment acting on a foil as a result of swaying, yawing and rolling motions. Then, from Ref. 1, equation (21),

$$L_d = L_{NC} + L_C \tag{37}$$

where the subscript NC denotes noncirculatory and C circulatory. In equations (23) and (24) of Ref. 1, we substitute

$-\dot{\eta}_2 \sin\Gamma + (y\cos\Gamma + z\sin\Gamma)\dot{\eta}_4$ for $\dot{z}$

$\eta_6 \sin\Gamma$ for θ

and obtain

$$L_{NC} = \pi\rho b\left(\frac{c}{2}\right)^2 [(s\ddot{\eta}_6 - U\dot{\eta}_6)\sin\Gamma + \ddot{\eta}_2 \sin\Gamma - (y\cos\Gamma + z\sin\Gamma)\ddot{\eta}_4] \tag{38}$$

$$L_C = \frac{1}{2}\rho U S C_{L\alpha} C(k)[\{(s - \frac{c}{4})\dot{\eta}_6 - U\eta_6\}\sin\Gamma + \dot{\eta}_2 \sin\Gamma - (y\cos\Gamma + z\sin\Gamma)\dot{\eta}_4] - \frac{\partial L}{\partial h} C(k) y\eta_4 \tag{39}$$

where the last term in (39) has been obtained by intuitive analogy with the last term of equation (24) in Ref. 1.

Similarly, from equation (22) of Ref. 1

$$N_d = -L_{NC}s - L_c x - \frac{\pi\rho b c^3 \sin\Gamma}{16}(U\dot{\eta}_6 + \frac{c}{8}\ddot{\eta}_6) \tag{40}$$

Consider now the foil exciting force and moment and denote by L_W and N_W the lift and moment due to wave action on the foil. Then from equations (38) and (39) of Ref. 1,

$$L_W = \frac{1}{2}\rho U S C_{L\alpha} S_e(k)\hat{w} + \frac{\partial L}{\partial h} C(k)\eta \tag{41}$$

$$N_W = -xL_W \tag{42}$$

where η is wave elevation at mid-chord and $\hat{w}$ the component of wave orbital velocity acting perpendicular to the foil:

$$\hat{w} = w\cos\Gamma + u\sin\Gamma \tag{43}$$

where w is the vertical component and u the horizontal component. u is regarded as positive in the direction of propagation of the seaway. For beam waves,

$$u = \omega e^{-k_w h} e^{ik_w y} \tag{44}$$

$$w = i\omega e^{-k_w h} e^{ik_w y} \tag{45}$$

$$\eta = e^{ik_w y} \tag{46}$$

where k_w is wave number.

Substitution of equations (37) to (46) into (33) to (35) yields the foil coefficients listed below. Summation is over all foil and strut elements.

$$A_{22}^F = \pi\rho\Sigma b(\tfrac{c}{2})^2\sin^2\Gamma \tag{47}$$

$$B_{22}^F = \tfrac{1}{2}\rho U\Sigma SC_{L\alpha}C(k)\sin^2\Gamma \tag{48}$$

$$A_{24}^F = A_{42}^F = -\pi\rho\Sigma b(\tfrac{c}{2})^2\sin\Gamma(y\cos\Gamma + z\sin\Gamma) \tag{49}$$

$$B_{24}^F = B_{42}^F = -\tfrac{1}{2}\rho U\Sigma SC_{L\alpha}C(k)\sin\Gamma(y\cos\Gamma + z\sin\Gamma) \tag{50}$$

$$C_{24}^F = -\tfrac{1}{2}\rho U^2\Sigma S\frac{\partial C_L}{\partial h}C(k)\,y\sin\Gamma \tag{51}$$

$$A_{26}^F = A_{62}^F = \pi\rho\Sigma b(\tfrac{c}{2})^2 s\sin^2\Gamma \tag{52}$$

$$B_{26}^F = \rho U\Sigma\sin^2\Gamma[-\pi b(\tfrac{c}{2})^2 + \tfrac{1}{2}SC_{L\alpha}C(k)(s - \tfrac{c}{4})] \tag{53}$$

$$C_{26}^F = -\tfrac{1}{2}\rho U^2\Sigma SC_{L\alpha}C(k)\sin^2\Gamma \tag{54}$$

$$F_2^F = -\tfrac{1}{2}\rho U\Sigma Se^{ik_w y}\sin\Gamma[U\frac{\partial C_L}{\partial h}C(k) + C_{L\alpha}S_e(k)\omega e^{-k_w h}(\sin\Gamma + i\cos\Gamma)] \tag{55}$$

$$A_{44}^F = \pi\rho\Sigma b(\tfrac{c}{2})^2(y\cos\Gamma + z\sin\Gamma)^2 \tag{56}$$

$$B_{44}^F = \frac{1}{2}\rho U \Sigma S C_{L\alpha} C(k)(y\cos\Gamma + z\sin\Gamma)^2 \quad (57)$$

$$C_{44}^F = \frac{1}{2}\rho U^2 \Sigma S \frac{\partial C_L}{\partial h} C(k)\, y\,(y\cos\Gamma + z\sin\Gamma) \quad (58)$$

$$A_{46}^F = A_{64}^F = -\pi\rho\Sigma b\left(\frac{c}{2}\right)^2 s\sin\Gamma(y\cos\Gamma + z\sin\Gamma) \quad (59)$$

$$B_{46}^F = \rho U \Sigma \sin\Gamma(y\cos\Gamma + z\sin\Gamma)\left[\pi b\left(\frac{c}{2}\right)^2 - \frac{1}{2}S C_{L\alpha} C(k)\left(s - \frac{c}{4}\right)\right] \quad (60)$$

$$C_{46}^F = \frac{1}{2}\rho U^2 \Sigma S C_{L\alpha} C(k)\sin\Gamma(y\cos\Gamma + z\sin\Gamma) \quad (61)$$

$$F_4^F = \frac{1}{2}\rho U \Sigma S e^{ik_w y}(y\cos\Gamma + z\sin\Gamma)\left[U\frac{\partial C_L}{\partial h} C(k) + C_{L\alpha} S_e(k) e^{-k_w h}\omega(\sin\Gamma + i\cos\Gamma)\right] \quad (62)$$

$$B_{62}^F = \frac{1}{2}\rho U \Sigma x S C_{L\alpha} C(k)\sin^2\Gamma \quad (63)$$

$$B_{64}^F = -\frac{1}{2}\rho U \Sigma x S C_{L\alpha} C(k)\sin\Gamma(y\cos\Gamma + z\sin\Gamma) \quad (64)$$

$$C_{64}^F = -\frac{1}{2}\rho U^2 \Sigma x S \frac{\partial C_L}{\partial h} C(k)\, y\sin\Gamma \quad (65)$$

$$A_{66}^F = \pi\rho\Sigma\left[s^2 b\left(\frac{c}{2}\right)^2 + \frac{bc^4}{128}\right]\sin^2\Gamma \quad (66)$$

$$B_{66}^F = \rho U \Sigma\left[-\pi b\left(\frac{c}{2}\right)^2 + \frac{1}{2}x S C_{L\alpha} C(k)\right]\left(s - \frac{c}{4}\right)\sin^2\Gamma \quad (67)$$

$$C_{66}^F = -\frac{1}{2}\rho U^2 \Sigma x S C_{L\alpha} C(k)\sin^2\Gamma \quad (68)$$

$$F_6^F = -\frac{1}{2}\rho U \Sigma x S e^{ik_w y}\sin\Gamma\left[U\frac{\partial C_L}{\partial h} C(k) + C_{L\alpha} S_e(k)\omega e^{-k_w h}(\sin\Gamma + i\cos\Gamma)\right] \quad (69)$$

The flap coefficients are obtained by using equations (50) to (53) of Ref. 1 to evaluate the lift and moment due to deflecting a flap through angle β (Fig. 3). Resolution of this force and moment via equations (33) to (35) results in the flap terms given below.

$$A_{2\beta} = -2\rho b_F T_1 (\frac{c_F}{2})^3 \sin\Gamma \qquad (70)$$

$$B_{2\beta} = -\frac{1}{2}\rho U b_F c_F^2 (T_4 - \frac{1}{2\pi} C_{L\alpha} C(k) T_{11}) \sin\Gamma \qquad (71)$$

$$C_{2\beta} = \rho U^2 b_F c_F C_{L\alpha} C(k) e_\beta \sin\Gamma \qquad (72)$$

$$A_{4\beta} = 2\rho b_F T_1 (\frac{c_F}{2})^3 (y_F \cos\Gamma + z_F \sin\Gamma) \qquad (73)$$

$$B_{4\beta} = \frac{1}{2}\rho U b_F c_F^2 (T_4 - \frac{1}{2\pi} C_{L\alpha} C(k) T_{11})(y_F \cos\Gamma + z_F \sin\Gamma) \qquad (74)$$

$$C_{4\beta} = -\rho U^2 b_F c_F C_{L\alpha} C(k) e_\beta (y_F \cos\Gamma + z_F \sin\Gamma) \qquad (75)$$

$$A_{6\beta} = A_{2\beta} s + 2\rho b_F (\frac{c_F}{2})^4 (T_7 + pT_1) \sin\Gamma \qquad (76)$$

$$B_{6\beta} = \frac{1}{2}\rho U b_F c_F^2 \sin\Gamma [-T_4 s + \frac{1}{2\pi} C_{L\alpha} C(k) T_{11} x - \frac{c_F}{2}(T_1 - T_8 - pT_4 + \frac{1}{2}T_{11})] \qquad (77)$$

$$C_{6\beta} = C_{2\beta} x - 2\rho U^2 b_F (\frac{c_F}{2})^2 (T_4 + T_{10}) \sin\Gamma \qquad (78)$$

where p is the distance from the flap hinge line to mid-chord divided by the semi-chord (see Fig. 3). e_β is the flap effectiveness parameter. The T_i's are given in Ref. 1. The contribution from both port and starboard flaps has been summed in the above equations. y_F and z_F apply to the port flap, and β is positive for port flap down.

Consider now the rudder. Side force due to rudder deflection may be calculated by substituting δ for ϕ and $-\frac{c}{4}$ for s in equations (23) and (24) of Ref. 1. Then

$$L_R = \pi\rho b (\frac{c}{2})^2 (-\frac{c}{4}\ddot{\delta} - U\dot{\delta}) + \frac{1}{2}\rho U S C_{L\alpha} C(k)(-\frac{c}{2}\dot{\delta} - U\delta) \qquad (79)$$

where L_R is rudder side force, assumed positive when acting in the negative y-direction in keeping with our convention regarding dihedral angles. Rudder moment is given by

$$N_R = \pi\rho b(\tfrac{c}{2})^2 s(\tfrac{c}{4}\ddot{\delta} + U\dot{\delta}) + \tfrac{1}{2}\rho USC_{L\alpha}C(k)x(\tfrac{c}{2}\dot{\delta} + U\delta) - \pi\rho b\frac{c^3}{16}(U\dot{\delta} + \frac{c\ddot{\delta}}{8}) \qquad (80)$$

Substitution of (79) and (80) into (33) to (35) yields the rudder terms.

$$A_{2\delta} = -\pi\rho b_R \frac{c_R{}^3}{16} \qquad (81)$$

$$B_{2\delta} = -\rho US_R \frac{c_R}{4}(\pi + C_{L\alpha}C(k)) \qquad (82)$$

$$C_{2\delta} = -\tfrac{1}{2}\rho U^2 S_R C_{L\alpha}C(k) \qquad (83)$$

$$A_{4\delta} = -A_{2\delta}z_R \qquad (84)$$

$$B_{4\delta} = -B_{2\delta}z_R \qquad (85)$$

$$C_{4\delta} = -C_{2\delta}z_R \qquad (86)$$

$$A_{6\delta} = A_{2\delta}s_R + \pi\rho b_R \frac{c_R{}^4}{128} \qquad (87)$$

$$B_{6\delta} = -\rho US_R \frac{c_R}{4}(\pi[s_R - \frac{c_R}{4}] + C_{L\alpha}C(k)x_R) \qquad (88)$$

$$C_{6\delta} = C_{2\delta}x_R \qquad (89)$$

2.3.2 Zero Forward Speed

At zero forward speed, viscous drag forces opposing lateral motions act on the foils. By regarding the foils as oscillating flat plates and equating the energy dissipated by the non-linear viscous effect during one cycle to that dissipated by a linear damping term, we obtain the following viscous roll damping coefficient:

$$B_{44}^F = \frac{4}{3\pi}\rho\omega\hat{\eta}_4\Sigma(y^2 + z^2)^{3/2}\, SC_n \sin\alpha \qquad (90)$$

where $\hat{\eta}_4$ is roll amplitude and C_n is the normal-force coefficient for a flat plate tilted at angle α to the flow. From Ref. 3,

$$C_n = \begin{cases} 0.0467\alpha & \alpha < 40° \\ 1.17 & \alpha > 40° \end{cases} \tag{91}$$

and from geometrical considerations

$$\tan\alpha = \left|\frac{y/z + \tan\Gamma}{1-(y/z)\tan\Gamma}\right| \tag{92}$$

Similar equations may be derived for the other foil damping terms, but these are much less significant than the viscous roll damping term. Equations are given below for B^F_{22} and B^F_{66}.

$$B^F_{22} = \frac{4}{3\pi}\rho\omega\eta_2 \Sigma SC_n \sin\alpha \tag{93}$$

$$B^F_{66} = \frac{4}{3}\rho\omega\eta_2 \Sigma SC_n |s|^3 \sin\alpha \tag{94}$$

where $\hat{\eta}_2$ and $\hat{\eta}_6$ are sway and yaw amplitudes, and

$$\alpha = |\Gamma| \tag{95}$$

2.3.3 Strut Wave-Making Damping

A strut in or near the free surface will generate waves when oscillated laterally. The resultant damping terms due to wave-making affect roll significantly at low speeds. For a vertical strut, the sway wave-making damping term is

$$B^W_{22} = \frac{\pi}{2}\rho\omega b^2 c\, C_W \tag{96}$$

where C_W is a function of $\frac{\omega^2 b}{g}$. A curve obtained using the Frank close-fit method is given in Fig. 4.

Roll and yaw wave-making damping terms are obtained by multiplying B^W_{22} by the appropriate foil coordinates.

3. COMPUTER PROGRAM

Based on the foregoing mathematical model, a computer program has been developed to predict hullborne hydrofoil lateral motions in beam seas. A program listing is given in the Appendix, together with detailed descriptions of input and output. Note that since hull viscous damping is neglected, this program applies only to the "foils down" case. A further restriction is that the foil system must be of the fully submerged type and either canard or airplane in configuration, i.e. one foil unit in an inverted T while the other is either an inverted π or two inverted T's. Full details are given in the Appendix.

4. COMPARISON OF THEORY WITH EXPERIMENT

The Davidson Laboratory has recently measured wave-induced motions for a 1:20-scale model of the 220-ton PHM hydrofoil craft during hullborne operation in sea states 3 and 5 (Ref. 4). Representative wave height spectra, as measured during the tests, are shown in Fig. 5 for the full-scale craft.

Unfortunately, Ref. 4 gives rather scanty lateral motion data because of towing tank test restrictions. The only useful frequency response measurements are for beam sea rolling at zero speed (Fig. 6). Root mean square roll, yaw rate, and lateral acceleration were measured across the speed range in sea state 3 (Fig. 7), but the rather academic nature of this spectrum (Fig. 5) does not permit generalizations based on these results, since little or no seaway energy is present in the frequency range of greatest interest (.3 to 1.5 rad/sec).

Fig. 6 shows generally satisfactory agreement between computed and measured beam sea roll response at zero speed. One may reasonably conclude from this comparison that hove-to rolling predictions should be satisfactory.

Predicted and measured beam sea root mean square lateral motions are compared in Fig. 7. Agreement is satisfactory but, as mentioned above, because of the peculiar nature of the seaway spectrum, one cannot base general conclusions on this comparison.

5. CONCLUDING REMARKS

Although, as demonstrated above, predictions agree well with the measurements available, the latter are not sufficiently extensive to permit meaningful assessment of the general reliability of predictions. One may reasonably expect, however, that hove-to rolling predictions should be satisfactory as indicated by the agreement between limited experimental data and predictions.

Computational experience has shown that the foils and struts dominate hullborne lateral motions, even at zero speed, and this dominance becomes more pronounced with increasing speed. Foil system damping completely swamps hull damping, and at nonzero speeds the dominant forcing function arises from action of the horizontal component of wave orbital velocity on the struts. Further, the control system is effective in reducing roll angles, particularly for full-scale speeds in excess of 10 knots.

The present work and Ref. 1 together furnish computerized procedures for predicting hullborne hydrofoil motions in the five major degrees of freedom. However, the present work applies to beam seas and Ref. 1 to head seas. Work is in progress to synthesize the two and produce a computer program which will predict motions in five degrees of freedom at arbitrary headings to the sea.

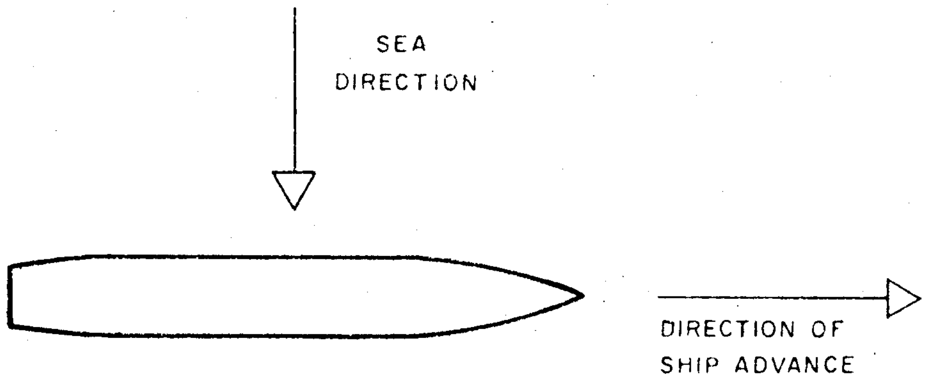

FIG I SHIP AND SEA DIRECTIONS

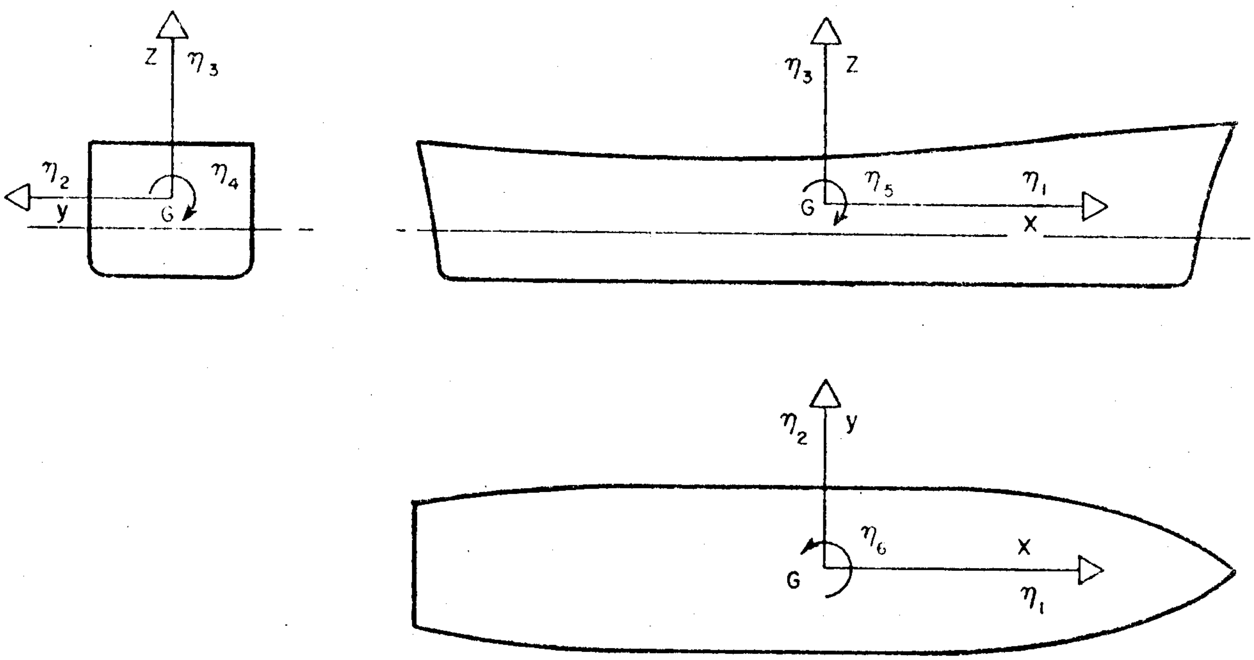

FIG 2 AXIS SYSTEM

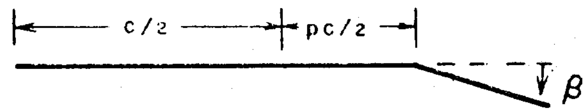

FIG 3 IDEALIZED FLAPPED HYDROFOIL

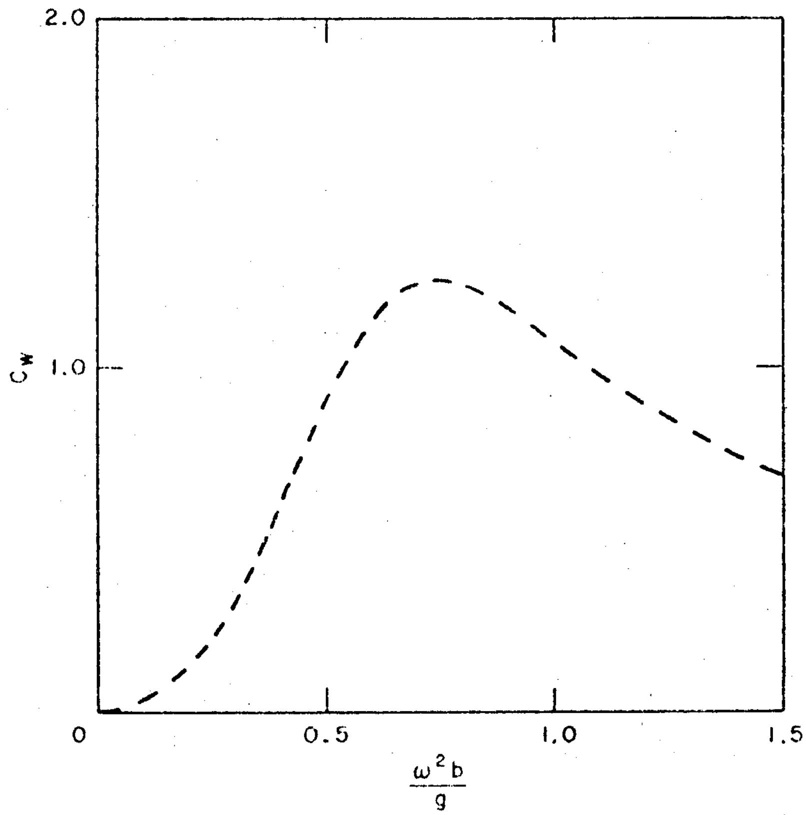

FIG 4 STRUT WAVE-MAKING DAMPING COEFFICIENT

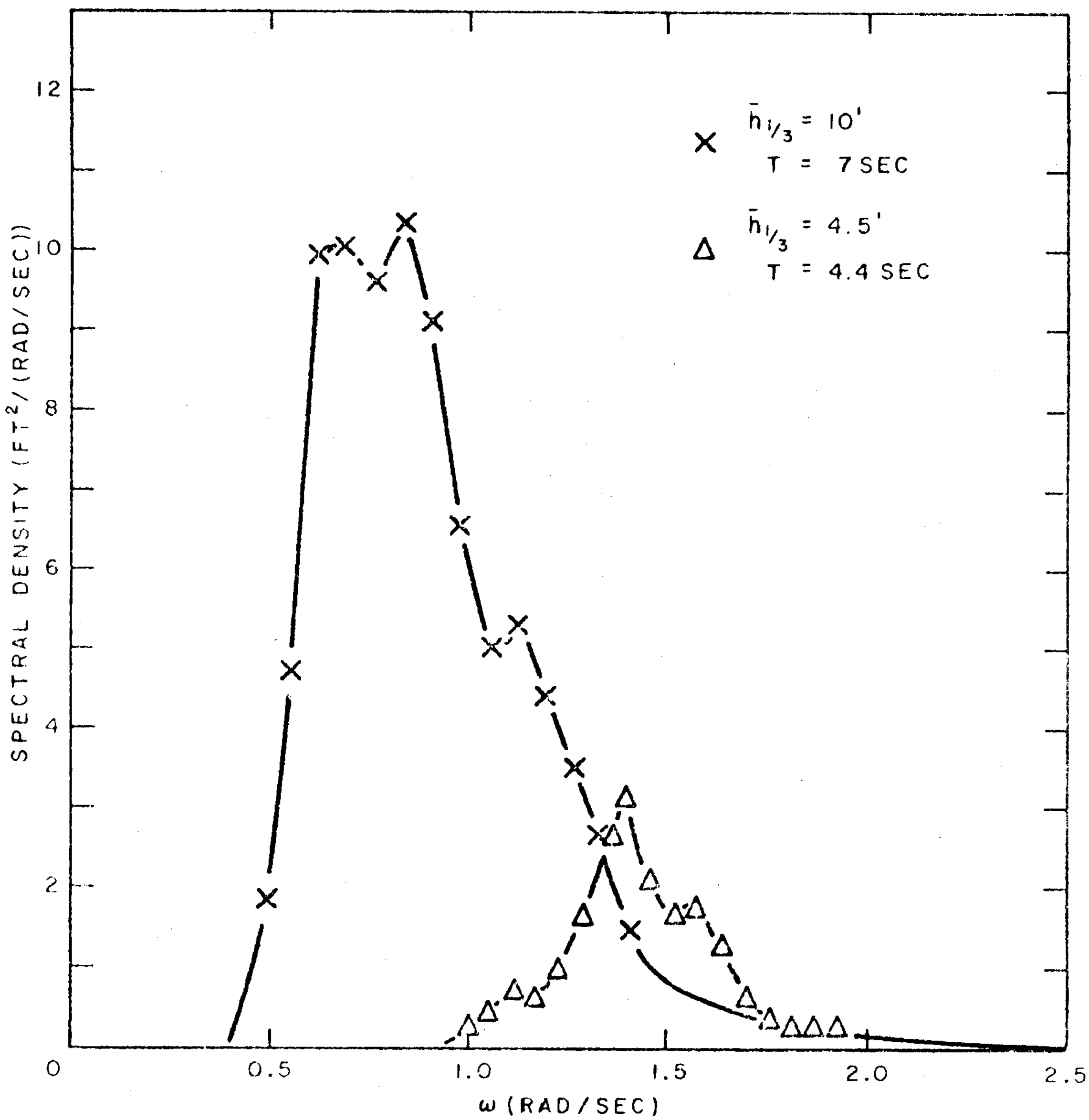

FIG 5 REPRESENTATIVE WAVE SPECTRA

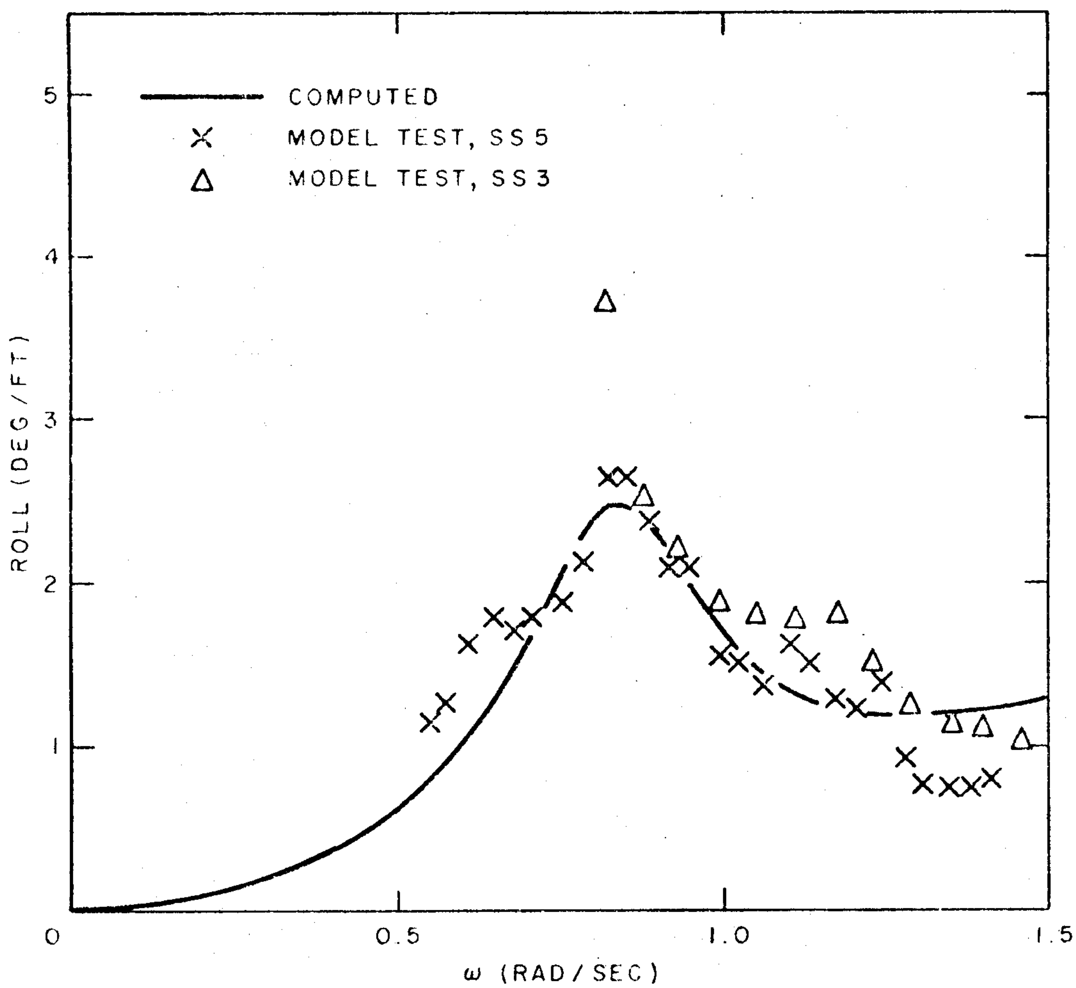

FIG 6 BEAM SEA ROLL RESPONSE, O KT

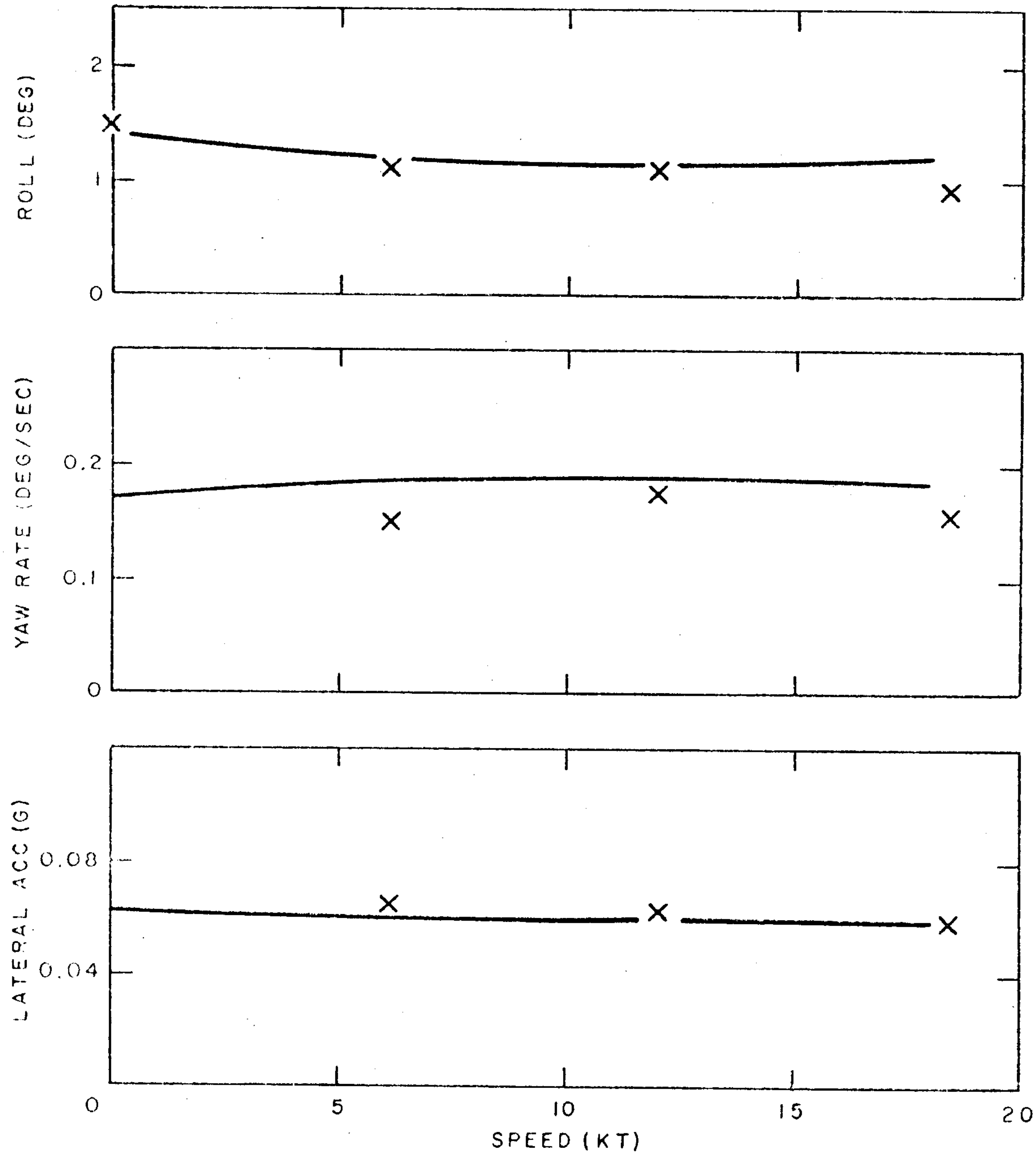

FIG 7 RMS LATERAL MOTIONS IN BEAM SEA STATE 3

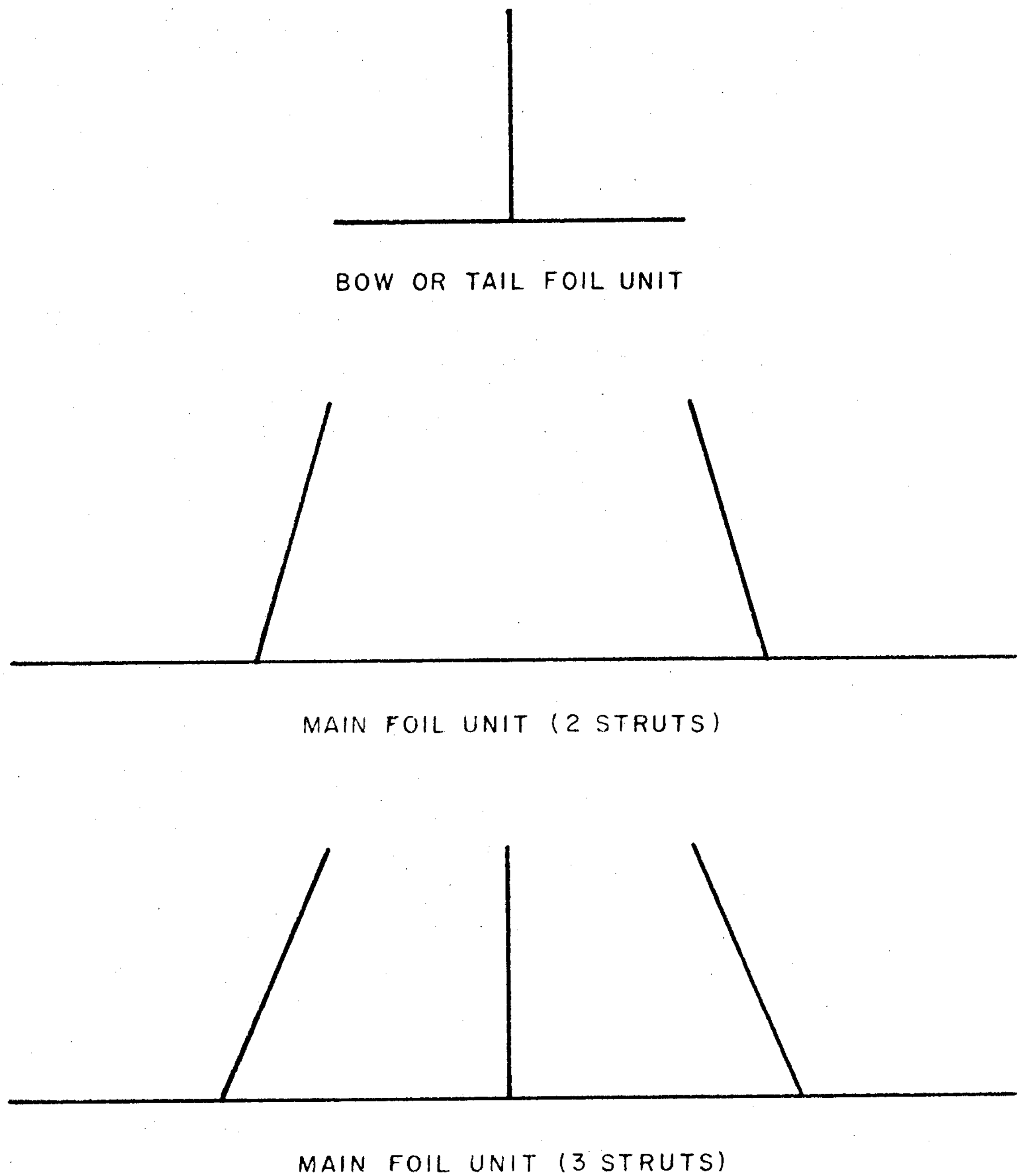

FIG 8 SIMPLIFIED SKETCH OF FOIL UNITS

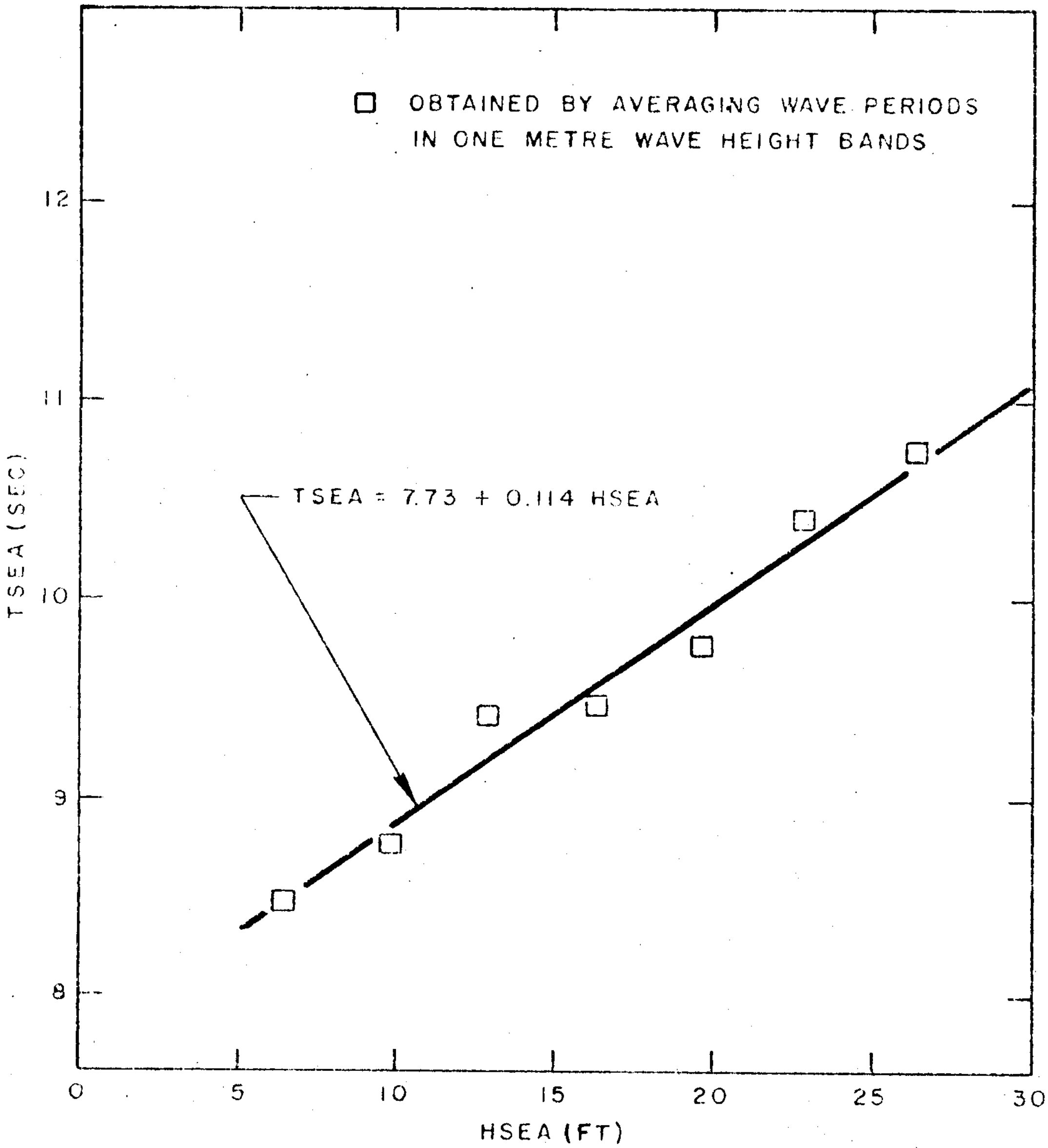

FIG 9 TSEA vs HSEA

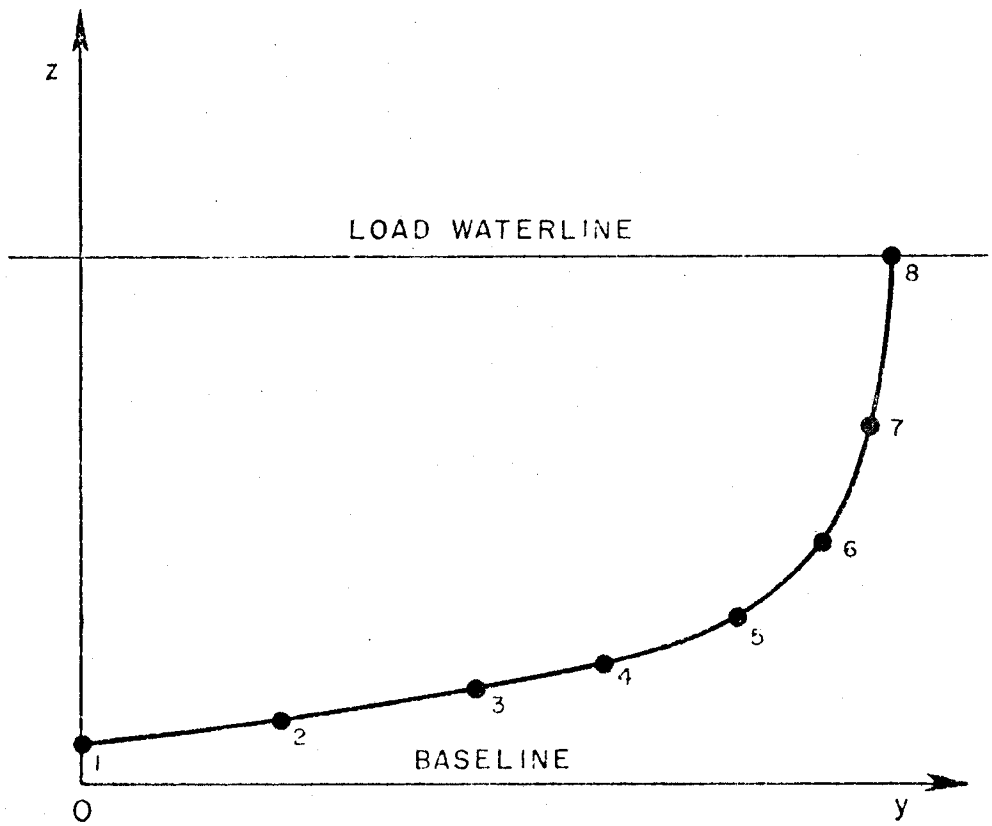

FIG 10 STATION OFFSETS

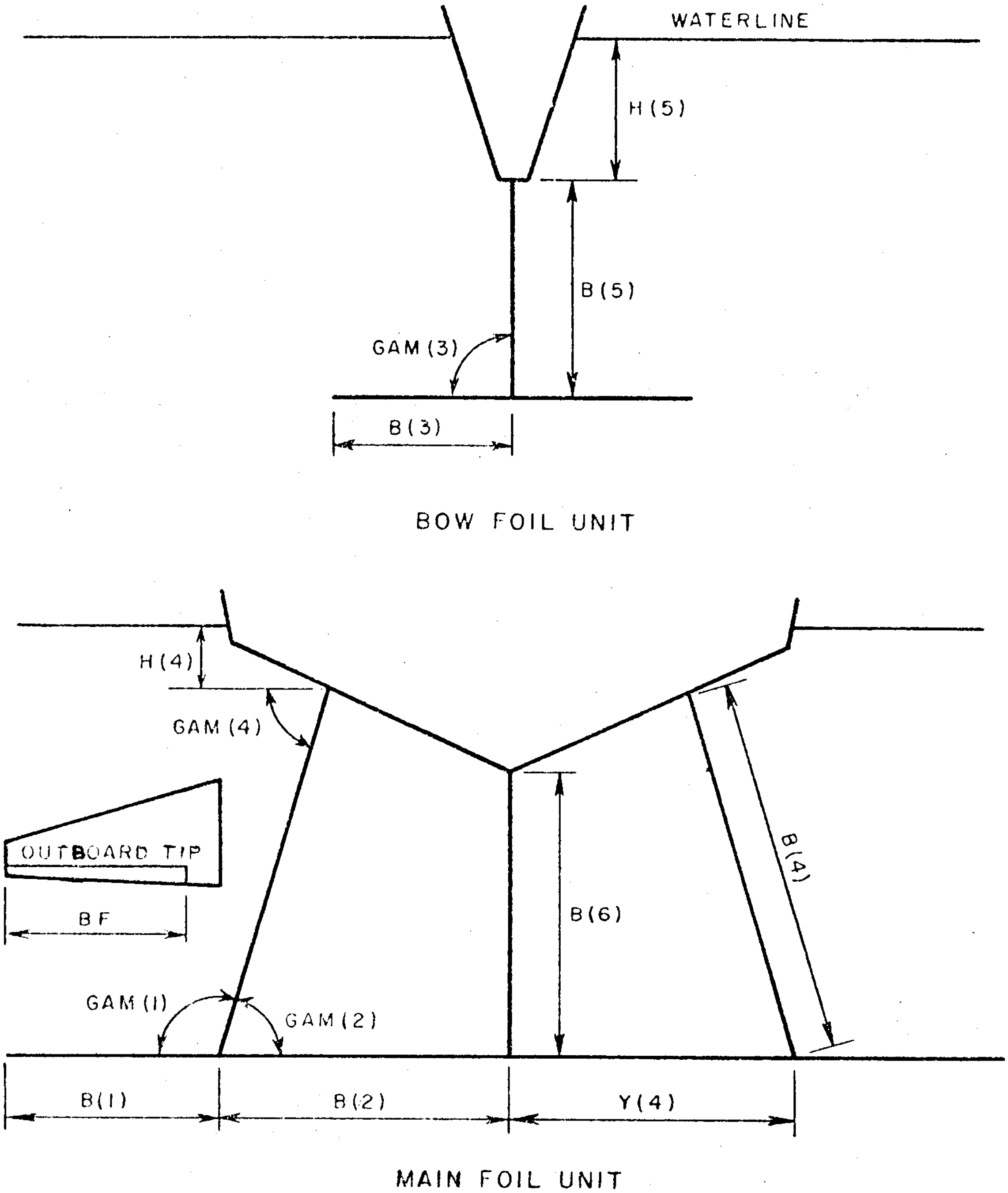

FIG II FOIL SYSTEM INPUTS

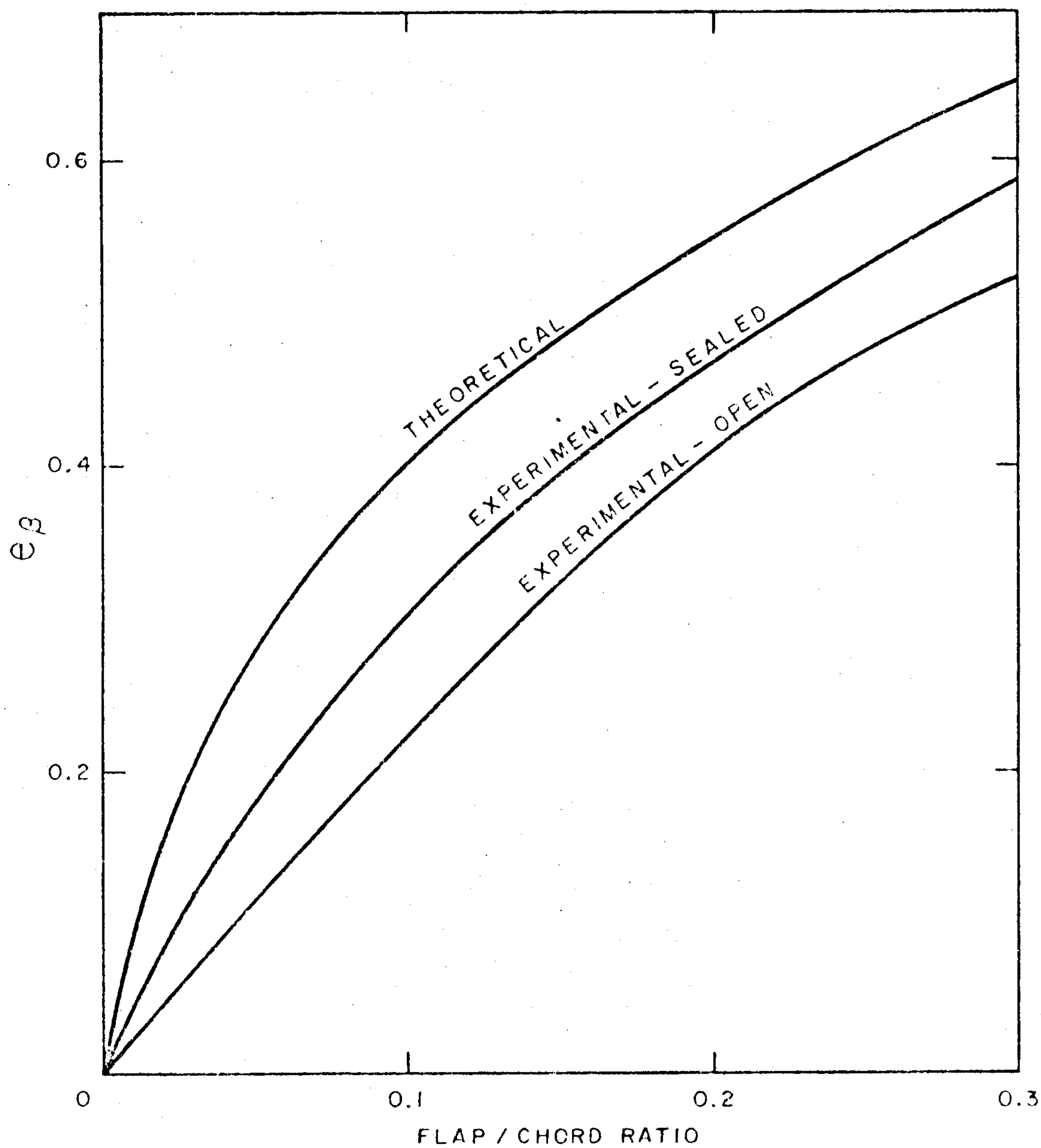

FIG 12 FLAP EFFECTIVENESS

REFERENCES

1. Schmitke, R. T.: Prediction of Pitch and Heave Motions of Hullborne Hydrofoil Vessels. DREA Report 74/2, January 1974.

2. Salvesen, N.; Tuck, E. O., and Faltinsen, O.: Ship Motions and Sea Loads. Trans. SNAME, Vol. 78, 1970.

3. Hoerner, S. F.: Fluid Dynamic Drag. Published by the author, 1958.

4. Henry, C. J.: PHM Hullborne Wave Tests. Davidson Laboratory Report SIT-DL-74-1759, 1974.

5. Miles, M.: Wave Spectra Estimated from a Stratified Sample of 323 North Atlantic Wave Records. NRC Report LTR-SH-118A, May 1972.

6. Gospodnetic, D., and Miles, M.: Some Aspects of the Average Shape of Wave Spectra at Station 'India' (59°N, 19°W). International Symposium on the Dynamics of Marine Vehicles and Structures in Waves, London, April 1974.

APPENDIX

COMPUTER PROGRAM DETAILS

The computer program applies to a hydrofoil ship with a fully submerged foil system of either a canard or airplane configuration. The main foil is an inverted π (Fig. 8), while the bow foil (canard configuration) or tail foil (airplane configuration) is an inverted T. Specification of a third strut on the main foil unit is an optional input; another option is to split the main foil into two T's. The bow (or tail) foil also acts as the ship's rudder, and the flaps for roll control are on the outboard tips of the main lifting foil.

A. INPUT DESCRIPTION

(a) ONE CARD, FORMAT (8F10.4)

U	speed (kt)
EL	length between perpendiculars (ft)
HCG	height of CG above waterplane (ft)
XCG	distance from CG to forward perpendicular (ft)
RRG	roll radius of gyration ÷ EL
YRG	yaw radius of gyration ÷ EL
DISP	displacement (tons)
RHO	fluid density (slug/ft^3)

(b) ONE CARD (I2,2F10.3)

NFR	number of frequencies at which responses are to be calculated
FR1	lowest frequency (rad/sec)
DFR	increment in frequency (rad/sec)

Notes (1) If computing motions in irregular seas with U > 0, set NFR=18, FR1=.3, and DFR=.1. If U=0, it may be necessary to set DFR=.05.

(c) ONE CARD (2I3)

NSEA	number of sea states (maximum of 10)
NPOS	number of positions at which swaying motions in irregular seas are to be computed (maximum of 10)

Notes (1) If motions in irregular waves are not desired, use a blank card for (c).
(2) If NSEA=0, ignore data cards (d) and (e). If NSEA > 0, but NPOS=0, ignore data card (e).

(d) NSEA CARDS (2F10.4)

HSW(I) significant wave height (ft)
TSW(I) energy-averaged wave period (sec)

Notes (1) Fig. 9, obtained using the data of Ref. 5, is offered as a guide to the variation of TSEA with HSEA. Caution should be exercised in applying this curve, however, since considerable variation of wave period with significant wave height is exhibited by natural seaways (see, for example, Fig. 1 in Ref. 6).

(e) NPOS CARDS (2F10.4)

XPOS(I) x - coordinate of position I (stations aft of FP)
z - coordinate of position I (ft above CG)

(f) ONE CARD (F10.4)

GMIN metacentric height (ft)

Notes (1) If metacentric height is not specified on input, (i.e. GMIN=0), the program will use a value computed from the offset data. This GM is not, however, corrected for internal free surfaces.

(g) ONE CARD (3F10.4)

FIAV expected roll amplitude (deg)
YAWAV expected yaw amplitude (deg)
SWAYAV expected sway amplitude (ft)

Notes (1) These data are only required for U=0. For U > 0, use a blank card.
(2) When computing motions in irregular seas, set these inputs equal to 1.25 times the expected root mean square values.

(h) ONE CARD (12)

NST number of stations for which offsets are input

Notes (1) The program assumes a 20-station hull representation, with station 0 at the forward perpendicular and station 20 at the transom.
(2) The maximum value of NST is 25. However, since the foil system dominates lateral response, in the interest of computational efficiency it is generally desirable to use no more than 10 stations to define the hull. These should, however, be equally spaced and include the transom.
(3) One each of data cards (i), (j) and (k) is required for each of the NST stations.

(i) <u>ONE CARD (F10.3)</u>

XA(I) station number

(j) <u>ONE CARD (8F10.4)</u>

YA(I,J) J=1, 8 horizontal offsets of station I (ft)

(k) <u>ONE CARD (8F10.4)</u>

ZA(I,J) J=1, 8 vertical offsets of station I (ft)

Notes (1) <u>Exactly</u> 8 offset points must be specified for each station.
(2) The first point is at the intersection of the centerline with the station contour while the eighth point is at the intersection of the load waterline with the station contour (see Fig. 10).
(3) The vertical offsets are input as heights above hull baseline (waterline zero).
(4) The points and the straight lines between them should provide a good geometric description of the station shape.

(l) <u>ONE CARD (I1)</u>

NSTRUT number of struts on main foil unit (2 or 3)

(m) <u>NSTRUT + 3 CARDS (8F10.4)</u>

GAM(I) input dihedral angle (deg)
SWEEP(I) quarter-chord sweep angle (deg)
ALF(I) angle-of-attack relative to zero lift (deg)
B(I) span (ft)
CR(I) root chord (ft)
CE(I) tip chord (ft)
TC(I) thickness/chord ratio

Notes (1) The number system is shown in Fig. 11.
No. 1 - main foil outboard tip
No. 2 - main foil inboard span
No. 3 - bow lifting foil
No. 4 - main foil outboard strut
No. 5 - bow foil strut
No. 6 - main foil centre strut (if present)
(2) The method of inputting dihedral angles is shown in Fig. 11. These angles are converted to the conventional form (equation (36)) internally.

(n) ONE CARD (5F10.4)

X(4)	main foil strut x - coordinate (ft)
Y(4)	distance from main foil strut tip to centre line (ft)
H(4)	depth of main foil strut root (ft)
X(5)	bow foil strut x - coordinate (ft)
H(5)	bow foil strut root depth (ft)

Notes (1) Strut x - coordinates are measured from the quarter-chord line to the CG. X(4) is negative, X(5) is positive.
(2) Y(4) and H(4) are shown in Fig. 11. For the particular case shown, Y(4)=B(2). If Y(4) > horizontally projected value of B(2), the main foil is assumed to be split.
(3) Strut tips are taken to be at the intersection of the struts with the lifting foils (i.e. project the foils and struts through the intersection pods).

(o) ONE CARD (5F10.4)

BF	flap span (ft)
PF	distance from hinge line to mid-chord ÷ semi-chord
EFF	flap effectiveness
WF	flap control system natural frequency (rad/sec)
ZETF	flap control system damping ratio

Notes (1) The flap is assumed to extend to the tip of foil No. 1 (Fig. 11).
(2) Flap effectiveness is plotted against flap-chord ratio in Fig. 12. Note that this plot is based on aerodynamic data and that considerable doubt exists as to whether flaps are as effective in water as they are in air.

(p) ONE CARD (2F10.4)

WR	rudder control system natural frequency (rad/sec)
ZETR	rudder control system damping ratio

Notes (1) It is assumed that the bow foil is the rudder.

(q) ONE CARD (3F10.4)

QFDD	roll acceleration gain (sec^2)
QFD	roll velocity gain (sec)
QF	roll gain

(r) ONE CARD (3F10.4)

QRDD	yaw acceleration gain (sec^2)
QRD	yaw velocity gain (sec)
QR	yaw gain

B. SAMPLE INPUT

A sample case of FHROLL input data is given on the following page for a hypothetical 400-ton hydrofoil ship at a speed of 10 knots. Note that the hull is trimmed up 1½° and that offsets are given in local section coordinates, i.e. the first point is (0,0) for all stations.

10.0	150.0	2.0	95.25	.086	.258	400.0	1.99
18 .3	.1						
3 8							
8.0	8.64						
10.0	8.87						
12.0	9.10						
0.0	10.0						
5.0	9.0						
10.0	8.0						
15.0	7.0						
20.0	6.0						
10.0	1.0						
10.0	15.0						
10.0	22.0						
0.0							
10							
2.	2						
0.0	.4592	.9184	1.3776	1.8369	2.1801	2.7553	3.2145
0.0	.7379	1.4759	2.2138	2.9519	3.3898	4.4278	5.166
4.0	2						
0.0	.8639	1.7279	2.5918	3.4558	4.3197	5.1836	6.0475
0.0	.7974	1.5949	2.3922	3.1897	3.9871	4.7845	5.582
6.	2						
0.0	1.277	2.554	3.831	5.108	6.385	7.662	8.939
0.0	.8569	1.7137	2.5706	3.4275	4.2843	5.1412	5.998
8.0	2						
0.0	1.6291	3.2583	4.8874	6.5166	8.1457	9.7749	11.404
0.0	.9172	1.8344	2.7516	3.6688	4.5860	5.5033	6.415
10.	2						
0.0	2.2417	4.4833	6.7250	8.9667	11.2083	13.45	13.5015
0.0	1.1052	2.2103	3.3154	4.4206	5.5257	6.63	6.831
12.0	2						
0.0	2.3233	4.6467	6.9700	9.2933	11.6167	13.94	14.102
0.0	1.0827	2.1654	3.2480	4.3307	5.4134	6.5	7.247
14.	2						
0.0	2.3233	4.6467	6.9700	9.2933	11.6167	13.94	14.192
0.0	1.0827	2.1654	3.2480	4.3307	5.4134	6.5	7.663
16.0	2						
0.0	2.3233	4.6467	6.9700	9.2933	11.94	13.94	14.2825
0.0	1.0827	2.1654	3.2480	4.3307	5.4134	6.5	8.079
18.	2						
0.0	2.145	4.29	6.435	8.58	10.725	12.87	13.2405
0.0	.9996	1.9991	2.9987	3.9983	4.9979	6.0	7.495
20.0	2						
0.0	1.7867	3.5733	5.3600	7.1467	8.933	10.72	10.9455
0.0	.8326	1.6652	2.4978	3.3304	4.1629	5.0	5.912
2							
104.0	15.0	4.2	18.5	11.4	3.8	.065	
76.0	0.0	4.2	14.5	11.4	11.4	.065	
90.0	15.0	4.2	9.75	6.3	2.1	.065	
76.0	0.0	0.0	21.3	12.5	12.5	.12	
90.0	6.0	0.0	13.0	7.0	6.0	.12	
-9.75	14.5	2.9	67.75	5.0			
14.0	.5	.45	17.45	1.45			
17.45	1.45						
0.0	-2.0	0.0					
0.0	-2.0	0.0					

C. SAMPLE OUTPUT

A sample case of FHROLL output is given below. This output results from the above input data and is fairly self-explanatory. Running time is about 100 seconds on a CDC-6400.

The first three pages of output are basically a listing of input data. On the next page are the principal coefficients of the roll equation; at each frequency the foil coefficients form the first line, with the hull coefficients immediately below.

Sway, roll and yaw transfer functions are then listed, with phases relative to wave elevation at the CG. The final three pages give root mean square values of roll, yaw, flap angle and sway in the three specified sea states; also output are absolute motions at the locations specified. The quadratic regression spectrum of Ref. 6, obtained by analyzing 295 wave spectra measured at station 'India' in the North Atlantic (59°N, 19°W), is used in the irregular sea computations.

U	EL	HCG	XCG	RRG	YRG	DISP	RHO
10.0000	150.0000	2.0000	95.2500	.0860	.2580	400.0000	1.9900

NFR= 18   FR1= .300   DFR= .100

NSEA= 3   NPOS= 8

HSW	TSW
8.0000	8.6400
10.0000	8.8700
12.0000	9.1000

	XPOS	ZPOS
(1)	0.0000	10.0000
(2)	5.0000	9.0000
(3)	10.0000	8.0000
(4)	15.0000	7.0000
(5)	20.0000	6.0000
(6)	10.0000	1.0000
(7)	10.0000	15.0000
(8)	10.0000	22.0000

GMIN= 0.0000

FIAV= -0.0000   YAWAV= -0.0000   SWAYAV= -0.0000

STATION 2.00

ABSCISSAS

0.0000	.4592	.9184	1.3776	1.8369	2.2961	2.7553	3.2145

ORDINATES

0.0000	.7379	1.4759	2.2138	2.9519	3.3898	4.4278	5.1660

STATION 4.00

ABSCISSAS

0.0000	.8639	1.7279	2.5918	3.4558	4.3197	5.1836	6.0475

ORDINATES

0.0000	.7974	1.5949	2.3922	3.1897	3.9871	4.7845	5.5820

STATION 6.00

ABSCISSAS

0.0000	1.2770	2.5540	3.8310	5.1080	6.3850	7.6620	8.9390

ORDINATES

0.0000	.8569	1.7137	2.5706	3.4275	4.2843	5.1412	5.9980

STATION 8.00

ABSCISSAS

0.0000	1.6291	3.2583	4.8874	6.5166	8.1457	9.7749	11.4040

ORDINATES

0.0000	.9172	1.8344	2.7516	3.6688	4.5860	5.5033	6.4150

STATION 10.00

ABSCISSAS

0.0000	2.2417	4.4833	6.7250	8.9667	11.2083	13.4500	13.5015

ORDINATES

0.0000	1.1052	2.2103	3.3154	4.4206	5.5257	6.6300	6.8310

STATION 12.00

ABSCISSAS

0.0000	2.3233	4.6467	6.9700	9.2933	11.6167	13.9400	14.1020

ORDINATES

0.0000	1.0827	2.1654	3.2480	4.3307	5.4134	6.5000	7.2470

STATION 14.00

ABSCISSAS

0.0000	2.3233	4.6467	6.9700	9.2933	11.6167	13.9400	14.1920

ORDINATES

0.0000	1.0827	2.1654	3.2480	4.3307	5.4134	6.5000	7.6630

STATION 16.00

ABSCISSAS

0.0000	2.3233	4.6467	6.9700	9.2933	11.9400	13.9400	14.2825

ORDINATES

0.0000	1.0827	2.1654	3.2480	4.3307	5.4134	6.5000	8.0790

STATION 18.00

ABSCISSAS

0.0000	2.1450	4.2900	6.4350	8.5800	10.7250	12.8700	13.2405

ORDINATES

0.0000	.9996	1.9991	2.9987	3.9983	4.9979	6.0000	7.4950

STATION 20.00

ABSCISSAS

0.0000	1.7867	3.5733	5.3600	7.1467	8.9330	10.7200	10.9455

ORDINATES

0.0000	.8326	1.6652	2.4978	3.3304	4.1629	5.0000	5.9120

GMCALC= 8.0188

NFOIL= 3   NSTRUT= 2

GAM	SWEEP	ALF	B	CR	CE	TC
104.0000	15.0000	4.2000	18.5000	11.4000	3.8000	.0650
76.0000	0.0000	4.2000	14.5000	11.4000	11.4000	.0650
90.0000	15.0000	4.2000	9.7500	6.3000	2.1000	.0650
76.0000	0.0000	0.0000	21.3000	12.5000	12.5000	.1200
90.0000	6.0000	0.0000	13.0000	7.0000	6.0000	.1200

X(4) = -9.7500   Y(4) = 14.5000   H(4) = 2.9000   X(5) = 87.7500   H(5) = 5.0000

BF = 14.0000   PF = .5000   EF = .4500   WF = 17.4500   ZETF = 1.4500

WR = 17.4500   ZETR = 1.4500

GFDD = 0.0000   QFD = -2.0000   QF = 0.0000

QRDD = 0.0000   QRD = -2.0000   QR = 0.0000

ROLL COEFFICIENTS

W	A44	B44R	B44I	C44R	C44I	F4R	F4I
.300	.2906E+07	.1317E+08	-.1363E+07	.1040E+05	-.7552E+03	-.1078E+06	.2559E+05
	.3486E+07	.1321E+08	-.1363E+07	.3578E+07	-.7552E+03	-.1078E+06	.1570E+05
.400	.2906E+07	.1296E+08	-.1690E+07	.1029E+05	-.9721E+03	-.1368E+06	.4080E+05
	.3498E+07	.1300E+08	-.1690E+07	.3578E+07	-.9721E+03	-.1367E+06	.2335E+05
.500	.2906E+07	.1274E+08	-.1959E+07	.1016E+05	-.1170E+04	-.1617E+06	.5676E+05
	.3512E+07	.1278E+08	-.1959E+07	.3577E+07	-.1170E+04	-.1614E+06	.2983E+05
.600	.2906E+07	.1286E+08	-.2169E+07	.1002E+05	-.1347E+04	-.1826E+06	.7228E+05
	.3528E+07	.1292E+08	-.2169E+07	.3577E+07	-.1347E+04	-.1816E+06	.3420E+05
.700	.2906E+07	.1362E+08	-.2327E+07	.9871E+04	-.1501E+04	-.1991E+06	.8646E+05
	.3543E+07	.1370E+08	-.2327E+07	.3577E+07	-.1501E+04	-.1970E+06	.3586E+05
.800	.2906E+07	.1503E+08	-.2439E+07	.9709E+04	-.1632E+04	-.2110E+06	.9858E+05
	.3553E+07	.1514E+08	-.2439E+07	.3577E+07	-.1632E+04	-.2072E+06	.3432E+05
.900	.2906E+07	.1709E+08	-.2512E+07	.9544E+04	-.1742E+04	-.2179E+06	.1080E+06
	.3557E+07	.1724E+08	-.2512E+07	.3577E+07	-.1742E+04	-.2118E+06	.2907E+05
1.000	.2906E+07	.1884E+08	-.2555E+07	.9378E+04	-.1830E+04	-.2193E+06	.1143E+06
	.3549E+07	.1904E+08	-.2555E+07	.3577E+07	-.1830E+04	-.2111E+06	.1941E+05
1.100	.2906E+07	.1977E+08	-.2573E+07	.9213E+04	-.1899E+04	-.2151E+06	.1171E+06
	.3531E+07	.2003E+08	-.2573E+07	.3576E+07	-.1899E+04	-.2056E+06	.4545E+04
1.200	.2906E+07	.1953E+08	-.2571E+07	.9053E+04	-.1951E+04	-.2054E+06	.1162E+06
	.3504E+07	.1986E+08	-.2571E+07	.3576E+07	-.1951E+04	-.1964E+06	-.1620E+05
1.300	.2906E+07	.1890E+08	-.2555E+07	.8898E+04	-.1988E+04	-.1908E+06	.1116E+06
	.3470E+07	.1928E+08	-.2555E+07	.3576E+07	-.1988E+04	-.1850E+06	-.4306E+05
1.400	.2906E+07	.1813E+08	-.2527E+07	.8750E+04	-.2011E+04	-.1720E+06	.1037E+06
	.3433E+07	.1856E+08	-.2527E+07	.3576E+07	-.2011E+04	-.1725E+06	-.7566E+05
1.500	.2906E+07	.1726E+08	-.2492E+07	.8610E+04	-.2023E+04	-.1502E+06	.9316E+05
	.3396E+07	.1773E+08	-.2492E+07	.3576E+07	-.2023E+04	-.1602E+06	-.1130E+06
1.600	.2906E+07	.1627E+08	-.2450E+07	.8478E+04	-.2025E+04	-.1267E+06	.8059E+05
	.3361E+07	.1677E+08	-.2450E+07	.3576E+07	-.2025E+04	-.1492E+06	-.1534E+06
1.700	.2906E+07	.1504E+08	-.2404E+07	.8353E+04	-.2019E+04	-.1028E+06	.6690E+05
	.3329E+07	.1556E+08	-.2404E+07	.3576E+07	-.2019E+04	-.1402E+06	-.1949E+06
1.800	.2906E+07	.1357E+08	-.2355E+07	.8237E+04	-.2007E+04	-.7976E+05	.5294E+05
	.3301E+07	.1410E+08	-.2355E+07	.3576E+07	-.2007E+04	-.1337E+06	-.2354E+06
1.900	.2906E+07	.1183E+08	-.2304E+07	.8129E+04	-.1989E+04	-.5856E+05	.3949E+05
	.3277E+07	.1237E+08	-.2304E+07	.3575E+07	-.1989E+04	-.1298E+06	-.2726E+06
2.000	.2906E+07	.9977E+07	-.2252E+07	.8028E+04	-.1967E+04	-.3995E+05	.2719E+05
	.3256E+07	.1052E+08	-.2252E+07	.3575E+07	-.1967E+04	-.1284E+06	-.3045E+06

FREQUENCY RESPONSE

SWAY AMP IS NON-DIMENSIONAL, ROLL AND YAW AMPS IN DEG/FT

	SWAY		ROLL		YAW		
W	AMP	PHASE	AMP	PHASE	AMP	PHASE	W.L./L
.300	1.296	48.474	.923	-165.209	.241	-176.369	14.987
.400	1.241	26.472	1.328	171.154	.278	157.245	8.430
.500	1.110	7.628	1.560	151.444	.285	134.347	5.395
.600	.914	-4.345	1.529	136.183	.256	116.406	3.747
.700	.717	-8.282	1.307	125.526	.206	103.366	2.753
.800	.563	-7.490	1.043	118.250	.157	93.397	2.107
.900	.448	-5.041	.804	113.303	.119	84.078	1.665
1.000	.380	-4.728	.653	111.074	.097	76.392	1.349
1.100	.343	-6.823	.567	111.482	.083	72.522	1.115
1.200	.332	-11.605	.536	114.039	.078	72.276	.937
1.300	.330	-17.518	.530	117.795	.076	74.205	.798
1.400	.334	-24.104	.541	122.022	.078	76.727	.688
1.500	.342	-31.234	.573	125.851	.083	78.557	.599
1.600	.355	-38.790	.623	128.479	.091	79.089	.527
1.700	.372	-46.956	.695	129.222	.098	78.042	.467
1.800	.393	-55.798	.787	127.728	.105	75.281	.416
1.900	.416	-65.561	.898	123.686	.110	70.570	.374
2.000	.434	-75.974	1.014	117.254	.112	64.017	.337

ROOT MEAN SQUARES IN SEA STATE 4   HSEA = 8.00   TSEA = 8.64

	ROLL AND YAW DISPLACEMENT DEG	VELOCITY DEG/SEC	ACCELERATION DEG/SEC**2
ROLL	2.379	1.674	1.473
YAW	.392	.265	.219
FLAP	3.322	2.902	3.524

	SWAY AT POSITION INDICATED DISPLACEMENT FT	VELOCITY FT/SEC	ACCELERATION FT/SEC**2
CG	1.446	.977	.828
X= 0.0,Z=10.0	1.494	1.048	.925
X= 5.0,Z= 9.0	1.547	1.069	.934
X= 10.0,Z= 8.0	1.628	1.110	.959
X= 15.0,Z= 7.0	1.733	1.169	.998
X= 20.0,Z= 6.0	1.858	1.243	1.051
X= 10.0,Z= 1.0	1.419	.966	.825
X= 10.0,Z=15.0	1.859	1.271	1.106
X= 10.0,Z=22.0	2.105	1.443	1.262

ROOT MEAN SQUARES IN SEA STATE 5   HSEA = 10.00   TSEA = 8.87

	ROLL AND YAW DISPLACEMENT DEG	VELOCITY DEG/SEC	ACCELERATION DEG/SEC**2
ROLL	3.054	2.100	1.821
YAW	.508	.335	.272
FLAP	4.167	3.586	4.352

	SWAY AT POSITION INDICATED DISPLACEMENT FT	VELOCITY FT/SEC	ACCELERATION FT/SEC**2
CG	1.883	1.237	1.028
X= 0.0,Z=10.0	1.930	1.317	1.144
X= 5.0,Z= 9.0	2.005	1.349	1.157
X= 10.0,Z= 8.0	2.116	1.405	1.190
X= 15.0,Z= 7.0	2.258	1.483	1.241
X= 20.0,Z= 6.0	2.424	1.579	1.308
X= 10.0,Z= 1.0	1.844	1.222	1.022
X= 10.0,Z=15.0	2.415	1.608	1.373
X= 10.0,Z=22.0	2.732	1.825	1.566

ROOT MEAN SQUARES IN SEA STATE 5   HSEA = 12.00   TSEA = 9.10

	ROLL AND YAW DISPLACEMENT DEG	VELOCITY DEG/SEC	ACCELERATION DEG/SEC**2
ROLL	3.734	2.511	2.140
YAW	.628	.404	.322
FLAP	4.984	4.215	5.072

	SWAY AT POSITION INDICATED DISPLACEMENT FT	VELOCITY FT/SEC	ACCELERATION FT/SEC**2
CG	2.338	1.497	1.217
X= 0.0,Z=10.0	2.378	1.582	1.350
X= 5.0,Z= 9.0	2.478	1.624	1.367
X= 10.0,Z= 8.0	2.622	1.696	1.407
X= 15.0,Z= 7.0	2.802	1.794	1.469
X= 20.0,Z= 6.0	3.013	1.913	1.550
X= 10.0,Z= 1.0	2.286	1.475	1.209
X= 10.0,Z=15.0	2.990	1.941	1.623
X= 10.0,Z=22.0	3.379	2.201	1.851

D. COMPUTER PROGRAM LISTING

A complete listing for FHROLL follows. It is worth noting that FHROLL departs slightly from Ref. 1 in using the methods of Jones* to calculate C(k) and $S_e(k)$; this modification is made because Jones' formulation takes aspect ratio into account. Another noteworthy point is that in calculating strut roll damping terms, account is taken of the variation in roll velocity along the strut's span.

*Jones, R. T.: The Unsteady Lift of a Wing of Finite Aspect Ratio. NACA Report 681, 1940.

```
      PROGRAM FHROLL(INPUT,OUTPUT,TAPE5=INPUT,TAPE2=INPUT,TAPE6=OUTPUT)
      COMMON/COM1/QQ,G(10,11)
      COMMON/NEW/XA(25),DXA(25),XCG,EL,NST,HCG,C44H,DISP,RHO
      COMMON/NEW2/W,U,A22,B22,A24,B24,A26,B26,A44,B44,A46,B46,
     1A62,B62,A64,B64,A66,B66,EF(10)
      COMMON/NEW3/A22F,A24F,A26F,A44F,A46F,A66F
      COMMON/NEW5/GAM(6),S(6),SX(6),Y(6),Z(6),NFS,B(6),COSS(6),SING(6)
      COMMON/NEW6/FIAV,YAWAV,SWAYAV
      COMPLEX AI,B22,B24,B26,C24,C26,F2,B44,B46,C44,C46,F4,B62,B64,B66,
     1C64,C66,F6,CK,SE,QI,QQ,B2F,C2F,B4F,C4F,B6F,C6F,B2R,C2R,B4R,
     2C4R,B6R,C6R,AIW
      COMMON PI,HPI,QPI,TPI,MD,MODE,DPH,CR,RAT,SUR,DEG,IST,DRT,HBM,SG,N
     1OE,PDM,VOL,DEW,UN,OMEGA,CP,WVH,ID,DOG,IG,XX(25,7),YY(25,7),DEL(25,
     27),SNE(25,7),CSE(25,7),FR(7),BLOG(25,7,7),YLOG(25,7,7),CON(14,1),C
     3T(14,14),PSI1(7,7),PSI2(7,7),PHA(7),PRV(7)
      DIMENSION XPOS(10),ZPOS(10),SWEEP(6),ALF(6),CR(6),TC(6),
     1CE(6),CBAR(6),X(6),H(6),CLA(6),CLH(6),A0(6),ZP1(6),HB(6),
     2A(6),SC(6),YZ(6),OUTM(40,10),DSP(15),
     3VEL(15),ACC(15),SPEC(10),SPP(2),Y4(6),HSW(10),TSW(10)
      PI=3.1415927
      TPI=2.*PI
  999 READ 13,U,EL,HCG,XCG,RRG,YRG,DISP,RHO
      IF(EOF(5LINPUT).NE.0.0)STOP 1111
      WRITE 101
      WRITE 13,U,EL,HCG,XCG,RRG,YRG,DISP,RHO
      READ 40,NFR,FR1,DFR
      WRITE 43,NFR,FR1,DFR
      READ 50,NSEA,NPOS
      WRITE 51,NSEA,NPOS
      IF(NSEA.LE.0)GO TO 67
      WRITE 53
      DO 52 I=1,NSEA
      READ 13,HSW(I),TSW(I)
   52 WRITE 13,HSW(I),TSW(I)
      IF(NPOS.LE.0) GO TO 67
      WRITE 1009
      DO 82 I=1,NPOS
      READ 13,XPOS(I),ZPOS(I)
   82 WRITE 1001,I,XPOS(I),ZPOS(I)
   67 CONTINUE
      CALL HULLI
      NFOIL = 3
      READ 18,NSTRUT
      WRITE 1014,NFOIL,NSTRUT
      NFS=NFOIL+NSTRUT
      WRITE 1002
      DO 83 I=1,NFS
      READ 13,GAM(I),SWEEP(I),ALF(I),B(I),CR(I),CE(I),TC(I)
   83 WRITE 13,GAM(I),SWEEP(I),ALF(I),B(I),CR(I),CE(I),TC(I)
      READ 13,X(4),Y(4),H(4),X(5),H(5)
      WRITE 1003,X(4),Y(4),H(4),X(5),H(5)
      IF(NSTRUT.LE.2)GO TO 24
      X(NFS)=X(4)
      Y(NFS) = 0.0
      H(NFS)=-.5*B(NFS)
   24 CONTINUE
      READ 13, BF,PF,EFF,WF,ZETF
```

```
      WRITE 1004,BF,PF,EFF,WF,ZETF
      READ 13,WR,ZETR
      WRITE 1005,WR,ZETR
      READ 13,QFDD,QFD,QF
      WRITE 1006,QFDD,QFD,QF
      READ 13,QRDD,QRD,QR
      WRITE 1007,QRDD,QRD,QR
      YF = B(1)-BF
      CF=CR(1)-(CR(1)-CE(1))*(YF+.5*BF)/B(1)
C     PUT DIHEDRAL ANGLES IN CONVENTIONAL FORM
      G1 = (GAM(1)-90.)/57.3
      GAM(1)=180.-GAM(1)-GAM(4)
      GAM(2)=GAM(2)-GAM(4)
      GAM(3)=90.-GAM(3)
      GAM(4)=-GAM(4)
      GAM(5)=-90.
      GAM(6)=-90.
C     CHANGE ANGLES FROM DEGREES TO RADIANS
      DO 1 I=1,NFS
      SWEEP(I)=SWEEP(I)/57.3
      P=GAM(I)/57.3
      SING(I)=SIN(P)
    1 COSS(I)=COS(P)
      DO 2 I=1,NFS
      ALF(I)=ALF(I)/57.3
      CBAR(I)=.5*(CR(I)+CE(I))
    2 CONTINUE
      DO 3 I=1,NFS
    3 S(I)=B(I)*CBAR(I)
      HINT=H(4)+B(4)*ABS(SING(4))
      H(6)=H(5)+HINT+B(2)*SING(2)
      ZF=-HCG-HINT+(YF+.42*BF)*SING(1)
      YF=Y(4)+(YF+.42*BF)*COSS(1)
      Q=(B(1)*COSS(1)+B(2)*COSS(2))**2/(S(1)*COSS(1)+S(2)*COSS(2))
      T=B(2)*COSS(2)-Y(4)
      IF(ABS(T).LE.0.01)GO TO 4
      ISPLIT=1
      H(2)=HINT+.42*B(2)*SING(2)
      Y(2)=Y(4)-.42*B(2)*COSS(2)
      A(2)=Q
      GO TO 5
    4 ISPLIT=0
      B(2)=Y(4)/COSS(2)
      H(2)=HINT+.5*B(2)*SING(2)
      Y(2)=Y(4)-.5*B(2)*COSS(2)
      A(2)=2.*Q
    5 CONTINUE
      H(1)=HINT-.42*B(1)*SING(1)
      H(3)=B(5)-.42*B(3)*SING(3)+H(5)
      H(4)=HINT-.5*B(4)*ABS(SING(4))
      H(5)=.50*B(5)+H(5)
      X(1)=X(2)=X(4)
      X(3)=X(5)
      DO 6 I=1,NFS
      SX(I)=X(I)+.25*CBAR(I)
    6 Z(I)=-HCG-H(I)
      Y(1)=Y(4)+.42 *B(1)*COSS(1)
```

```
      Y(3)=.42*H(3)*COSS(3)
      Y(4)=Y(4)-.50*B(4)*COSS(4)
      Y(5)=0.0
      A(1) = A(2)
      DO 7 I=3,NFS
    7 A(I)=2.*B(I)/CBAR(I)
      EM=2240.*DISP/(32.2*RHO)
      U=1.689*U
      XI=(RRG*EL)**2*EM
      ZI=(YRG*EL)**2*EM
      AI=(0.0,1.0)
C     LIFT CURVE SLOPE CALCULATIONS
C
C     INCLUDE FREE SURFACE EFFECTS FOR FOILS 1 AND 3
      DO 22 I = 1,NFS
      CLA(I) = CLH(I) = 0.0
22    A0(I) = TPI*(1.-.96*TC(I))*COS(SWEEP(I))
      IF (U .LE. 0.0) GO TO 28
      DO 23 I = 1,3,2
      HCSQ = 20.0*(H(I)/CBAR(I))**2
      A0(I) = A0(I)*(1.+HCSQ)/(2.+HCSQ)
      HS = H(I)/B(I)
      ZP1(I)=1.0+BIPL(HS)
23    CONTINUE
      ZP1(2) = ZP1(5) = 1.0
C     STRUT END PLATE EFFECTS
      HB(4) = 1.9*B(1)*COS(G1)/B(4)
      HB(5) = 1.9*B(3)*COSS(3)/B(5)
      IF (NSTRUT .LE. 2) GO TO 25
      HB(6) = 1.9*(B(1)*COSS(1)+B(2)*COSS(2))/B(6)
      ZP1(6) = 1.0
25    CONTINUE
      DO 26 I = 4,NFS
26    A(I) = A(I)*(1.0+HB(I))
      HS = Y(4)/B(4)*2**(3-NSTRUT)
      ZP1(4) = 1.0+BIPL(HS)
      DO 27 I = 1,NFS
      CLA(I) = CLALF(A0(I),A(I),ZP1(I))
27    CONTINUE
      DO 9 I = 1,3,2
      HCSQ = 20.0*(1.05*H(I)/CBAR(I))**2
      A0(I) = TPI*(1.-.96*TC(I))*COS(SWEEP(I))*(1.+HCSQ)/(2.+HCSQ)
      HS = 1.05*H(I)/B(I)
      ZP1(I)=1.0+BIPL(HS)
      CLH(I) = ALF(I)*(CLALF(A0(I),A(I),ZP1(I))-CLA(I))/(.05*H(I))
9     CONTINUE
28    CONTINUE
      DO 91 I=1,NFS
      CLH(I)=S(I)*CLH(I)
      SC(I)=S(I)*CLA(I)
      YZ(I)=Y(I)*COSS(I)+Z(I)*SING(I)
   91 CONTINUE
      DO 92 I=4,NFS
      YR=Y(I)-.5*B(I)*COSS(I)
      ZR=Z(I)+.5*B(I)*ABS(SING(I))
      YRR=YR*COSS(I)+ZR*SING(I)
      Y4(I)=((YRR+B(I))**3-YRR**3)/(3.0*B(I))
```

```
92    CONTINUE
      DO 93 I=1,3
   93 Y4(I)=YZ(I)**2
      B(5)=.5*B(5)
      SC(5)=.5*SC(5)
      IF(NSTRUT.LE.2)GO TO 130
      B(NFS)=.5*B(NFS)
      SC(NFS)=.5*SC(NFS)
  130 CONTINUE
C     COMPUTE FREQUENCY INDEPENDENT TERMS
      A22=A24=A26=A44=A46=A66=0.0
      DO 10 I=1,NFS
      Q=TPI*B(I)*(CBAR(I)/2.)**2
      QQ=Q*SING(I)**2
      A22=A22+QQ
      A24=A24-Q*SING(I)*YZ(I)
      A26=A26+QQ*SX(I)
      A44=A44+Q*Y4(I)
      A46=A46-Q*SX(I)*SING(I)*YZ(I)
      A66=A66+QQ*SX(I)**2+TPI*B(I)*CBAR(I)**4/128.*SING(I)**2
   10 CONTINUE
      A64=A46
      A62=A26
      A22F=A22
      A24F=A24
      A26F=A26
      A44F=A44
      A46F=A46
      A66F=A66
      YZF=YF*COSS(1)+ZF*SING(1)
      CALL FLAP(PF,T1,T4,T7,T8,T10,T11)
      A2F=-2.*BF*T1*(CF/2.)**3
      A4F=-A2F*YZF
      A2F=A2F*SING(1)
      A6F=A2F*SX(1)+2.*BF*(CF/2.)**4*(T7+PF*T1)*SING(1)
      A2R=-TPI*B(5)*CBAR(5)**3/16.
      A4R=-A2R*Z(5)
      A6R=A2R*SX(5)+TPI*B(5)*CBAR(5)**4/128.
      WRITE 1042
      WRITE 1043
      DO 99 IFR=1,NFR
      W=FR1+(IFR-1)*DFR
      QW=W*W/32.2
      B22=B24=C24=B26=C26=F2=(0.0,0.0)
      B44=C44=B46=C46=F4=(0.0,0.0)
      B62=B64=C64=B66=C66=F6=(0.0,0.0)
      BB=B(4)
      DO 20 I=4,5
      IF(I.EQ.4)GO TO 19
      BB=2.*B(5)
   19 CONTINUE
      Q=PI*B(I)*CBAR(I)*SDAMP(W,BB)
      B22=B22+Q
      B44=B44+Q*Y4(I)
      B66=B66+Q*SX(I)**2
   20 CONTINUE
      IF(NSTRUT.LE.2)GO TO 133
```

```
      I=NFS
      BB=2.*B(NFS)
      Q=PI*B(I)*CBAR(I)*SDAMP(W,BB)
      B22=B22+Q
      B44=B44+Q*Y4(I)
      B66=B66+Q*SX(I)**2
133   CONTINUE
      IF(U.GT.0.0)GO TO 16
      CALL ZERO(W,B22,B44,B66)
      B2F=B4F=B6F=C2F=C4F=C6F=(0.0,0.0)
      B2R=B4R=B6R=C2R=C4R=C6R=(0.0,0.0)
      GO TO 17
 16   CONTINUE
      DO 11 I=1,NFS
      Q=.5*CBAR(I)*W/U
      CALL THEOJON(A(I),Q,CK,SE)
      P=SING(I)**2
      R=SING(I)*YZ(I)
      T=SX(I)-CBAR(I)/4.
      QI=U*SC(I)*CK
      QQ=P*QI
      B22=B22+QQ
      B62=B62+QQ*X(I)
      B24=B24-QI*R
      B44=B44+QI*Y4(I)
      B64=B64-QI*R*X(I)
      BA=-U*TPI*B(I)*(CBAR(I)/2.)**2
      QQ=QI*T
      B26=B26+P*(BA+QQ)
      B46=B46-R*(BA+QQ)
      B66=B66+P*(T*BA+X(I)*QQ)
      QI=-U**2*CLH(I)*CK*Y(I)
      C24=C24+QI*SING(I)
      C44=C44-QI*YZ(I)
      C64=C64+QI*SING(I)*X(I)
      QI=-U**2*SC(I)*CK*SING(I)
      C26=C26+QI*SING(I)
      C46=C46-QI*YZ(I)
      C66=C66+QI*SING(I)*X(I)
      IF (I .LE. 3) GO TO 94
      IF (I .GT. 4) GO TO 95
      YR = Y(I)-.5*B(I)*COSS(I)
      ZR = Z(I)+.5*B(I)*ABS(SING(I))
      YRR = YR*COSS(I)+ZR*SING(I)
      BB = B(I)
      H0 = H(I)-.5*B(I)*ABS(SING(I))
      HT = H(I)+.5*B(I)*ABS(SING(I))
      GO TO 96
95    CONTINUE
      BB = 2.*B(I)
      YRR = -Z(I) - B(I)
      H0 = H(I) - B(I)
      HT = H0 + BB
96    CONTINUE
      QWW = QW*ABS(SING(I))
      YTT = YRR + BB
      TR = QWW*YRR
```

```
      TT = QWW*YTT
      T = EXP(TR-QW*H0)/(6H*QWW**2)
      P = -T*(EXP(-TR)*(TR+1.)-EXP(-TT)*(TT+1.))
      R = -SING(I)
      T = -Y(I)
      TT = EXP(-QW*H0)-EXP(-QW*HT)
      TT = TT/(QW*(HT-H0))
      DO 97 J=1,2
      P = -P
      R = -R
      T = -T
      QI = -.5*U*CEXP(AI*QW*T)*SC(I)*SE*W*(R+AI*COSS(I))
      F2 = F2 + QI*R*TT
      F4 = F4 - QI*P
      F6 = F6 + QI*R*X(I)*TT
97    CONTINUE
      GO TO 98
94    CONTINUE
      P=-YZ(I)
      R=-SING(I)
      T=-Y(I)
      DO 12 J=1,2
      P=-P
      R=-R
      T=-T
      QI=-.5*U*CEXP(AI*QW*T)*(U*CLH(I)*CK+SC(I)*SE*W*EXP(-QW*H(I))*(R
     1+AI*COSS(I)))
      F2=F2+QI*R
      F4=F4-QI*P
      F6=F6+QI*R*X(I)
 12   CONTINUE
 98   CONTINUE
      IF(I.NE.1)GO TO 11
      P=YF*COSS(1)+ZF*SING(1)
      QI=T4-CLA(1)*CK*T11/TPI
      QI=-.5*U*BF*CF**2*QI
      B2F=QI*SING(1)
      B4F=-QI*P
      QI=T4*SX(1)-CLA(1)*CK*T11*X(1)/TPI
      QI=QI+.5*CF*(T1-T8-PF*T4+.5*T11)
      B6F=-.5*U*BF*CF**2*QI*SING(1)
      QI=U**2*BF*CF*CLA(1)*CK*EFF
      C2F=QI*SING(1)
      C4F=-QI*P
      C6F=C2F*X(1)-.5*U**2*BF*CF**2*(T4+T10)*SING(1)
 11   CONTINUE
      QI=CLA(5)*CK
      P=-.25*U*S(5)*CBAR(5)
      B2R=P*(PI+QI)
      B4R=-B2R*Z(5)
      B6R=P*(PI*(SX(5)-.25*CBAR(5))+QI*X(5))
      C2R=-.5*U**2*S(5)*QI
      C4R=-C2R*Z(5)
      C6R=C2R*X(5)
 17   CONTINUE
      WRITE 1040,W,A44F,B44,C44,F4
      C44=C44+C44R
```

```
      CALL HULLW
C     CALCULATION OF A'S,B'S,C'S AND F'S NOW COMPLETE
C     COMPUTE HYDRODYNAMIC MATRIX
      AIW=AI*W
      W2=W*W
      QQ=-W2*(A22+EM)+AIW*B22
      CALL MATG(1,1)
      QQ=-W2*A24+AIW*B24+C24
      CALL MATG(1,3)
      QQ=-W2*A26+AIW*B26+C26
      CALL MATG(1,5)
      QQ=-W2*A2F+AIW*B2F+C2F
      CALL MATG(1,7)
      QQ=-W2*A2R+AIW*B2R+C2R
      CALL MATG(1,9)
      QQ=-W2*A24+AIW*B24
      CALL MATG(3,1)
      QQ=-W2*(A44+XI)+AIW*B44+C44
      CALL MATG(3,3)
      QQ=-W2*A46+AIW*B46+C46
      CALL MATG(3,5)
      QQ=-W2*A4F+AIW*B4F+C4F
      CALL MATG(3,7)
      QQ=-W2*A4R+AIW*B4R+C4R
      CALL MATG(3,9)
      QQ=-W2*A62+AIW*B62
      CALL MATG(5,1)
      QQ=-W2*A64+AIW*B64+C64
      CALL MATG(5,3)
      QQ=-W2*(A66+ZI)+AIW*B66+C66
      CALL MATG(5,5)
      QQ=-W2*A6F+AIW*B6F+C6F
      CALL MATG(5,7)
      QQ=-W2*A6R+AIW*B6R+C6R
      CALL MATG(5,9)
      QQ=(-W2*QFDD+AIW*QFD+QF)*(-WF**2)
      CALL MATG(7,3)
      QQ=-W2+AIW*2.*ZETF*WF+WF**2
      CALL MATG(7,7)
      QQ=(-W2*QRDD+AIW*QRD+QR)*(-WR**2)
      CALL MATG(9,5)
      QQ=-W2+AIW*2.*ZETR*WR+WR**2
      CALL MATG(9,9)
      QQ=(0.0,0.0)
      CALL MATG(7,1)
      CALL MATG(7,5)
      CALL MATG(7,9)
      CALL MATG(9,1)
      CALL MATG(9,3)
      CALL MATG(9,7)
C     COMPUTE EXCITING FORCE VECTOR
      EF(1)=REAL(F2)+EF(1)
      EF(2)=AIMAG(F2)+EF(2)
      EF(3)=REAL(F4)+EF(3)
      EF(4)=AIMAG(F4)+EF(4)
      EF(5)=REAL(F6)+EF(5)
      EF(6)=AIMAG(F6)+EF(6)
```

```
      DO 14 I=7,10
   14 EF(I)=0.0
C     SOLVE FOR MOTIONS
      DO 15 I=1,10
   15 G(I,11)=EF(I)
      WRITE 1041,A44,B44,C44,EF(3),EF(4)
      CALL SOLV(G,EF,10,11,INDX,ICK)
      DO 225 J=1,10
  225 OUTM(IFR,J)=EF(J)
   99 CONTINUE
C     OUTPUT FREQUENCY RESPONSE
      WRITE(6,212)
      WRITE(6,231)
      WRITE(6,214)
      WRITE(6,215)
      DO 227 LW=1,NFR
      W=FR1+(LW-1)*DFR
      WL=TPI*32.2/W**2
      WSLP=TPI/WL
      WL=WL/EL
      SAMP=SQRT(OUTM(LW,1)**2+OUTM(LW,2)**2)
      SPH=57.3*ATAN2(OUTM(LW,2),OUTM(LW,1))
      RAMP=SQRT(OUTM(LW,3)**2+OUTM(LW,4)**2)*57.3
      RPH=57.3*ATAN2(OUTM(LW,4),OUTM(LW,3))
      YAMP=SQRT(OUTM(LW,5)**2+OUTM(LW,6)**2)*57.3
      YPH=57.3*ATAN2(OUTM(LW,6),OUTM(LW,5))
      WRITE(6,216)W,SAMP,SPH,RAMP,RPH,YAMP,YPH,WL
  227 CONTINUE
      IF(NSEA.LE.0)GO TO 1000
      DO 54 JS=1,NSEA
      HSEA=HSW(JS)
      TSEA=TSW(JS)
      IF(HSEA.GT.0.0) GO TO 30
      ISEA=0
      GO TO 35
   30 IF(HSEA.GT.1.0) GO TO 31
      ISEA=1
      GO TO 35
   31 IF(HSEA.GT.3.0) GO TO 32
      ISEA=2
      GO TO 35
   32 IF(HSEA.GT.5.0) GO TO 33
      ISEA=3
      GO TO 35
   33 IF(HSEA.GT.8.0) GO TO 34
      ISEA=4
      GO TO 35
   34 IF(HSEA.GT.12.0) GO TO 46
      ISEA=5
      GO TO 35
   46 IF(HSEA.GT.20.0) GO TO 47
      ISEA=6
      GO TO 35
   47 IF(HSEA.GT.40.0) GO TO 48
      ISEA=7
      GO TO 35
   48 ISEA=8
```

```
 35   CONTINUE
      NTOT=NPOS+3
      DO 70 I=1,NTOT
 70   DSP(I)=VEL(I)=ACC(I)=0
      BETD=BETV=BETA=0.0
      DO 71 LW=1,NFR
      W=FR1+(LW-1)*DFR
      W2=W*W
      W4=W2*W2
      FW=SEAST(HSEA,TSEA,W)
      Q=FW*(OUTM(LW,7)**2+OUTM(LW,8)**2)
      BETD=BETD+Q
      BETV=BETV+Q*W2
      BETA=BETA+Q*W4
      DO 72 I=1,3
      J=2*I
 72   SPEC(I)=FW*(OUTM(LW,J-1)**2+OUTM(LW,J)**2)
      DO 73 I=1,3
      DSP(I)=DSP(I)+SPEC(I)
      VEL(I)=VEL(I)+SPEC(I)*W2
 73   ACC(I)=ACC(I)+SPEC(I)*W4
      IF(NPOS.LE.0) GO TO 71
      DO 76 I=1,NPOS
      DO 77 J=1,2
 77   SPP(J)=OUTM(LW,J)-ZPOS(I)*OUTM(LW,J+2)-(XPOS(I)*EL/20.-XCG)*OUTM(L
     *W,J+4)
 76   SPEC(I)=FW*(SPP(1)**2+SPP(2)**2)
      DO 78 J=4,NTOT
      DSP(J)=DSP(J)+SPEC(J-3)
      VEL(J)=VEL(J)+SPEC(J-3)*W2
 78   ACC(J)=ACC(J)+SPEC(J-3)*W4
 71   CONTINUE
      DO 74 I=2,3
      DSP(I)=SQRT(DFR*DSP(I))*57.3
      VEL(I)=SQRT(DFR*VEL(I))*57.3
 74   ACC(I)=SQRT(DFR*ACC(I))*57.3
      WRITE(6,217)ISEA,HSEA,TSEA
      WRITE(6,218)
      WRITE(6,219)
      WRITE(6,220)
      WRITE(6,221)DSP(2),VEL(2),ACC(2)
      WRITE(6,222)DSP(3),VEL(3),ACC(3)
      BETD=SQRT(DFR*BETD)*57.3
      BETV=SQRT(DFR*BETV)*57.3
      BETA=SQRT(DFR*BETA)*57.3
      WRITE(6,226)BETD,BETV,BETA
      DSP(3)=DSP(1)
      VEL(3)=VEL(1)
      ACC(3)=ACC(1)
      DO 75 I=3,NTOT
      DSP(I)=SQRT(DFR*DSP(I))
      VEL(I)=SQRT(DFR*VEL(I))
 75   ACC(I)=SQRT(DFR*ACC(I))
      WRITE(6,223)
      WRITE(6,219)
      WRITE(6,224)
      WRITE(6,228)DSP(3),VEL(3),ACC(3)
```

```
      IF(NPOS.LE.0)GO TO 54
      WRITE(6,240)(XPOS(I-3),ZPOS(I-3),DSP(I),VEL(I),ACC(I),I=4,NTOT)
   54 CONTINUE
1000  IF(EOF(5LINPUT))909,999
909   STOP
  18  FORMAT(I1)
212   FORMAT(1H1//25X*FREQUENCY RESPONSE*)
214   FORMAT(//15X4HSWAY,19X4HROLL,20X3HYAW,15X6HW.L./L)
215   FORMAT(3X,1HW,7X,3HAMP,5X,5HPHASE,10X,3HAMP,5X,5HPHASE,10X,3HAMP,5
     1X,5HPHASE)
216   FORMAT(F7.3,2F9.3,5X,2F9.3,5X,2F9.3,F15.3)
217   FORMAT(1H1//10X*ROOT MEAN SQUARES IN SEA STATE*I2,5X*HSEA =*F6.2,5
     1X*TSEA =*F5.2)
218   FORMAT(///15X*ROLL AND YAW*)
219   FORMAT(15X*DISPLACEMENT*11X*VELOCITY*11X*ACCELERATION*)
220   FORMAT(20X*DEG*15X*DEG/SEC*12X10HDEG/SEC**2)
221   FORMAT(/6X*ROLL*F15.3,2F20.3)
222   FORMAT(/6X*YAW*F16.3,2F20.3)
223   FORMAT(///15X*SWAY AT POSITION INDICATED*)
224   FORMAT(20X*FT*16X*FT/SEC*13X9HFT/SEC**2)
 226  FORMAT(/6X*FLAP*F15.3,2F20.3)
228   FORMAT(/5X*CG*3XF15.3,2F20.3)
  231 FORMAT(//5X*SWAY AMP IS NON-DIMENSIONAL, ROLL AND YAW AMPS IN DEG/
     FFT*)
240   FORMAT(/2X,*X=*F5.1*,Z=*F4.1,F9.3,2F20.3)
13    FORMAT(8F10.4)
40    FORMAT(I2,2F10.3)
43     FORMAT(/3X*NFR=*I3,5X*FR1=*F5.3,5X*DFR=*F5.3)
81    FORMAT(2F10.4,I2)
 101  FORMAT(1H1,5X*U*9X*EL*8X*HCG*7X*XCG*6X*RRG*7X*YRG*7X*DISP*7X*RHO*)
1001  FORMAT(/3X,*(*I2*)*2F10.4)
1002  FORMAT  (/5X*GAM*7X*SWEEP*5X*ALF*7X*B*9X*CR*8X*CE*8X*TC*)
1003  FORMAT  (/1X*X(4) = *F8.4,5X*Y(4) = *F7.4,5X*H(4) = *F7.4,5X*X(5) =
     $ *F8.4,5X*H(5) = *F7.4)
1004  FORMAT  (/1X*BF = *F8.4,5X*PF = *F6.4,5X*EF = *F6.4,5X*WF = *F8.4,
     $5X*ZETF = *F7.4)
1005  FORMAT  (/1X*WR = *F8.4,5X*ZETR = *F7.4)
1006  FORMAT  (/1X*QFDD = *F8.4,5X*QFD = *F8.4,5X*QF = *F8.4)
1007  FORMAT  (/1X*QRDD = *F8.4,5X*QRD = *F8.4,5X*QR = *F8.4)
1008  FORMAT(/3X*HSEA=*F12.2,3X*TSEA=*F12.2,3X,*NPOS=*,I3)
1009  FORMAT(/13X,*XPOS*10X*ZPOS*)
1010  FORMAT(/3X*GAM(I)*2X*SWEEP(I)*,4X,*ALF(I)*6X,*H(I)*5X* CR(I)*
     15X,*CT(I))*)
1014  FORMAT(/1X,*NFOIL= *I1,4X*NSTRUT= *,I1)
1040  FORMAT(F10.3,7E12.4)
 1041 FORMAT(10X,7E12.4)
1042  FORMAT(1H1//,5X*ROLL COEFFICIENTS*)
1043  FORMAT(//6X*W*10X*A44*8X*B44R*8X*B44I*8X*C44R*8X*C44I*9X*F4R*9X
     1*F4I*/)
   50 FORMAT(2I3)
   51 FORMAT(/5X*NSEA=*I2,5X*NPOS=*I2)
   53 FORMAT(/4X*HSW*7X*TSW*)
      END
```

```
      SUBROUTINE SOLV(A,X,N,M,INDX,ICK)
C
C     SOLUTIONS OF N LINEAR EQUATIONS IN N UNKNOWNS.
C
C     M=N+1
C
C     MATRIX EQUATION SOLVED IS
C
C               B*Y=C
C
C     WHERE     B(I,J=A(I,J)                               I,J=1,N
C                 Y(I)=X(I)                                  I=1,N
C                 C(I)=A(I,M)                                I=1,N
C
C     IF NO SOLUTION FOUND IOK IS SET EQUAL TO 1 FOR RETURN.
C
      DIMENSION A(N,M),X(N),INDX(N)
      ICK=0
      DO10 I=1,N
      INDX(I)=0
   10 X(I)=0.0
      DO 20 J=1,N
      ZZ=1.0E-10
      IROW=0
      DO 30 I=1,N
      IF(INDX(I).NE.0) GO TO 30
      TEST=ABS(A(I,J))
      IF(TEST.LE.ZZ) GO TO 30
      ZZ=TEST
      IROW=I
   30 CONTINUE
      IF(IROW.EQ.0)GO TO 20
   40 INDX(IROW)=J
      ZN=A(IROW,J)
      II=N+1
      DO 50 K=1,II
   50 A(IROW,K)=A(IROW,K)/ZN
      DO 60 I=1,N
      IF(I.EQ.IROW)GO TO 60
      I1=J+1
      II=N+1
      DO 61 K=I1,II
      A(I,K)=A(I,K)-A(I,J)*A(IROW,K)
   61 CONTINUE
   60 CONTINUE
   20 CONTINUE
      DO 80 I=1,N
      IF(INDX(I).GT.0) GO TO 80
      TEST=ABS(A(I,N+1))
      IF(TEST.GT.1.0E-8)GO TO 99
   80 CONTINUE
      DO 70 I=1,N
      IF(INDX(I).EQ.0) GO TO 70
      X(INDX(I))=A(I,N+1)
   70 CONTINUE
      RETURN
   99 WRITE(2,100)
```

```
100   FORMAT(20X11HNO SOLUTION)
      ICK=1
      RETURN
      END
```

```
      SUBROUTINE MATG(I,J)
      COMMON/COM1/QQ,G(10,11)
      COMPLEX QQ
      G(I,J)=REAL(QQ)
      G(I,J+1)=-AIMAG(QQ)
      G(I+1,J+1)=G(I,J)
      G(I+1,J)=-G(I,J+1)
      RETURN
      END
```

```
      FUNCTION SEAST(HH,TT,WW)
C     HH IS SIG. WAVE HT. IN FT, TT IS PERIOD IN SEC, WW IS FREQUENCY IN
C     RAD/SEC. OUTPUT SPECTRUM HAS UNITS FT**2/(RAD/SEC).
      COMMON/SSGM/A00(80),A10(80),A01(80),A20(80),A11(80),A02(80)
      DIMENSION F(2)
      H=HH*.3048-4.016
      T=TT-9.159
      W=WW*TT/6.283185
      IF (W.GT.0.05) GO TO 2
      SEAST=0.
      RETURN
2     IF (W.LE.4.0) GO TO 3
      SEAST=0.
      RETURN
3     CONTINUE
      N=INT(W/.05)
      DO 1 I=1,2
      M=N+I-1
1     F(I)=A00(M)+A10(M)*H+A01(M)*T+A20(M)*H*H+A11(M)*H*T+A02(M)*T*T
      S=F(1)+(F(2)-F(1))*(W-N*.05)*20.
      SEAST=S*HH**2*TT/101.1593
      RETURN
      END
```

```
 BLOCK DATA SEASTGM
 COMMON/SSGM/A00(80),A10(80),A01(80),A20(80),A11(80),A02(80)
 DATA A00/0.,0.,.00001,.00018,.00133,.00324,.00709,.01325,.02618,
1.05336,.11641,.2503,.4943,.83054,1.23195,1.59871,1.79955,1.76253,
21.56762,1.30231,1.07908,.91784,.77733,.66816,.57326,.49269,.43533,
3.38482,.33183,.28287,.25230,.23205,.21658,.2037,.19481,.18371,
4.17350,.16129,.14752,.14327,.13558,.12091,.10697,.09764,.09052,
5.08372,.07646,.06884,.05932,.05156,.04350,.03660,.03037,.02363,
6.01831,.01466,.01117,.00829,.00561,.00395,.00283,.00225,.00143,
7.00057,.00006,-.00041,-.00032,-.00012,-.00005,-.00032,-.00059,
8-.00077,-.00097,-.00080,-.00047,-.00032,-.00022,-.00014,-.00008,
9-.00003/
 DATA A10/0.0,0.0,-.00001,-.00004,-.00043,-.00134, .00255, .00387,
1-.00543,-.00475,-.00017,.00901,.02629,.04993,.06652,.06000,.03906,
2.00467,-.03727,-.06926,-.07963,-.06424,-.05265,-.04332,-.03261,
3-.01857,-.01263,-.00911,-.00801,-.00336,.00342,.00539,.00458,.004,
4.00652,.00907,.00923,.01084,.01613,.01451,.01063,.00839,.00592,
5.00532,.00714,.00877,.01007,.01077,.01001,.00923,.00750,.00467,
6.00175,.00034,.00066,.00106,.00095,.00090,.00102,.00091,.00068,
7.00036,.00050,.00077,.00093,.00073,.00027,.00018,.00015,.00003,
8-.00009,-.00013,-.00013,-.00009,-.00006,-.00003,-.00001,-.00001,
90.0,0.0/
 DATA A01/0.0,0.0,.00001,.00003,0.0,-.00067,-.0024,-.00558,-.00822,
1-.01065,-.01169,-.01241,-.00664,.01278,.03974,.06999,.08177,.0558,
2.01841,.0027,-.00276,-.01522,-.03524,-.03485,-.03189,-.03983,
3-.03554,-.03005,-.02822,-.02864,-.02787,-.02231,-.01716,-.01219,
4-.01098,-.01213,-.01061,-.01317,-.02021,-.00812,.00344,.00783,
5.01083,.01190,.01113,.01021,.00988,.00930,.01115,.01152,.01164,
6.01193,.01243,.01189,.01054,.00913,.00785,.00674,.00554,.00475,
7.00422,.00403,.00345,.00256,.00184,.00129,.00124,.00120,.00109,
8.00093,.00073,.00051,.00027,.00021,.00023,.00021,.00017,.00013,
9.00007,.00004/
 DATA A20/0.,0.,0.,0.,0.,.00005,.00009,.00016,.00035,.00033,.00022,
1.00079,.00172,.00417,.00481,.00119,-.0066,-.00935,-.00604,-.00044,
2.00188,.00049,.00021,-.00021,-.0003,-.00107,-.00137,-.00081,
3.00131,.00251,.00183,.00020,-.00063,-.00076,-.00087,-.0006,-.0005,
4.00013,.00108,.0005,-.00001,.00023,.00042,.00046,.00045,.00052,
5.0003,.00017,-.00002,-.00015,-.00011,.00002,.00011,.00008,-.00012,
6-.00028,-.00012,.00011,.00036,.0004,.00035,.00013,.00027,.00054,
7.00058,.00040,-.00003,-.00014,-.0001,.00001,.00014,.0002,.00022,
8.00015,.00004,-.00001,-.00003,-.00003,-.00002,-.00001/
 DATA A11/0.,0.,0.,.00002,.0002,.00041,.00077,.00112,.00146,.00103,
1-.00103,-.00667,-.01387,-.02494,-.02849,-.01366,.01256,.02414,
2.02513,.01785,.01365,.01369,.01287,.0119,.00914,.00604,.00441,
3.00222,-.00303,-.00754,-.00807,-.00403,-.00067,.00046,.00026,
4-.00086,-.00096,-.0031,-.00798,-.00544,-.00238,-.00232,-.00222,
5-.00222,-.00281,-.00349,-.00324,-.00292,-.00199,-.00146,-.00011,
6-.00094,-.00047,-.00007, .00031,.00056,.00019,-.00028,-.00073,
7-.00075,-.00059,-.00010,-.00016,-.00055,-.00054,-.0003,.0003,
8.00048,.00036,.00016,-.00002,-.0001,-.00011,-.00005,.00006,.00013,
9.00015,.00014,.00009,.00005/
 DATA A02/0.,0.,0.,-.00004,-.00021,-.00016,.00027,.0014,.00193,
1.00188,.00082,.00042,-.00032,.00428,.00436,-.00858,-.02142,-.0177,
2-.01166,-.00411,.00016,.00259,.00845,.00818,.00924,.01304,.01044,
3.00776,.00819,.00995,.00943,.00585,.00222,-.00011,-.00139,-.00171,
4-.00314,-.00183,.00268,-.00207,-.00614,-.0063,-.00615,-.00599,
5-.00532,-.00432,-.0036,-.0029,-.003,-.00267,-.00211,-.00171,
```

```
6-.00145,-.00095,-.00043,-.00001,.00051,.00094,.00126,.00134,
7.00133,.00118,.00108,.00104,.0009,.00078,.00062,.0005,.00044,
8.00043,.00035,.00029,.00025,.00022,.00018,.00014,.00008,.00004,
9.00002,.00001/
 END


      SUBROUTINE ZERO(W,B22,B44,B66)
      COMMON/NEW6/FIAV,YAWAV,SWAYAV
      COMMON/NEW5/GAM(6),S(6),SX(6),Y(6),Z(6),NFS,B(6),COSS(6),SING(6)
      COMPLEX B22,B44,B66
      DO 1 I=1,NFS
      T=.8488*W*S(I)
      P=GAM(I)/57.3
      IF(I.LE.3)GO TO 94
      IF(I.GT.4)GO TO 95
      YR=Y(I)-.5*B(I)*COSS(I)
      ZR=Z(I)+.5*B(I)*ABS(SING(I))
      YRR=YR*COSS(I)+ZR*SING(I)
      BB=B(I)
      GOTO 96
   95 CONTINUE
      BB=2.*B(I)
      YRR = -Z(I) - B(I)
   96 CONTINUE
      ARM3=((YRR+BB)**4-YR**4)/(4.*BB)
      B44=B44+1.17*T*ARM3*FIAV
      GO TO 3
   94 CONTINUE
      SI=TAN(P)
      S2=-Y(I)/Z(I)
      ALF=ABS((S2-SI)/(1.+SI*S2))
      ALF=ATAN(ALF)
      ARM=SQRT(Y(I)**2+Z(I)**2)
      B44=B44+T*ARM**3*CNS(ALF)*FIAV
    3 CONTINUE
      ALF=ABS(P)
      T=T*CNS(ALF)
      B22=B22+T*SWAYAV
      B66=B66+T*YAWAV*(ABS(SX(I)))**3
    1 CONTINUE
      RETURN
      END


      FUNCTION CNS(ALF)
      A=57.3*ALF
      IF(A.LT.40) GO TO 1
      CNS=1.17*SIN(ALF)
      RETURN
    1 CNS=.0467*A*SIN(ALF)
      RETURN
      END
```

```
      FUNCTION SDAMP(W,B)
      DIMENSION F(16)
      DATA F/0.0,.024,.048,.298,.574,.905,1.124,1.238,1.238,1.167,1.071
     *,.981,.893,.821,.747,.686/
      T=W*W*B/32.2
      IF(T.GT.0.0) GO TO 1
      SDAMP=0.0
      RETURN
    1 P=T/0.1+1.0
      N=INT(P)
      IF(N.LT.15)GO TO 2
      N=15
    2 C=F(N)+(P-N)*(F(N+1)-F(N))
      IF(C.GE.0.0)GO TO 3
      C=0.0
    3 CONTINUE
      SDAMP=C*W*B
      RETURN
      END


      FUNCTION CLALF(A0,A,ZP1)
      A0PI = A0/3.141593
      CLALF = A0*A/(A0PI*ZP1+SQRT(A**2+A0PI**2))
      RETURN
      END


      FUNCTION BIPL(H)
      BIPL = (1.0-.66*H)/(1.055+3.7*H)
      IF (BIPL .GE. 0.0) GO TO 1
      BIPL = 0.0
    1 RETURN
      END


      SUBROUTINE FLAP(P,T1,T4,T7,T8,T10,T11)
      P2=P*P
      X1=SQRT(1.-P2)
      X2=ASIN(X1)
      T1=-X1*(2.+P2)/3.+P*X2
      T4=-X2+P*X1
      T7=-X2*(.125+P2)+.125*P*X1*(7.+2.*P2)
      T8=-X1*(1.+2.*P2)/3.+P*X2
      T10=X1+X2
      T11=X2*(1.-2.*P)+(2.-P)*X1
      RETURN
      END
```

```
      SUBROUTINE THEUJUN(A,Q,CK,SE)
      COMPLEX AI,C,C6,C3,G,G6,G3,QI,CK,SE
      AI = (0.0,1.0)
      QI=AI*Q
      C=1.0-QI*(.165/(.045+QI)+.335/(.3+QI))
      C6=1.0-.361*QI/(.381+QI)
      C3=1.0-.283*QI/(.54+QI)
      G=1.0-QI*(.236/(.058+QI)+.513/(.364+QI)+.171/(2.42+QI))
      G6=1.0-QI*(.448/(.29+QI)+.272/(.725+QI)+.193/(3.0+QI))
      G3=1.0-QI*(.679/(.558+QI)+.227/(3.2+QI))
      AC=CABS(C)
      PC=ARGD(C)
      AC6=CABS(C6)
      PC6=ARGD(C6)
      AC3=CABS(C3)
      PC3=ARGD(C3)
      AG=CABS(G)
      PG=ARGD(G)
      AG6=CABS(G6)
      PG6=ARGD(G6)
      AG3=CABS(G3)
      PG3=ARGD(G3)
      IF (A .GT. 6.0) GO TO 1
      AF = F36(A,AC3,AC6)
      PF = F36(A,PC3,PC6)
      AG = F36(A,AG3,AG6)
      PG = F36(A,PG3,PG6)
      GO TO 2
    1 CONTINUE
      AF = FGT6(A,AC3,AC6,AC)
      PF = FGT6(A,PC3,PC6,PC)
      AG = FGT6(A,AG3,AG6,AG)
      PG = FGT6(A,PG3,PG6,PG)
    2 CONTINUE
      CK = AF*(COS(PF) + AI*SIN(PF))
      SE = AG*(COS(PG) + AI*SIN(PG))
      RETURN
      END
```

```
FUNCTION F36(A,Y3,Y6)
F36 = Y3 + (Y6-Y3)/3.0*(A-3.0)
RETURN
END
```

```
FUNCTION FGT6(A,Y3,Y6,YC)
S = (Y6-Y3)/3.0
AA = 12.0*(Y6-YC + 3.0*S)
B = -36.0*(6.0*S + Y6 - YC)
FGT6 = YC + AA/A + B/A**2
RETURN
END
```

```
FUNCTION ARGD(Z)
COMPLEX Z
X=REAL(Z)
Y=AIMAG(Z)
ARGD=ATAN2(Y,X)
RETURN
END
```

```
      SUBROUTINE HULLI
      COMMON/GR/NUT,NON,CAY,AMC,DFC,YA(25,8),ZA(25,8)
      COMMON PI,HPI,QPI,TPI,MD,MODE,DPH,CR,RAT,SUR,DEG,IST,DRT,HBM,SG,N
     1OE,PDM,VOL,DEW,UN,OMEGA,CP,WVH,ID,DOG,IG,XX(25,7),YY(25,7),DEL(25,
     27),SNE(25,7),CSE(25,7),FR(7),BLOG(25,7,7),YLOG(25,7,7),CON(14,1),C
     3T(14,14),PSI1(7,7),PSI2(7,7),PRA(7),PRV(7)
      COMMON/NEW/XA(25),DXA(25),XCG,EL,NST,HCG,C44H,DISP,RHO
      COMMON/NEW6/FIAV,YAWAV,SWAYAV
      HPI=.5*PI
      QPI=.5*HPI
   67 READ(5,13)GMIN
      WRITE(6,206)GMIN
      READ(5,13)FIAV,YAWAV,SWAYAV
      WRITE(6,207)FIAV,YAWAV,SWAYAV
      YAWAV=YAWAV/57.3
      FIAV = FIAV/57.3
      READ(5,201)NST
      DO 1 IST=1,NST
      READ  (5,44)XA(IST)
      READ(5,13)(YA(IST,J),J=1,8)
      READ(5,13)(ZA(IST,J),J=1,8)
      WRITE(6,205)XA(IST)
      WRITE(6,36)
      WRITE(6,13)(YA(IST,J),J=1,8)
      WRITE(6,37)
1     WRITE(6,13)(ZA(IST,J),J=1,8)
      DO 45 I=1,NST
45    XA(I)=XA(I)*EL/20.
      DXA(1)=.5*XA(2)
       NP=NST-1
       DO 65 I=2,NP
65    DXA(I)=.5*(XA(I+1)-XA(I-1))
      DXA(NST)=EL-.5*(XA(NST)+XA(NST-1))
      DO 66 I=1,NST
66     XA(I)=XCG-XA(I)
      NON=7
      NUT=8
      DO 424 I=1,NST
      DO 424 J=1,NUT
424   ZA(I,J)=ZA(I,J)-ZA(I,NUT)
      NOE=2*NON
      C44H=0.0
      DO 90 IST=1,NST
      C4=0.
      DO 89 I=1,NON
      XINT=YA(IST,I+1)-YA(IST,I)
      YINT=ZA(IST,I+1)-ZA(IST,I)
      DEL(IST,I)=SQRT(XINT*XINT+YINT*YINT)
      SNE(IST,I)=YINT/DEL(IST,I)
      CSE(IST,I)=XINT/DEL(IST,I)
      XX(IST,I)=.5*(YA(IST,I+1)+YA(IST,I))
      YY(IST,I)=.5*(ZA(IST,I+1)+ZA(IST,I))
89    C4=XX(IST,I)*(XINT*XX(IST,I)+YINT*(YY(IST,I)-HCG))+C4
   90 C44H=C44H+64.4*C4*DXA(IST)
      GMCALC=C44H*RHO/(2240.*DISP)
      WRITE(6,208)GMCALC
      IF(GMIN.LE.0.0)GO TO 230
```

```
      C44H=2240.*DISP*GMIN/RHO
 230  CONTINUE
      SG=-1.0
      MD=2
      CR=0
      DPH=0.
      DO 300 IST=1,NST
      DO 301 J=1,NUT
      YA(IST,J)=YA(IST,J)/EL
301   ZA(IST,J)=ZA(IST,J)/EL
      DO 302 J=1,NON
      DEL(IST,J)=DEL(IST,J)/EL
      XX(IST,J)=XX(IST,J)/EL
302   YY(IST,J)=YY(IST,J)/EL
      CALL FIND
300   CONTINUE
      RETURN
13    FORMAT(8F10.4)
36    FORMAT(1H0,5X,9HABSCISSAS)
37    FORMAT(1H0,5X,9HORDINATES)
44    FORMAT(F10.3)
 201  FORMAT(I2)
205   FORMAT(1H0,7HSTATION,F6.2)
  206 FORMAT(/5X*GMIN=*F8.4)
  207 FORMAT(/5X*FIAV=*F8.4,5X*YAWAV=*F8.4,5X*SWAYAV=*F8.4)
  208 FORMAT(/5X*GMCALC=*F8.4)
      END
```

```
      SUBROUTINE HULLW
      COMPLEX B22,B24,B26,B44,B46,B62,B64,B66
      COMMON/GR/NUT,NON,CAY,AMC,DFC,YA(25,8),ZA(25,8)
      COMMON PI,HPI,GPI,TPI,MD,MODE,DPH,CR,RAT,SUR,DEG,IST,DRT,HBM,SG,N
     1OE,PDM,VOL,DEW,UN,OMEGA,CP,WVH,ID,DOG,IG,XX(25,7),YY(25,7),DEL(25,
     27),SNE(25,7),CSE(25,7),FR(7),BLOG(25,7,7),YLOG(25,7,7),CON(14,1),C
     3T(14,14),PSI1(7,7),PSI2(7,7),PRA(7),PRV(7)
      COMMON/NEW/XA(25),DXA(25),XCG,EL,NST,HCG,C44H,DISP,RHO
      COMMON/NEW2/W,U,A22,B22,A24,B24,A26,B26,A44,B44,A46,B46,
     1A62,B62,A64,B64,A66,B66,EF(10)
      COMMON/NEW3/A22F,A24F,A26F,A44F,A46F,A66F
      DIMENSION ER(3,25),FI(3,25),HR(3,25),HI(3,25),AM(3,25),DF(3,25)
      Q=W*W/32.2
      WL=TPI*32.2/W**2
      DD=EL
      CAY=Q*DD
      UN=CAY
      OMEGA=SQRT(UN)
      DO 100 IST=1,NST
      DO 100 MODE=2,3
      GO TO (303,303,304)MODE
303   DO 305 J=1,NON
305   FR(J)=-SNE(IST,J)
      GO TO 80
304   DO 306 J=1,NON
306   FR(J)=(YY(IST,J)-HCG/DD)*SNE(IST,J)+XX(IST,J)*CSE(IST,J)
80    CALL FREQ
      ER(MODE,IST)=0.
      FI(MODE,IST)=0.
      HR(MODE,IST)=0.
      HI(MODE,IST)=0.
      DO 41 I=1,NON
      Q2=EXP(CAY*YY(IST,I))*DEL(IST,I)*32.2*DD
      Q3=CAY*XX(IST,I)
      Q4=SIN(Q3)
      Q5=COS(Q3)
      Q6=SNE(IST,I)*Q5-CSE(IST,I)*Q4
      FI(MODE,IST)=FI(MODE,IST)-FR(I)*Q2*Q4
      HR(MODE,IST)=HR(MODE,IST)+Q2*PRV(I)*Q6
41    HI(MODE,IST)=HI(MODE,IST)+Q2*PRV(I)*Q6
      GO TO (50,50,51)MODE
50    AM(MODE,IST)=AMC*DD*DD
      DF(MODE,IST)=W*DFC*DD*DD
      GO TO 100
51    AM(1,IST)=0.
      DF(1,IST)=0.
      ER(3,IST)=DD*ER(3,IST)
      FI(3,IST)=DD*FI(3,IST)
      HR(3,IST)=DD*HR(3,IST)
      HI(3,IST)=DD*HI(3,IST)
      DO 52 I=1,NON
      AM(1,IST)=AM(1,IST)-SNE(IST,I)*PRA(I)*DEL(IST,I)
52    DF(1,IST)=DF(1,IST)-SNE(IST,I)*PRV(I)*DEL(IST,I)
      AM(1,IST)=AM(1,IST)*64.4*(DD/W)**2
      DF(1,IST)=DF(1,IST)*64.4*DD**2/W
      AM(MODE,IST)=AMC*DD**4
      DF(MODE,IST)=DFC*DD**4*W
```

```
100   CONTINUE
      UW=U/W**2
 307  A22=-UW*DF(2,NST)+A22F
      B22=U*AM(2,NST)+B22
      A24=-UW*DF(1,NST)+A24F
      B24=U*AM(1,NST)+B24
      A26=-UW*XA(NST)*DF(2,NST)+U*UW*AM(2,NST)+A26F
      B26=U*XA(NST)*AM(2,NST)+U*UW*DF(2,NST)+B26
      A44=-UW*DF(3,NST)+A44F
      B44=U*AM(3,NST)+B44
      A46=-UW*XA(NST)*DF(1,NST)+U*UW*AM(1,NST)+A46F
      B46=U*XA(NST)*AM(1,NST)+U*UW*DF(1,NST)+B46
      A62=-UW*XA(NST)*DF(2,NST)+A26F
      B62=U*XA(NST)*AM(2,NST)+B62
      A64=-UW*XA(NST)*DF(1,NST)+A46F
      B64=U*XA(NST)*AM(1,NST)+B64
      A66=-UW*XA(NST)**2*DF(2,NST)+U*UW*XA(NST)*AM(2,NST)+A66F
      B66=U*XA(NST)**2*AM(2,NST)+U*UW*XA(NST)*DF(2,NST)+B66
      U2=2.*U/W
      EF(1)=U2*HI(2,NST)
      EF(2)=-U2*HR(2,NST)
      EF(3)=U2*HI(3,NST)
      EF(4)=-U2*HR(3,NST)
      EF(5)=EF(1)*XA(NST)
      EF(6)=EF(2)*XA(NST)
308    CONTINUE
      DO 103 IST=1,NST
      XDX=XA(IST)*DXA(IST)
      XDX2=XA(IST)**2*DXA(IST)
      D2=2.*DXA(IST)
      A22=A22+AM(2,IST)*DXA(IST)
      B22=B22+DF(2,IST)*DXA(IST)
      A24=A24+AM(1,IST)*DXA(IST)
      B24=B24+DF(1,IST)*DXA(IST)
      A26=A26+AM(2,IST)*XDX+UW*DF(2,IST)*DXA(IST)
      B26=B26+DF(2,IST)*XDX-U*AM(2,IST)*DXA(IST)
      A44=A44+AM(3,IST)*DXA(IST)
      B44=B44+DF(3,IST)*DXA(IST)
      A46=A46+AM(1,IST)*XDX+UW*DF(1,IST)*DXA(IST)
      B46=B46+DF(1,IST)*XDX-U*AM(1,IST)*DXA(IST)
      A62=A62+AM(2,IST)*XDX-UW*DF(2,IST)*DXA(IST)
      B62=B62+DF(2,IST)*XDX+U*AM(2,IST)*DXA(IST)
      A64=A64+AM(1,IST)*XDX-UW*DF(1,IST)*DXA(IST)
      B64=B64+DF(1,IST)*XDX+U*AM(1,IST)*DXA(IST)
      A66=A66+AM(2,IST)*XDX2+U*UW*AM(2,IST)*DXA(IST)
      B66=B66+DF(2,IST)*XDX2+U*UW*DF(2,IST)*DXA(IST)
      EF(1)=EF(1)+D2*(ER(2,IST)+HR(2,IST))
      EF(2)=EF(2)+D2*(FI(2,IST)+HI(2,IST))
      EF(3)=EF(3)+D2*(ER(3,IST)+HR(3,IST))
      EF(4)=EF(4)+D2*(FI(3,IST)+HI(3,IST))
      EF(5)=EF(5)+D2*(XA(IST)*(ER(2,IST)+HR(2,IST))+U*HI(2,IST)/W)
103   EF(6)=EF(6)+D2*(XA(IST)*(FI(2,IST)+HI(2,IST))-U*HR(2,IST)/W)
      RETURN
      END
```

```
      SUBROUTINE FIND
      COMMON/GR/NUT,NON,CAY,AMC,DFC,YA(25,8),ZA(25,8)
      COMMON PI,HPI,QPI,TPI,MD,MODE,DPH,CR,RAT,SUR,DEG,IST,DRT,HBM,SG,N
     1OE,PDM,VOL,DEW,UN,OMEGA,CP,WVH,ID,DOG,IG,XX(25,7),YY(25,7),DEL(25,
     27),SNE(25,7),CSE(25,7),FR(7),BLOG(25,7,7),YLOG(25,7,7),CON(14,1),C
     3T(14,14),PSI1(7,7),PSI2(7,7),PRA(7),PRV(7)
      DO 1 I=1,NON
      XM1=XX(IST,I)-YA(IST,1)
      YM1=YY(IST,I)-ZA(IST,1)
      XP1=XX(IST,I)+YA(IST,1)
      YP1=YY(IST,I)+ZA(IST,1)
      FPR1=.5*ALOG(XM1**2+YM1**2)
      FPL1=.5*ALOG(XP1**2+YM1**2)
      FCR1=.5*ALOG(XM1**2+YP1**2)
      FCL1=.5*ALOG(XP1**2+YP1**2)
      APR1=ATAN2(YM1,XM1)
      APL1=ATAN2(YM1,XP1)
      ACR1=ATAN2(YP1,XM1)
      ACL1=ATAN2(YP1,XP1)
      DO 1 J=1,NON
      XM2=XX(IST,I)-YA(IST,J+1)
      YM2=YY(IST,I)-ZA(IST,J+1)
      XP2=XX(IST,I)+YA(IST,J+1)
      YP2=YY(IST,I)+ZA(IST,J+1)
      FPR2=.5*ALOG(XM2**2+YM2**2)
      FPL2=.5*ALOG(XP2**2+YM2**2)
      FCR2=.5*ALOG(XM2**2+YP2**2)
      FCL2=.5*ALOG(XP2**2+YP2**2)
      APR2=ATAN2(YM2,XM2)
      J1=J+1
      IF(XM2.GT.0.0)GO TO 4
      IF(J1.GT.I) GO TO 6
      IF(YM2.LT.0.0)APR2=APR2+TPI
      GO TO 5
6     IF(YM2.GE.0.0)APR2=APR2-TPI
5     IF(YP2.LT.0.0) GO TO 4
      ACR2=-PI
      GO TO 3
4     CONTINUE
      ACR2=ATAN2(YP2,XM2)
3     CONTINUE
      ACL2=ATAN2(YP2,XP2)
      APL2=ATAN2(YM2,XP2)
      SIMJ=SNE(IST,I)*CSE(IST,J)-SNE(IST,J)*CSE(IST,I)
      CIMJ=CSE(IST,I)*CSE(IST,J)+SNE(IST,I)*SNE(IST,J)
      SIPJ=SNE(IST,I)*CSE(IST,J)+SNE(IST,J)*CSE(IST,I)
      CIPJ=CSE(IST,I)*CSE(IST,J)-SNE(IST,I)*SNE(IST,J)
      DPNR=SIMJ*(FPR1-FPR2)+CIMJ*(APR1-APR2)
99    PPR=CSE(IST,J)*(XM1*FPR1-YM1*APR1-XM1-XM2*FPR2+YM2*APR2+
     1XM2)+SNE(IST,J)*(YM1*FPR1+XM1*APR1-YM1-YM2*FPR2-XM2*APR2+YM2)
      DPNL=SIPJ*(FPL2-FPL1)+CIPJ*(APL2-APL1)
      PPL=CSE(IST,J)*(XP2*FPL2-YM2*APL2-XP2-XP1*FPL1+YM1*APL1+
     1XP1)+SNE(IST,J)*(YM1*FPL1+XP1*APL1+YM2-YM2*FPL2-XP2*APL2-YM1)
      DCNR=SIPJ*(FCR1-FCR2)+CIPJ*(ACR1-ACR2)
      PCR=CSE(IST,J)*(XM1*FCR1-YP1*ACR1-XM1-XM2*FCR2+YP2*ACR2+
     1XM2)+SNE(IST,J)*(YP2*FCR2+XM2*ACR2+YP1-YP1*FCR1-XM1*ACR1-YP2)
      DCNL=SIMJ*(FCL2-FCL1)+CIMJ*(ACL2-ACL1)
```

```
      PCL=CSE(IST,J)*(XP2*FCL2-YP2*ACL2-XP2-XP1*FCL1+YP1*ACL1+XP
     11)+SNE(IST,J)*(YP2*FCL2+XP2*ACL2-YP2-YP1*FCL1-XP1*ACL1+YP1)
      BLOG(IST,I,J)=DPNR+SG*DPNL-DCNR-SG*DCNL
      YLOG(IST,I,J)=PPR+SG*PPL-PCR-SG*PCL
      IF(J-NON)2,1,1
2     XM1=XM2
      YM1=YM2
      XP1=XP2
      YP1=YP2
      FPR1=FPR2
      FPL1=FPL2
      FCR1=FCR2
      FCL1=FCL2
      APR1=APR2
      APL1=APL2
      ACR1=ACR2
      ACL1=ACL2
1     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FREJ
      COMMON PI,HPI,QPI,TPI,MD,MODE,DPH,CR,RAT,SUR,DEG,IST,DRT,HBM,SG,N
     1OE,PDM,VOL,DEW,UN,OMEGA,CP,AVH,ID,DOG,IG,XX(25,7),YY(25,7),DEL(25
     2,7),SNE(25,7),CSE(25,7),FR(7),BLOG(25,7,7),YLOG(25,7,7),CON(14,1)
     3,CT(14,14),PSI1(7,7),PSI2(7,7),PRA(7),PRV(7)
      COMMON/GR/NUT,NON,CAY,AMC,DFC,YA(25,8),ZA(25,8)
10    DO 1 I=1,NON
      NI=NON+I
      CON(I,1)=0.
      CON(NI,1)=OMEGA*FR(I)
      XR1=UN*(XX(IST,I)-YA(IST,1))
      YR1=-UN*(YY(IST,I)+ZA(IST,1))
      XL1=UN*(XX(IST,I)+YA(IST,1))
      YL1=YR1
      CALL DAVID (XR1,YR1,EJ1,CXR1,SXR1,RAR1,RBR1,CR1,SR1)
      CALL DAVID (XL1,YL1,EJ1,CXL1,SXL1,RAL1,RBL1,CL1,SL1)
      DO 1 J=1,NON
      NJ=NON+J
      XR2=UN*(XX(IST,I)-YA(IST,J+1))
      YR2=-UN*(YY(IST,I)+ZA(IST,J+1))
      XL2=UN*(XX(IST,I)+YA(IST,J+1))
      YL2=YR2
      CALL DAVID (XR2,YR2,EJ2,CXR2,SXR2,RAR2,RBR2,CR2,SR2)
      CALL DAVID (XL2,YL2,EJ2,CXL2,SXL2,RAL2,RBL2,CL2,SL2)
      SIPJ=SNE(IST,I)*CSE(IST,J)+SNE(IST,J)*CSE(IST,I)
      CIPJ=CSE(IST,I)*CSE(IST,J)-SNE(IST,I)*SNE(IST,J)
      SIMJ=SNE(IST,I)*CSE(IST,J)-SNE(IST,J)*CSE(IST,I)
      CIMJ=CSE(IST,I)*CSE(IST,J)+SNE(IST,I)*SNE(IST,J)
      CT(I,J)=BLOG(IST,I,J)+2.*(SIPJ*(CR1-CR2)-CIPJ*(SR1-SR2)-SG*(SI
     1MJ*(CL1-CL2)-CIMJ*(SL1-SL2)))
      PSI1(I,J)=YLOG(IST,I,J)+2./UN*(SNE(IST,J)*(RAR1-RAR2)+CSE(IST,J
     1)*(RBR1-RBR2)+SG*(SNE(IST,J)*(RAL1-RAL2)+CSE(IST,J)*(RBL2-RBL1)))
      CT(NI,NJ)=CT(I,J)
      CT(I,NJ)=TPI*(EJ2*(SXR2*CIPJ-CXR2*SIPJ)-EJ1*(SXR1*CIPJ-CX
     1R1*SIPJ)-SG*(EJ2*(SXL2*CIMJ-CXL2*SIMJ)-EJ1*(SXL1*CIMJ-CXL1
     2*SIMJ)))
      PSI2(I,J)=TPI/UN*(EJ1*(SXR1*CSE(IST,J)-CXR1*SNE(IST,J))-EJ2*
     1(SXR2*CSE(IST,J)-CXR2*SNE(IST,J))-SG*(EJ1*(SXL1*CSE(IST,J)+CXL1*SN
     2E(IST,J))-EJ2*(SXL2*CSE(IST,J)+CXL2*SNE(IST,J))))
      CT(NI,J)=-CT(I,NJ)
      IF(J-NON)7,1,1
7     XR1=XR2
      YR1=YR2
      XL1=XL2
      YL1=YL2
      EJ1=EJ2
      CR1=CR2
      SR1=SR2
      CL1=CL2
      SL1=SL2
      RAR1=RAR2
      RBR1=RBR2
      RAL1=RAL2
      RBL1=RBL2
      CXR1=CXR2
      SXR1=SXR2
      CXL1=CXL2
```

```
      SXL1=SXL2
1     CONTINUE
      CALL MATINV(CT,NOE,CON,1,DOG,ID)
      GO TO (2,6),ID
2     DO 3 I=1,NON
      PRA(I)=0.
      PRV(I)=0.
      DO 4 J=1,NON
      NJ=NON+J
      PRA(I)=PRA(I)+CON(J,1)*PSI2(I,J)-CON(NJ,1)*PSI1(I,J)
4     PRV(I)=PRV(I)+CON(J,1)*PSI1(I,J)+CON(NJ,1)*PSI2(I,J)
      PRA(I)=OMEGA*PRA(I)
3     PRV(I)=OMEGA*PRV(I)
      AMC=0.0
      DFC=0.0
      DO 5 I=1,NON
      AMC=AMC+PRA(I)*DEL(IST,I)*FR(I)
5     DFC=DFC+PRV(I)*DEL(IST,I)*FR(I)
      AMC=2.0*AMC
      DFC=2.0*DFC
      AMC=AMC/UN
      DFC=DFC/UN
6     RETURN
      END
```

```
C     DAVI - COMPUTATION OF FREQUENCY DEPENDENT PARTS OF
C     2-D POTENTIALS AND KERNELS
      SUBROUTINE DAVID(X,Y,E,C,S,RA,RB,CIN,SON)
      AT=ATAN2(X,Y)
      ARG=AT-1.5707963
      E=EXP(-Y)
      C=COS(X)
      S=SIN(X)
      R=X**2+Y**2
      TEST=0.00001
      IF(R.LT.1.0) GO TO 5
      TEST=0.1*TEST
      IF(R.LT.2.0) GO TO 5
      TEST=0.1*TEST
      IF(R.LT.4.0) GO TO 5
      TEST=0.1*TEST
    5 AL=0.5*ALOG(R)
      SUMC=0.57721566+AL+Y
      SUMS=AT+X
      TC=Y
      TS=X
      DO 1 K=1,500
      TO=TC
      COX=K
      CAY=K+1
      FACT=COX/(CAY*CAY)
      TC=FACT*(Y*TC-X*TS)
      TS=FACT*(Y*TS+X*TO)
      SUMC=SUMC+TC
      SUMS=SUMS+TS
      IF(K.GE.500) GO TO 3
      IF((ABS(TC)+ABS(TS)).GT.TEST) GO TO 1
    3 CIN=E*(C*SUMC+S*SUMS)
      SON=E*(S*SUMC-C*SUMS)
      RA=AL-CIN
      RB=ARG+SON
      GO TO 4
    1 CONTINUE
    4 RETURN
      END
```

```
      SUBROUTINE MATINV(A,NR,B,NC,DETERM,ID)
C     MATRIX INVERSION WITH ACCOMPANYING SOLUTION OF LINEAR EQUATIONS
C     PIVOT METHOD
C     FORTRAN IV SINGLE PRECISION WITH ADJUSTABLE DIMENSION
C     FEBRUARY 1966    S GOOD  DAVID TAYLOR MODEL BASIN   AM MAT4
C          WHERE CALLING PROGRAM MUST INCLUDE
C              DIMENSION A(NR,NR), B(NR,NC), INDEX(NR,3)
C           N      IS THE ORDER OF A
C           M      IS THE NUMBER OF COLUMN VECTORS IN B(MAY BE 0)
C          DETERM WILL CONTAIN DETERMINANT ON EXIT
C           ID     WILL BE SET BY ROUTINE TO 2 IF MATRIX A IS SINGULAR
C                  1 IF INVERSION WAS SUCCESSFUL
C           A      THE INPUT MATRIX WILL BE REPLACED BY A INVERSEE
C           B      THE COLUMN VECTORS WILL BE REPLACED BY CORRESPONDING
C                  SOLUTION VECTORS
C           INDEX WORKING STORAGE ARRAY
C          IF IT IS DESIRED TO SCALE THE DETERMINANT CARD      MAY BE
C          DELETED AND DETERM PRESET BEFORE ENTERING THE ROUTINE
C
      EQUIVALENCE (IROW,JROW), (ICOLUM,JCOLUM), (AMAX, T, SWAP)
      DIMENSION A(NR,NR),B(NR,NC),INDEX(30,3)
      N1=NR
      M1=NC
C
C      INITIALIZATION
C
       N=N1
      M=M1
      DETERM = 0.0
       DO 20 J=1,N
   20 INDEX(J,3) = 0
       DO 550 I=1,N
C
C     SEARCH FOR PIVOT ELEMENT
C
      AMAX = 0.0
      DO 105 J=1,N
      IF(INDEX(J,3)-1) 60, 105, 60
   60 DO 100 K=1,N
      IF(INDEX(K,3)-1) 80, 100, 715
   80 IF (        AMAX -ABS (A(J,K))) 85, 100, 100
   85 IROW=J
      ICOLUM =K
      AMAX = ABS (A(J,K))
  100 CONTINUE
  105 CONTINUE
      INDEX(ICOLUM,3) = INDEX(ICOLUM,3) +1
      INDEX(I,1)=IROW
      INDEX(I,2)=ICOLUM
C
C     INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL
C
      IF (IROW-ICOLUM) 140, 310, 140
  140 DETERM=-DETERM
      DO 200 L=1,N
```

```
      SWAP=A(IROW,L)
      A(IROW,L)=A(ICOLUM,L)
  200 A(ICOLUM,L)=SWAP
      IF(M) 310, 310, 210
  210 DO 250 L=1, M
      SWAP=B(IROW,L)
      B(IROW,L)=B(ICOLUM,L)
  250 B(ICOLUM,L)=SWAP
C
C     DIVIDE PIVOT ROW BY PIVOT ELEMENT
C
  310 PIVOT   =A(ICOLUM,ICOLUM)
      DETERM=DETERM*PIVOT
  330 A(ICOLUM,ICOLUM)=1.0
      DO 350 L=1,N
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
      IF(M) 380, 380, 360
  360 DO 370 L=1,M
  370 B(ICOLUM,L)=B(ICOLUM,L)/PIVOT
C
C     REDUCE NON-PIVOT ROWS
C
  380 DO 550 L1=1,N
      IF(L1-ICOLUM) 400, 550, 400
  400 T=A(L1,ICOLUM)
      A(L1,ICOLUM)=0.0
      DO 450 L=1,N
  450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
      IF(M) 550, 550, 460
  460 DO 500 L=1,M
  500 B(L1,L)=B(L1,L)-B(ICOLUM,L)*T
  550 CONTINUE
C
C     INTERCHANGE COLUMNS
C
      DO 710 I=1,N
      L=N+1-I
      IF (INDEX(L,1)-INDEX(L,2)) 630, 710, 630
  630 JROW=INDEX(L,1)
      JCOLUM=INDEX(L,2)
      DO 705 K=1,N
      SWAP=A(K,JROW)
      A(K,JROW)=A(K,JCOLUM)
      A(K,JCOLUM)=SWAP
  705 CONTINUE
  710 CONTINUE
      DO 730 K = 1,N
      IF(INDEX(K,3) -1) 715,720,715
 720   CONTINUE
 730   CONTINUE
       ID = 1
 810  RETURN
 715  ID = 2
       GO TO 810
       END
```

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13. ABSTRACT

To provide further capability for prediction and analysis of hydrofoil hullborne seakeeping, a mathematical model and computer program have been developed to predict roll, sway and yaw motions of hullborne hydrofoil ships in beam seas. Predictions agree well with towing tank data for a 1:20-scale model of the PHM hydrofoil craft.

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KEY WORDS

Hydrofoil

Hullborne

Roll

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Yaw

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