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PRELIMINARY INVESTIGATION OF ROLL CONTROLLABILITY OF A HYDROFOIL SMALL WATERPLANE AREA SHIP (HYSWAS)

by

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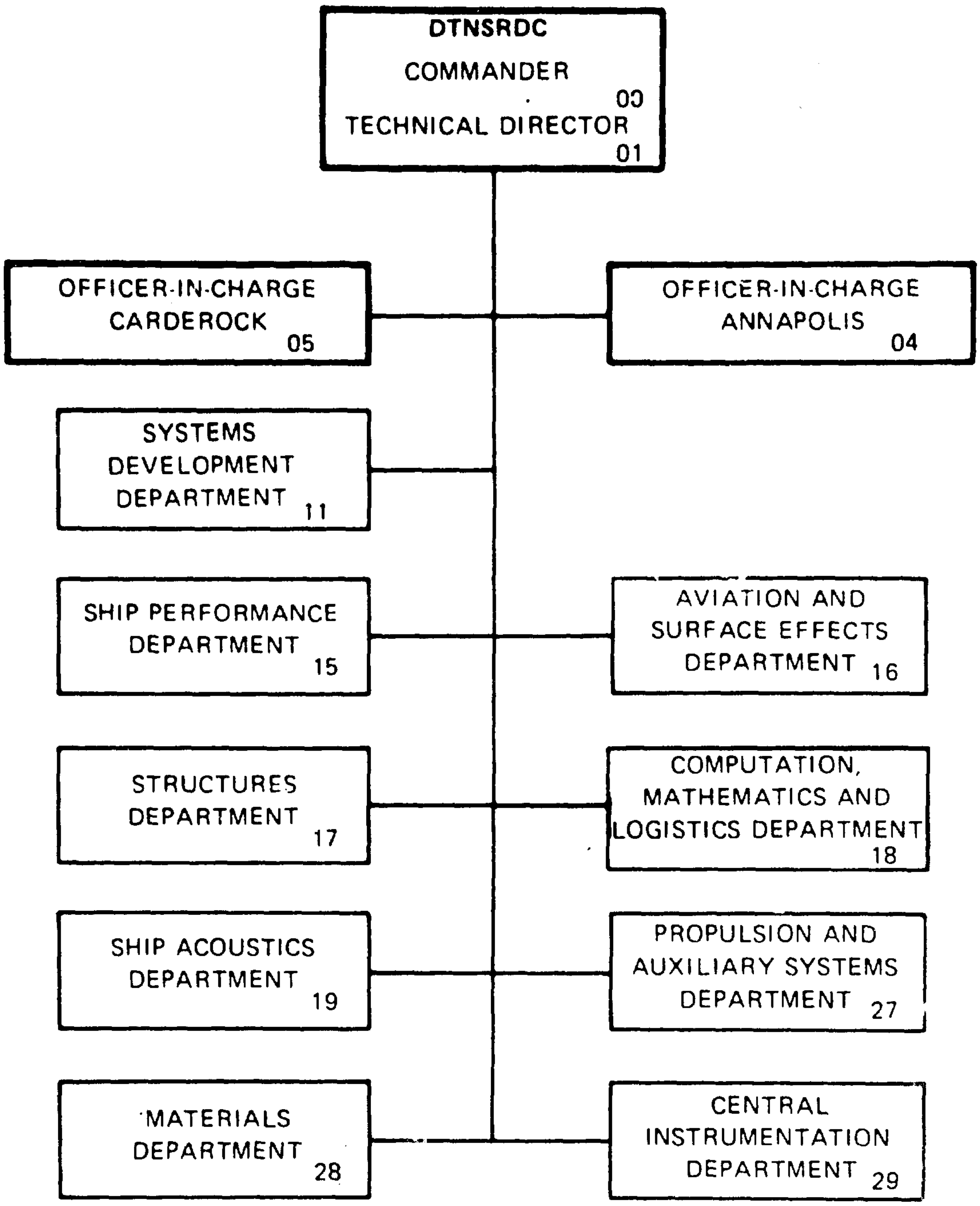

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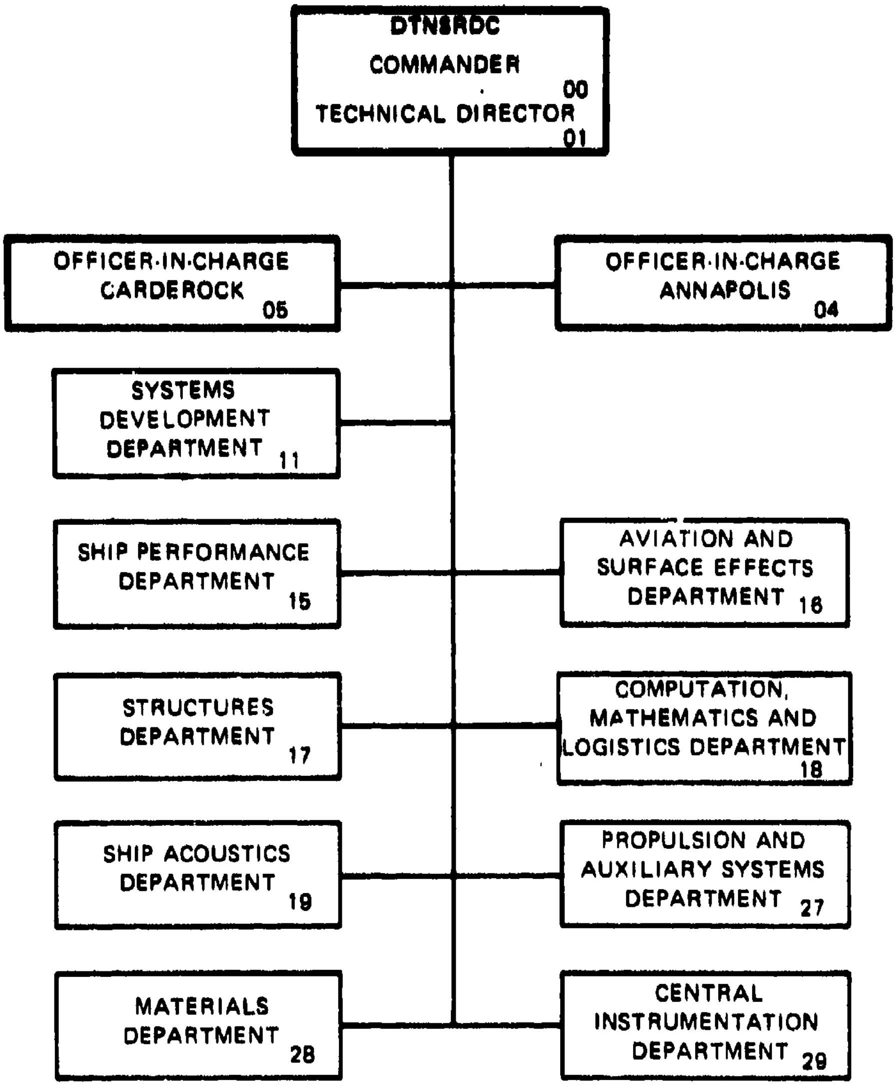

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ADMINISTRATIVE INFORMATION

This investigation was initiated at the request of the Advanced Concepts Office, Systems Development Department of the David W. Taylor Naval Ship R&D Center (DTNSRDC) under the DTNSRDC Ship Feasibility Studies Block Program (Task Area SF43411291, Work Unit 1100-001).

INTRODUCTION

The concept of a hydrofoil small waterplane area ship (HYSWAS) has been evolved from the development of hybrid ships in the Systems Development Department at the Center.[1] As shown in Figure 1, a HYSWAS consists of four major hull components, i.e., a slender torpedo-shaped lower hull, a narrow vertical strut, an upper hull, and a hydrofoil system attached to the lower hull. When a HYSWAS is in the foilborne condition, the foils support approximately thirty percent of the ship weight.

A major concern with the HYSWAS concept has been the controllability of roll motion which is excited by waves. Since a HYSWAS has little inherent roll restoring capability in a foilborne condition due to its small waterplane area, the roll stability must be maintained by actively controlled foils. This means that the foils should have lift capability not only to maintain the foilborne position but also to control excessive motion excited by waves.

The present investigation provides some of the necessary information which may be used for assessing the feasibility of controlling roll motion of a 2000-ton HYSWAS which will be designated as HYSWAS-2000 in this report. The principal characteristics of HYSWAS-2000 are shown in Table 1.

The investigation is conducted to determine the wave-excited roll moment on the HYSWAS at several foilborne drafts. It is assumed that the motion is restrained in all modes except forward motion which is constant. For a given

[1] Meyer, J.R. and J.H. King, "The Hydrofoil Small Waterplane Area Ship (HYSWAS)," AIAA/SNAME 3rd Advanced Vehicle Conference, Washington, D.C. 1976

draft, the wave-excited roll moments are determined at two to three forward speeds for three wave headings, namely, the stern quartering, beam, and bow quartering. The foregoing wave-excited roll moments are first obtained in the frequency domain in the form of transfer functions. These are converted to statistical average for sea conditions by using Bretschneider's sea spectra formula. Then, the necessary root mean square of the deflection angles of the foils to cancel the wave-excited roll moments are determined.

In order to examine a qualitative seakeeping performance of the ship, the probable numbers of free-surface contacts on the bottom of the upper hull for various conditions are computed. These results are obtained by using Bretschneider's spectra formula with the most probable modal periods for a given significant wave height.

ANALYSIS

A HYSWAS which is restrained from responding to incident waves is proceeding at a constant speed U, in regular waves of amplitude A and length λ. The objective is to find the wave-excited roll moment on the ship. The roll moment will be determined in two parts. The first part is the roll moment contributed by the submerged portion of the hull without the foils, and the other part is the roll moment contributed by the foils.

The wave-excited roll moment on the bare hull in the form of complex amplitude, the absolute value of which is the real amplitude, can be given by [2]

[2] Lee, C.M., "Theoretical Prediction of Motion of Small-Waterplane-Area, Twin-Hull (SWATH) Ships in Waves," DTNSRDC Report 76-0046, 1976.

$$F_4^{(b)} = -\frac{j\rho g A}{\omega_0}\int_L dx\, e^{jK_0 x\cos\beta}\int_{C(x)} d\ell\, \{ j\omega_0 [y N_3 - (z - z_0) N_2]$$

$$+ K_0 (-jN_2 \sin\beta + N_3)\, \phi_4 \}\, e^{K_0 (z - jy\sin\beta)}$$

$$- \frac{\rho}{2}\omega_0 A a_0 U \int_L dx\, d(x)\, (d_2 + z_0)\, e^{K_0(-d_2 + jx\cos\beta)} \qquad (1)$$

$$- \rho \frac{4}{3\pi}\omega_0 A C_D \int_L dx\, d\, (d_2 + z_0)\, e^{K_0(-d_2 + jx\cos\beta)}\, \dot{y}_1(x)$$

The notations used in the foregoing expression are defined as follows:

A = wave amplitude

a_o = viscous lift coefficient

$C(x)$ = immersed contour of the cross section at x at the mean position

C_D = cross-flow drag coefficient

d = sectional draft

d_2 = sectional depth at maximum breadth for section without strut or d/2 for section with strut

g = gravitational acceleration

j = $\sqrt{-1}$

K_o = $\frac{2\pi}{\lambda}$ = wave number

N_2, N_3 = y- and z-component, respectively, of two-dimensional unit normal vector on C(x)

U = forward speed

(x, y, z) = right-handed rectangular coordinate system; the x-axis is directed toward bow and the z-axis is directed upward

$\dot{y}_1$ = relative sway velocity of the body at the axes of the submerged hulls with respect to the horizontal wave-orbital velocity.

z_o = z-coordinate of center of roll moment

β = wave-heading angle; $\beta = 0$ for the following waves

ϕ_4 = two-dimensional velocity potential representing the fluid disturbances generated by the forced roll motion of the cross section at x.

ω_o = radian wave frequency

$\int_L$ = integral over the submerged hull length

The wave-exciting roll moment induced by the foils will be determined under the following assumptions:

1. The unsteady effect on the lift-curve slopes of the foils is neglected.

2. The spanwise distribution of circulation is elliptic.

3. The spanwise distribution of angle of attack due to the wave-induced fluid velocity is obtained by the ratio of the vertical wave-orbital velocity at the quarter-chord point to the ship speed.

Neglecting unsteady effect is based on Jones' theory.[3] The upper limit of the reduced frequency ($k = \frac{\omega c}{2U}$) in the present case is about 0.8 which is based on U = 16 knots, c = average chord = 3.94 m (12 ft), and ω = wave-encounter frequency $= \sqrt{\frac{2\pi g}{\lambda}} + \frac{2\pi U}{\lambda} = 15$ rad/sec for λ = 4.92 m (15 ft). For $k \doteq 0.8$ and aspect ratio less than 3, the unsteady effect, according to Jones, would reduce the lift coefficient of the steady case by 20 percent at most. As $k \to 0$ the unsteady effect diminishes. Thus, by neglecting the unsteady effect, we may overestimate the lift produced by the foils by 20 percent for the shorter wave lengths and by lesser amounts for the longer waves.

The assumption of an elliptic spanwise distribution of circulation represents the optimum lift distribution according to lifting-line theory.

[3] Jones, R.T., "The Unsteady Lift of a Wing of Finite Aspect Ratio," NACA Report 681, 1940.

In reality, this assumption may not be true; however, for the purpose of this feasibility study, this assumption is not expected to affect the final conclusions.

The third assumption may appear to be more controversial than the others. This assumption ignores the induced down-wash effects as well as the diffracted wave effects due to the body and foils. However, based on experimental results obtained from a SWATH model experiment,[4] these neglected effects are judged to be small.

With the foregoing assumptions, we can express the wave-excited roll moment contributed by a pair of foils as

$$F_4^{(f)} = \frac{\rho}{2} U^2 \left[\int_{-s-a}^{-a} + \int_{a}^{s+a} C_{L\alpha}'(y)\, c(y)\, \alpha(y)\, y\, dy \right] \tag{2}$$

where $C_{L\alpha}'(y)$ is the two-dimensional lift-curve slope, $c(y)$ the sectional chord, $\alpha(y)$ the sectional angle of attack, and s and a are as shown in Figure 2.

Since the incident plane wave potential ϕ_I can be expressed by

$$\phi_I(x,y,z) = -\frac{jgA}{\omega} e^{K_0 z + jK_0(x\cos\beta - y\sin\beta)} \tag{3}$$

the vertical fluid velocity induced by the waves V_w can be obtained by

$$V_w = \frac{\partial}{\partial z}\phi_I = -j\omega_0 A\, e^{K_0 z + jK_0(x\cos\beta - y\sin\beta)}$$

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[4]Lee, C.M. and L.O. Murray, "Experimental Investigation of Hydrodynamic Coefficients of a Small-Waterplane-Area, Twin-Hull Model," DTNSRDC Report SPD 747-01, 1977.

Hence, at the quarter-chord foil location, i.e., $z = -d_2$ and $x = \ell$, we find that

$$\alpha(y) = -\frac{j\omega_0 A}{U} e^{-K_0 d_2 + jK_0(\ell\cos\beta - y\sin\beta)} \tag{4}$$

Substituting Equation (4) into (2), we obtain for two pairs of foils

$$F_4^{(f)} = -j\frac{\rho}{2} U\omega_0 A e^{-K_0 d_2} \sum_{i=1}^{2} e^{jK_0 \ell_i \cos\beta} \left[\int_{-s_i-a_i}^{-a_i} + \int_{a_i}^{s_i+a_i} C'_{L\alpha_i} c_i e^{-jK_0 y\sin\beta} y\, dy \right] \tag{5}$$

where the subscript $i = 1$ indicates the main foils and $i = 2$ the stern foils.

Since the planform of the foils is trapezoidal, we have

$$c_i(y) = c_{ri} - \frac{c_{ri} - c_{ti}}{s_i}(y \mp a_i) \quad \text{for} \quad y \gtrless 0 \tag{6}$$

where the subscripts r and t, respectively, indicate the root and the tip of the ith foil.

For an elliptic distribution of circulation along the semispan of the foils, the sectional lift-curve slope can be obtained by

$$C'_{L\alpha_i}(y) = \frac{C'_{L\alpha_i}(\pm a_i)}{s_i}\sqrt{s_i^2 - (y \mp a_i)^2} \quad \text{for} \quad y \gtrless 0 \tag{7}$$

The lift-curve slope at the root $C_{L\alpha_i}$ $(\pm a_i)$ is approximated from the equation

$$C_{L\alpha_i} A_i^{(f)} = \frac{C'_{L\alpha_i}(\pm a_i)}{s_i}\int_{a_i}^{s_i+a_i} \sqrt{s_i^2 - (y \mp a_i)^2} \left\{ c_{ri} - \frac{c_{ri} - c_{ti}}{s_i}(y \mp a_i) \right\}$$

where $C_{L\alpha_i}$ and $A_i^{(f)}$ are, respectively, the lift-curve slope and the projected area of the ith foil. Thus, we have

$$C'_{L\alpha_i}(\pm a_i) = \frac{s_i C_{L\alpha_i} A_i^{(f)}}{\int_0^{s_i} \sqrt{s_i^2 - y^2}\,\left(C_{r_i} - \frac{C_{r_i} - C_{t_i}}{s_i}\, y\right) dy} \tag{8}$$

Since

$$\int_0^s \sqrt{s^2 - y^2}\, dy = \frac{\pi}{4} s^2 \quad \text{and}$$

$$\int_0^s y\sqrt{s^2 - y^2}\, dy = \frac{s^3}{3}, \quad \text{we get}$$

$$C'_{L\alpha_i}(\pm a_i) = \frac{C_{L\alpha_i} A_i^{(f)}}{s_i\left(\frac{\pi}{4} C_{r_i} - \frac{C_{r_i} - C_{t_i}}{3}\right)} \tag{9}$$

Substituting the expressions given by Equations (7) and (9) into (5), we obtain

$$F_4^{(f)} = -\frac{1}{2} j \rho \omega_0 U A e^{-K_0 d_2} \sum_{i=1}^{2} \left[\frac{C_{L\alpha_i} A_i^{(f)} e^{j K_0 \ell_j \cos\beta}}{s_i^2\left(\frac{\pi}{4} C_{r_i} - \frac{C_{r_i} - C_{t_i}}{3}\right)} \right.$$
$$\left\{ -2j \int_{a_i}^{s_i + a_i} \sqrt{s_i^2 - (y - a_i)^2}\, y \left[C_{r_i} - \frac{C_{r_i} - C_{t_i}}{s_i} (y - a_i) \right] \right.$$
$$\left.\left. \sin(K_0 y \sin\beta)\, dy \right\} \right] \tag{10}$$

The total wave-excited roll moment on a HYSWAS is then obtained by summing the expressions given by Equations (1) and (10), i.e.,

$$F_4^{(e)} = F_4^{(b)} + F_4^{(f)}$$

Using the response amplitude operator (RAO) for the wave-excited roll moment $R(\omega_o)$ and a given sea spectrum $S(\omega_o)$, we can obtain the statistical averages of the wave-excited moment by

$$\bar{F}_4 = \gamma \left[\int_0^\infty R(\omega_o) S(\omega_o) d\omega_o \right]^{\frac{1}{2}} \tag{11}$$

where

$$R(\omega_o) = |F_4^{(e)}|^2 / A^2$$

$$\gamma = \begin{cases} 1.0 \text{ for RMS value} \\ 2.0 \text{ for average value of the highest one-third values} \end{cases}$$

Once a statistical average of the wave-exciting roll moment for a given sea spectrum is obtained, we can find the corresponding fin deflection angles required to counteract the roll moment. This is done under the assumption that the foils are all movable and that stalling would not occur on the foils. Furthermore, foil deflection angles should be chosen in such a manner that no pitch moment would be induced on the ship. Let the horizontal distance from the axis of the submerged body to the centroid of the projected foil area of the forward and aft foils be represented by b_1 and b_2, respectively. Then, the following two equations will determine the unknown foil deflection angles, α_1 and α_2:

$$\begin{aligned} L_1 \alpha_1 + L_2 \alpha_2 &= \bar{F}_4 \\ L_1 \ell_1 \alpha_1 + L_2 \ell_2 \alpha_2 &= 0 \end{aligned} \tag{12}$$

where

$$L_i = \frac{\rho}{2} U^2 C_{L\alpha_i} A_i^{(f)} b_i \qquad \text{for } i = 1 \text{ and } 2,$$

and ℓ and ℓ_2 are,

respectively, the x-coordinates of the quarter-chord points at the average chord locations of the forward and aft foils. An implicit assumption made in the foregoing expressions is that the lift center of each semifoil is located at the point which is equal in spanwise to the centroid of the area and in chordwise to the quarter-chord point of the average chord.

From Equation (12) it can be readily found that

$$\alpha_1 = \frac{\bar{F}_4 \ell_2}{L_1 (\ell_2 - \ell_1)} \tag{13a}$$

$$\alpha_2 = \frac{\bar{F}_4 \ell_1}{L_2 (\ell_1 - \ell_2)} = - \frac{\ell_1 L_1}{\ell_2 L_2} \alpha_1 \tag{13b}$$

These foil angles represent the same statistical averages corresponding to $\bar{F}_4$ since the analysis is based on the linear relationship between the counteracting roll moment and the foil deflection angles. The proof can be readily established by the following steps. By substituting $|F_4^{(e)}|/A$ in place of $\bar{F}_4$ in Equation (13), we obtain new α_1 and α_2 which are the square roots of the RAO's of the foil motion. By using these RAO's together with a given sea spectrum, as shown by Equation (11), we find the statistical averages of the foil angles which are none other than the α_1 and α_2 given by Equations (13).

In reality, the rates of foil deflection would be limited to a certain range of frequencies, and the foil activation would not be necessary for those wave frequencies and wave amplitudes which cannot excite large roll motion. Thus, the integral over zero to infinite frequency range given in Equation (11) would yield the foil angles which could be overestimated. For the present investigation, however, it is considered that the values obtained by Equation (13) will serve the purposes.

The probable number of water contacts per hour on the bottom of the upper hull at a given point can be obtained from the probability of exceedance for a narrowly banded process having a normal distribution with zero mean by

$$N_W = \frac{1800}{\pi}\sqrt{\frac{E_V^{(R)}}{E^{(R)}}}\exp\left(-\frac{C_o^2}{2E^{(R)}}\right) \tag{14}$$

where

$$E^{(R)} = \int_0^\infty \frac{|\zeta_R|^2}{A^2} S(\omega_o)\, d\omega_o$$

$$E_V^{(R)} = \int_0^\infty \omega^2 \frac{|\zeta_R|^2}{A^2} S(\omega_o)\, d\omega_o$$

$$\zeta_R = \zeta_3 - x\,\zeta_5 + y\,\zeta_4 - \zeta(x,y)$$

ζ_3 = heave displacement

ζ_4 = roll-angle displacement

ζ_5 = pitch-angle displacement

ζ = wave elevation

C_o = vertical height of the point from the calm water surface

RESULTS AND DISCUSSIONS

The principal characteristics of the HYSWAS-2000 are given in Table 1 and a Schematic view of the ship is given in Figure 1.

The wave exciting roll moment $F_4^{(b)}$ and $F_4^{(f)}$ given, respectively, in Equations (1) and (10) for various drafts, speeds, wave lengths and wave headings are obtained from a computer program which was obtained by modifying an existing computer program.[5] These results with the Bretschneider wave spectra formula

$$S(\omega_0) = \frac{487.06\, H_{1/3}^2}{T_0^4} \exp\left(-\frac{1948.24}{T_0^2\, \omega_0^4}\right) \quad (m^2\text{-sec})$$

where

$H_{1/3}$ = significant wave height in meters

T_0 = modal period in seconds

ω_0 = wave frequency in radians per second,

were used to obtain the RMS values of the wave-excited roll moments for various significant wave heights and modal periods.

These values were converted to equivalent RMS deflection angles of all-movable foils by use of Equations (13). Table 2 shows the RMS values of foil deflection angles for various conditions for the most probable sea spectra. "The most probable sea spectra" means the sea spectra which are represented by

[5] McCreight, K.K., and C.M. Lee, "Manual for Mono-Hull or Twin-Hull Ship Motion Prediction Computer Program," DTNSRDC Report SPD-686-02, 1976

the Bretschneider spectra formula with the most probable modal periods of sea waves for given significant wave heights. These modal periods are presented in Table 3 which is excerpted from the paper of Ochi and Bales.[6]

With these RMS values of foil deflection angles, the foils are supposed to generate a roll moment to counteract the wave-excited roll moment. In reality, one cannot, of course, expect a perfect cancellation of the wave-excited roll moments; hence, the RMS values obtained here should be regarded as qualitative average of necessary foil deflection for given sea conditions and ship speeds.

Figures 3 through 6 show the RMS values of the deflection angles of the forward foils versus significant wave heights for various drafts and wave headings. The solid vertical lines represent the range of foil deflection angles which are obtained by using the range of modal periods for the 95 percent confidence limits shown in Table 3. The cross points indicate the foil deflection angles for the most probable values of modal period for each significant wave height.

The corresponding deflection angles for the aft foils can be obtained by multiplying the results shown in Figures 3 through 6 by $-\frac{\ell_1 L_1}{\ell_2 L_2}\alpha_1$ (see Equation (13b)), i.e., $0.82\alpha_1$.

Actual computations were made for two to three speeds for each draft at given wave headings. The results showed that the RMS values of the foil deflection angles at other speeds than shown in the figures were very closely proportional to the square power of the inverse ratio of the speeds. Thus, one can estimate the values at desired speeds up to 25 knots by using the results shown in Figures 3 through 6. The center roll moment was assumed to be at the center of gravity of the ship in the foregoing computations.

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[6] The compilation of the data is based on Walden's all season data or wave height and period observed in the North Atlantic Ocean and presented by Ochi, M.K. and S.L. Bales, entitled "Effect of Various Spectral Formulation in Predicting Responses of Marine Vehicles and Ocean Structures," paper No. OTC 2743, Offshore Tec. Conf. Houston, 1977

The results reveal that the deflection angles of the foils increase as:

I. the draft increases,

II. the forward speed decreases, and

III. the wave heading approaches beam direction.

The equivalent angles of deflection of the flaps of the foils should be about 2.5 times the deflection angles of the all-movable foils. This factor of 2.5 is based on a fully spanned flap of 0.2 flap having chord ratio of 0.2[7].

The vertical distance from the keel to the lowest point of the upper hull of HYSWAS-2000 is 10.9 m (33.1 ft). Thus, at the draft of 9.75 m the minimum upper hull clearance from the calm water surface is only 0.34 m. For the wave amplitudes far greater than this clearance, one can expect frequent water contacts on the bottom of the upper hull (see Table 6). However, the effects of these probable water contacts are not taken into account in the computation of the deflection angles of the foils. Also neglected in the computation is the wave-excited roll moment exerted on the upper hull when it plunges into waves. It is extremely difficult to include such effects in the linear analysis presently used.

One of the important criteria of assessing the seakeeping qualities of a HYSWAS is the frequency of water contacts of the bottom of the upper hull. Tables 4 through 6 and Figures 8 through 10 show these results.

The probable number of water contacts per hour on the upper hull at two stations for three different clearances from the calm-water level,

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[7] Hoerner, L.A. and H.V. Borst, "Fluid-Dynamic Lift," published by Mrs. L.A. Hoerner, 1975.

i.e., 3.05 m, 1.86 m and 1.1 m are presented, respectively, in Tables 4, 5 and 6. The stations chosen are; one at the longitudinal center of gravity and the other at 13.44 m aft of the nose of the lower hull where the knuckle of the upper hull begins. The results are given for the ship speeds of 21 (Table 6 only), 23 and 25 knots, for the wave headings from the bow-quartering and beam directions, and the sea conditions represented by Bretschneider's spectra formula with four different significant wave heights and corresponding most probable modal frequencies as shown in Table 3. The results are obtained under the assumption that the foils are locked at the positions which would maintain the ship in the even keel cruising in calm water.

One can observe from Tables 4 to 6 the following effects on the frequency of occurrence of water contacts:

1. Upper hull clearance - As one can easily infer from Equation (14), the number of water contacts is expected to decrease as the upper hull clearance increases. This expectation is well reflected in Tables 4 to 6. It is interesting to note that at the largest clearance (3.05 m) no water contact is made for the beam waves even for the significant wave height of 7.62 m. If we assume that the ship is held fixed in this wave condition, we can expect that there would be frequent water contacts since the significant wave amplitude ($\frac{7.62}{2} = 3.81$ m) is larger than the clearance. The fact that this is not the case implies that the ship is contouring with the waves well. As the clearance reduces to 1.86 m and to 1.1 m, the number of water contacts significantly increases, particularly for the larger wave heights. Those numbers in several hundreds should be interpreted as unrealistic since the foils would be activated to control the motion in these severe conditions.

2. Longitudinal location - For the bow-quartering waves, a greater number of water contacts is made at the bow than at the midship, whereas the phenomenon is slightly reversed for the beam waves.

3. Ship speed - For the bow-quartering waves, the number of water contacts slightly increases as the speed increases at both locations. For the beam waves, there is practically no change in the number of water contacts with respect to the ship speeds between 21 and 25 knots.

4. Wave heading - The number of water contacts is much greater in the bow-quartering waves than in the beam waves. The main reason for this phenomenon can be explained by comparing the densities of the sea spectra and the relative motion with respect to wave frequencies as shown in Figure 7. The sea spectrum shown is obtained by Bretschneider's formula with 3.05 m (10 ft) significant wave height and the modal frequency of 0.78 rad/sec. As can be inferred from Equation (14), the number of water contacts is directly related to the variances $E^{(R)}$ and $E_v^{(R)}$. The magnitudes of these variances are influenced by the relative disposition of the peaks of the curves. The closer the peaks are, the greater the magnitude is apt to be. For other significant wave heights, one can consult Table 3 to find the most probable modal frequencies of the sea spectra and compare with the modal frequencies of the relative motion curves. From these comparisons, one can find the reason for the greater number of water contacts in the bow-quartering waves.

Figures 8 through 10 present various effects on the number of water contacts on the upper hull. These effects are presented in the form of probable percentage of exceeding the given number of water contacts per hour by using the stratified sample of sea spectra obtained at Station India in the North Atlantic[8] together with the proper weighting factors for each sample obtained from the data compiled by Hogben and Lumb.[9] Figure 8 shows the effect of the upper hull clearance on the water contacts at the bow for $\beta = 90$ degrees and $U = 23$ knots. Similar trends apply for the other locations, wave headings, and speeds. Figure 9 shows the effect of the longitudinal location for $\beta = 135$ degrees, $U = 23$ knots and the upper hull clearance of 1.86m. Computed results show similar trends for other clearances and speeds at the same wave heading of $\beta = 135$ degrees; however, at $\beta = 90$ degrees there is no significant change in the number of water contacts with respect to the longitudinal location. Figure 10 shows the effect of wave heading at the bow location for $U = 25$ knots and the upper-hull clearance of 1.86 m. Similar trends apply to other speeds and clearances. The overall trends obtained by using the actually measured sea spectra are the same as those obtained by using Bretschneider's sea spectra.

[8] Miles, M., "Wave Spectra Estimated from a Stratified Sample of 323 North Atlantic Wave Records," National Research Council, Division of Mechanical Engineering Report LTR-SH-118, 1971.

[9] Hogben, N. and F.E. Lumb, "Ocean Wave Statistics," H.M. Stationary Office London, 1967.

SUMMARY AND CONCLUSION

An investigation on the feasibility of controlling the roll motion of HYSWAS-2000 by active foils is made in this report. The investigation was divided into two phases. The first phase was to compute the angles of deflection of the foils to counteract the wave-excited roll moments on the ship. The second phase was to compute the probable number of water contacts on the bottom of the upper hull induced by waves.

The deflection angles of the foils computed are the angles which would be necessary for the all-movable foils in addition to those required for maintaining the depth and trim in calm-water cruisings. The deflection angles are given in the root-mean-square values for given speed, draft, wave headings, and sea conditions. The results were obtained by assuming that the ship was restrained from moving except for the forward translating motion and that the wave forces on the upper hull do not contribute to the wave-excited roll moment. In the computation of the wave-induced lifting force on the foils, the effect of wave diffraction is neglected.

The deflection angles thus obtained are the root-mean-squares of the deflection amplitudes which would generate counteracting roll moments to the wave excitation. In practice, there is no device to directly measure the wave-excited roll moment on a ship; hence, the feed-back sensing device for the foil controls would not depend on the roll moment but rather on roll displacement or roll velocity (or both). Even if the foil controls are based on the roll moment as a sensing input, no control system can be designed to completely cancel the wave-excited roll moment. Furthermore, there is no need of cancelling the wave-excited roll moment completely to maintain a safe operation of a ship in waves.

Therefore, the RMS values of the foil angles presented in this report should be interpreted as a preliminary guideline to assess the feasibility of controlling the roll motion by active foils.

The probable number of water contacts on the bottom of the upper hull were obtained to assess gross seakeeping qualities of the ship. These numbers are closely related to the magnitudes of the relative vertical motion with respect to the wave surface. Since the relative vertical motion involves the heave, pitch, and roll motions, it is a good criterion of assessing the seakeeping qualities of a ship. The results were obtained under the assumption that the foils are inactive. Thus, the computed results would represent exaggerated conditions.

From the results obtained under the assumed conditions, the following conclusions are made:

1. It appears that there are no apparent critical conditions for controlling the roll motion of HYSWAS-2000 in moderate sea states.

2. The necessary foil deflection angles increase as:

   i. the draft increases,

   ii. the forward speed decreases, and

   iii. the wave heading approaches beam direction.

3. The probable number of water contacts on the upper-hull bottom increases as:

   i. the upper-hull clearance decreases,

   ii. the significant wave height increases,

iii. the wave heading deviates from the beam direction,

and

iv. the number of water contacts is greater at the bow than at the midship in the bow-quartering waves; whereas, in the beam waves, the number does not change much with respect to the longitudinal location.

4. If the avoidance of slamming on the upper-hull bottom is the major concern for the foil control, more frequent foil activation would be required for the wave headings other than the beam direction. However, the maximum foil deflections would be required in beam waves in severe sea states for the upper-hull clearance less than 3.05 m in (10 ft).

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TABLE 1

HULL AND FOIL GEOMETRIC CHARACTERISTICS OF HYSWAS-2000

HULL

Full Load Displacement	2,000	Long Tons
Design Buoyancy	1,400	Long Tons
Design Foil Lift	600	Long Tons
Lower Hull Length	78.3 m	(257 ft)
Lower Hull Maximum Diameter	4.6 m	(15.2 ft)
Strut Length	54.9 m	(180 ft)
Strut Maximum Thickness	2.2 m	(7.2 ft)
Hullborne Draft	11.4 m	(373 ft)
Foilborne Draft	7.3 m	(24 ft)
Tons per Foot Immersion	30	Long Tons
Upper Hull Length	70.1 m	(230 ft)
Upper Hull Maximum Beam	22.9 m	(75 ft)
Upper Hull Clearance from Foilborne Waterline	3.4 m	(11.3 ft) (At Chine)
Upper Hull Clearance from Foilborne Waterline	4.0 m	(13 ft) (At Strut Centerline)
Longitudinal Center of Buoyancy from the Nose of Lower Hull	37.5 m	(123 ft)
Vertical Center of Gravity from Keel	8.8 m	(29 ft)

FOILS

	Main	Aft
Semispan (not including hull)	10.8 m (35.5 ft)	5.0 m (16.4 ft)
Plane Form	Trapezoid	Trapezoid
Root Chord	4.7 m (15.4 ft)	3.4 m (11 ft)
Tip Chord	2.6 m (8.6 ft)	1.7 m (5.5 ft)
Thickness Ratio	0.1	0.1
Location of 1/4-Average Chord from Nose of Lower Hull	33.5 m (110 ft)	71.6 m (235 ft)

TABLE 2

RMS VALUES OF FOIL DEFLECTION ANGLES IN DEGREES

FOR VARIOUS CONDITIONS

Draft (m)	Speed (knot)	Wave* Heading	Sig. W. Ht. M. Foil	Foil Deflection Angle (deg.) 3 m A. Foil	3.5 m M.F.	3.5 m A.F.	4.6 m M.F.	4.6 m A.F.
9.8	18.5	B	9.4	3.0	10.8	3.4	13.5	4.3
		B-Q	3.1	1.0	4.0	1.3	6.2	1.9
	21.0	B	7.5	2.3	8.5	2.7	10.6	3.3
		B-Q	2.4	0.8	3.1	0.9	4.6	1.5
	23.0	B	6.3	2.0	7.1	2.2	8.9	2.8
		B-Q	1.9	0.6	2.5	0.8	3.8	1.2
9.0	21.0	B	6.7	2.1	7.5	2.4	9.3	2.9
		B-Q	2.2	0.7	2.7	1.0	4.2	1.4
	23.0	B	5.7	1.8	6.4	2.0	7.8	2.5
		B-Q	1.8	0.5	2.3	0.7	3.4	1.0
		S-Q	1.1	0.3	1.2	0.3	1.5	0.4
	25.0	B	4.8	1.5	5.5	1.8	6.8	2.1
		B-Q	1.5	0.5	1.9	0.6	1.9	0.9
		S-Q	0.9	0.3	1.0	0.3	1.3	0.4
8.2	23.0	B	5.1	1.6	5.7	1.8	6.9	2.2
		B-Q	1.7	0.6	2.1	0.6	3.1	1.0
		S-Q	1.0	0.3	1.1	0.4	1.5	0.4
	25.0	B	4.3	1.4	4.9	1.5	5.9	1.8
		B-Q	1.5	0.5	1.8	0.6	2.6	0.8
		S-Q	0.9	0.3	1.0	0.4	1.2	0.4
7.0	23.0	B	4.3	1.3	4.8	1.5	5.6	1.8
		B-Q	1.6	0.5	2.0	0.6	2.6	0.9
	25.0	B	3.8	1.2	4.2	1.3	4.8	1.5
		B-Q	1.4	0.4	1.6	0.5	2.3	0.7

* B = Beam
B-Q = Bow Quartering
S-Q = Stern Quartering

TABLE 3

MODAL FREQUENCIES (ω_m) IN RADIAN PER SEC. FOR VARIOUS

CONFIDENCE COEFFICIENTS

(Excerpt from Table 1 of Ref. [6])

		Significant wave height in feet (meters)					
		5.0 (1.52)	10.0 (3.05)	15.0 (4.57)	25.0 (7.62)	35.0 (10.67)	45.0 (13.72)
Lower ω_m	95%	0.73	0.58	0.49	0.38	0.32	0.28
	85%	0.79	0.63	0.52	0.41	0.34	0.30
	75%	0.83	0.66	0.54	0.43	0.36	0.32
	50%	0.87	0.69	0.58	0.45	0.38	0.33
Most probable		0.97	0.78	0.64	0.50	0.42	0.37
Upper ω_m	50%	1.05	0.83	0.69	0.54	0.45	0.39
	75%	1.11	0.88	0.74	0.57	0.47	0.41
	85%	1.15	0.92	0.76	0.59	0.49	0.43
	95%	1.24	1.00	0.82	0.63	0.52	0.46

TABLE 4

PROBABLE NUMBER OF WATER CONTACTS

PER HOUR ON UPPER HULL FOR CLEARANCE

OF 3.05 m (10 Ft)

Location	Speed knots	Heading deg.	Significant Wave Height meters			
			1.52	3.05	4.57	7.62
CG	23.0	135.0	0	0	3	40
Bow	23.0	135.0	0	0	15	88
CG	25.0	135.0	0	0	3	42
Bow	25.0	135.0	0	1	16	92
CG	23.0	90.0	0	0	0	0
CG	25.0	90.0	0	0	0	0
Bow	23.0	90.0	0	0	0	0
Bow	25.0	90.0	0	0	0	0

TABLE 5

PROBABLE NUMBER OF WATER

CONTACTS PER HOUR ON UPPER HULL FOR CLEARANCE

OF 1.86 m (6.1 Ft)

Location	Speed knots	Heading deg.	Significant Wave Height meters			
			1.52	3.05	4.57	7.62
CG	23.0	135.0	0	26	134	294
Bow	23.0	135.0	0	67	219	373
CG	25.0	135.0	0	27	140	305
Bow	25.0	135.0	0	70	229	388
CG	23.0	90.0	0	3	17	49
Bow	23.0	90.0	0	2	12	42
CG	25.0	90.0	0	3	16	46
Bow	25.0	90.0	0	2	12	40

TABLE 6

PROBABLE NUMBER OF WATER

CONTACTS PER HOUR ON UPPER HULL FOR CLEARANCE

OF 1.1 m (3.6 Ft)

Location	Speed knots	Heading deg.	Significant Wave Height meters			
			1.52	3.05	4.57	7.62
CG	21.0	135.0	11	318	493	568
Bow	21.0	135.0	26	406	556	598
CG	23.0	135.0	12	332	514	591
Bow	23.0	135.0	28	425	581	623
CG	25.0	135.0	13	346	536	615
Bow	25.0	135.0	29	444	605	648
CG	21.0	90.0	4	113	187	252
Bow	21.0	90.0	3	99	171	241
CG	23.0	90.0	5	116	192	257
Bow	23.0	90.0	3	102	176	245
CG	25.0	90.0	4	110	182	247
Bow	25.0	90.0	3	96	167	237

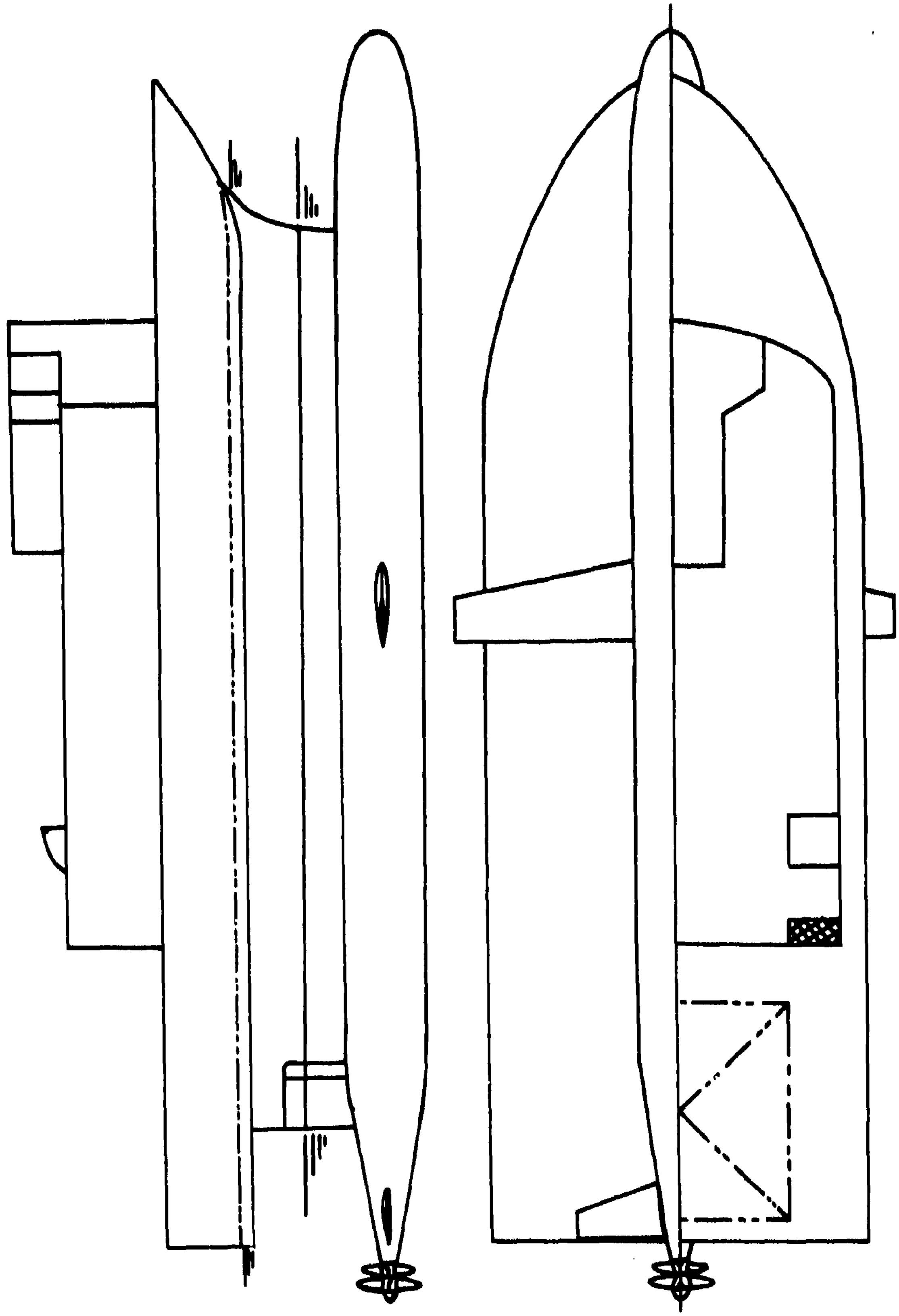

Figure 1 - Schematic View of a Hydrofoil Small Waterplane Area Ship (HYSWAS)

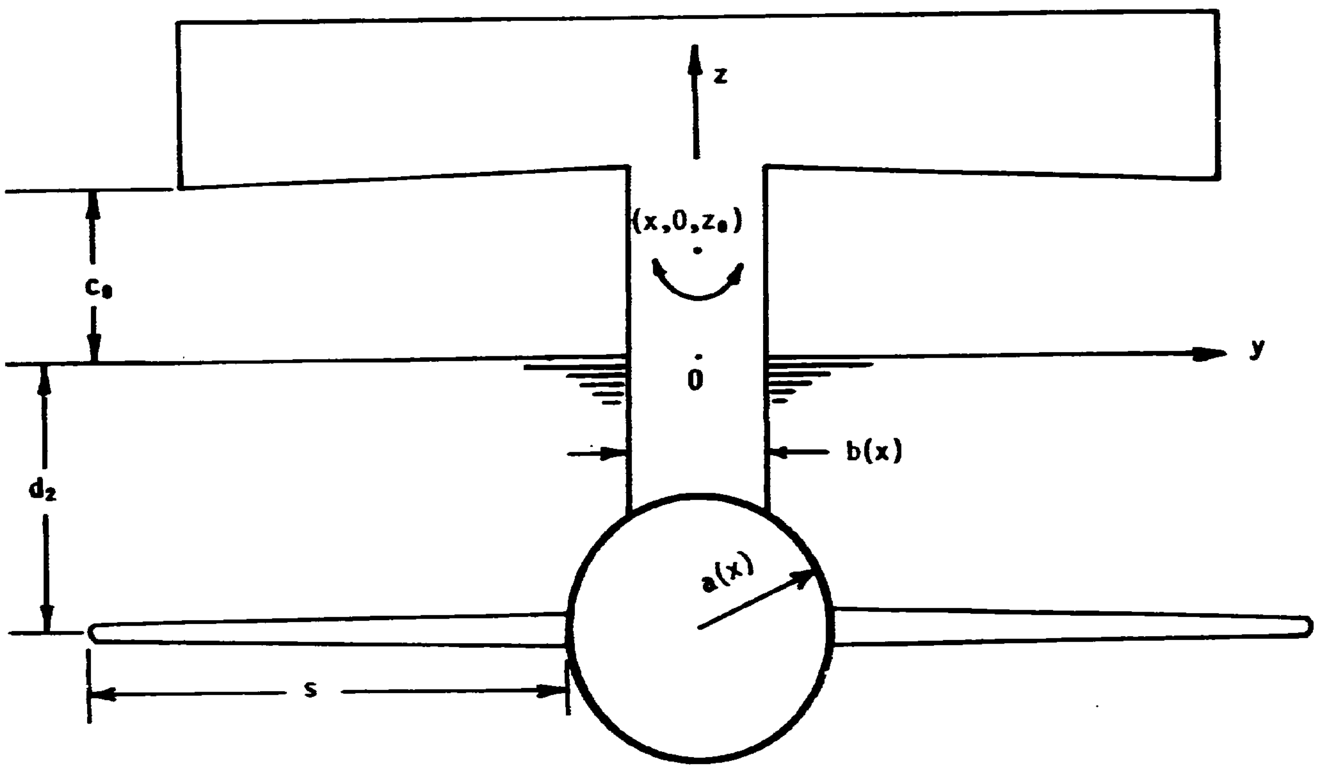

Figure 2 - Cross-Section View Looking Toward Stern at Main Foil Location

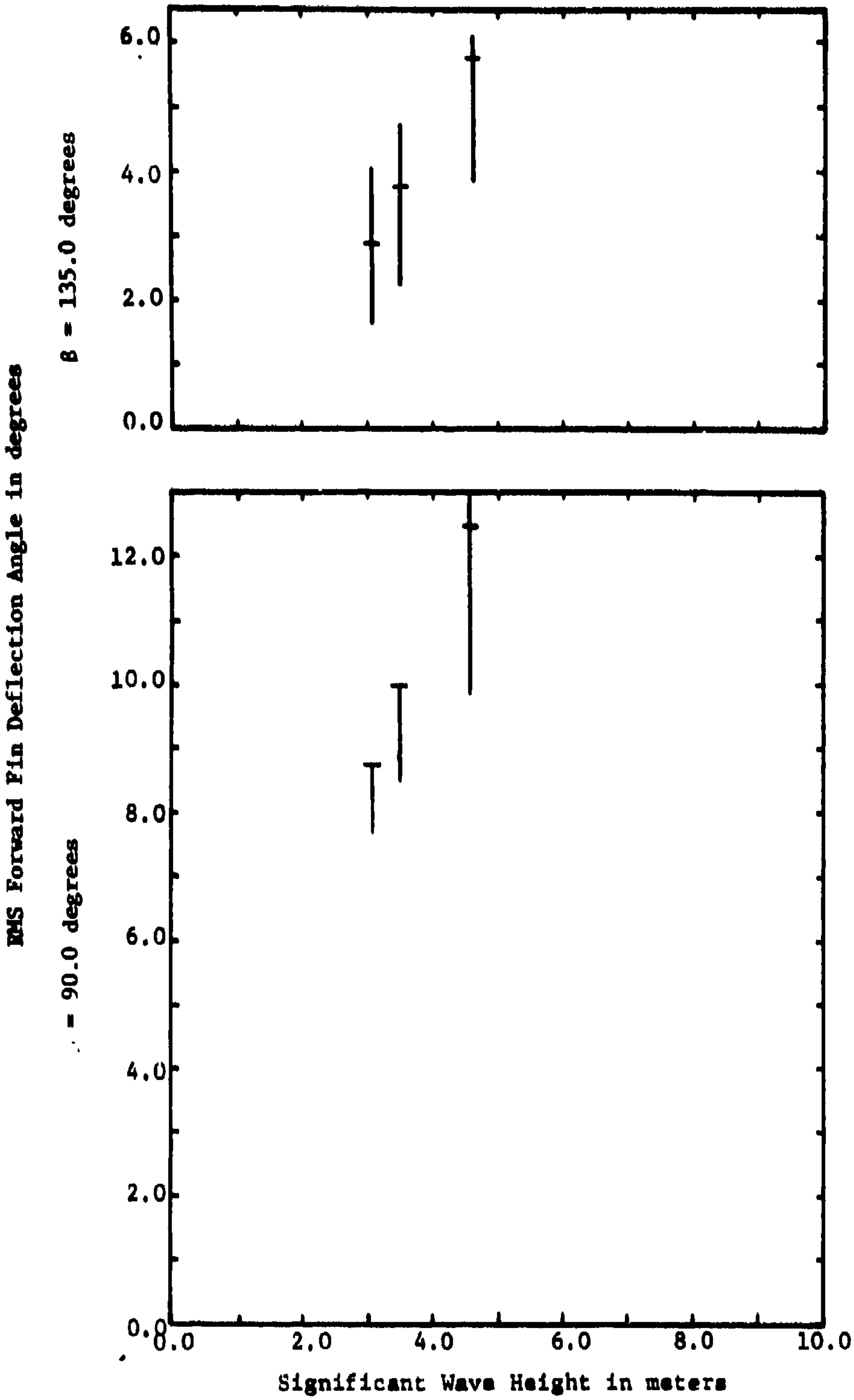

Figure 3 - RMS Values of Deflection Angles of All-Movable Main Foils at 18.5 knots and 9.75 m (32 ft) Draft

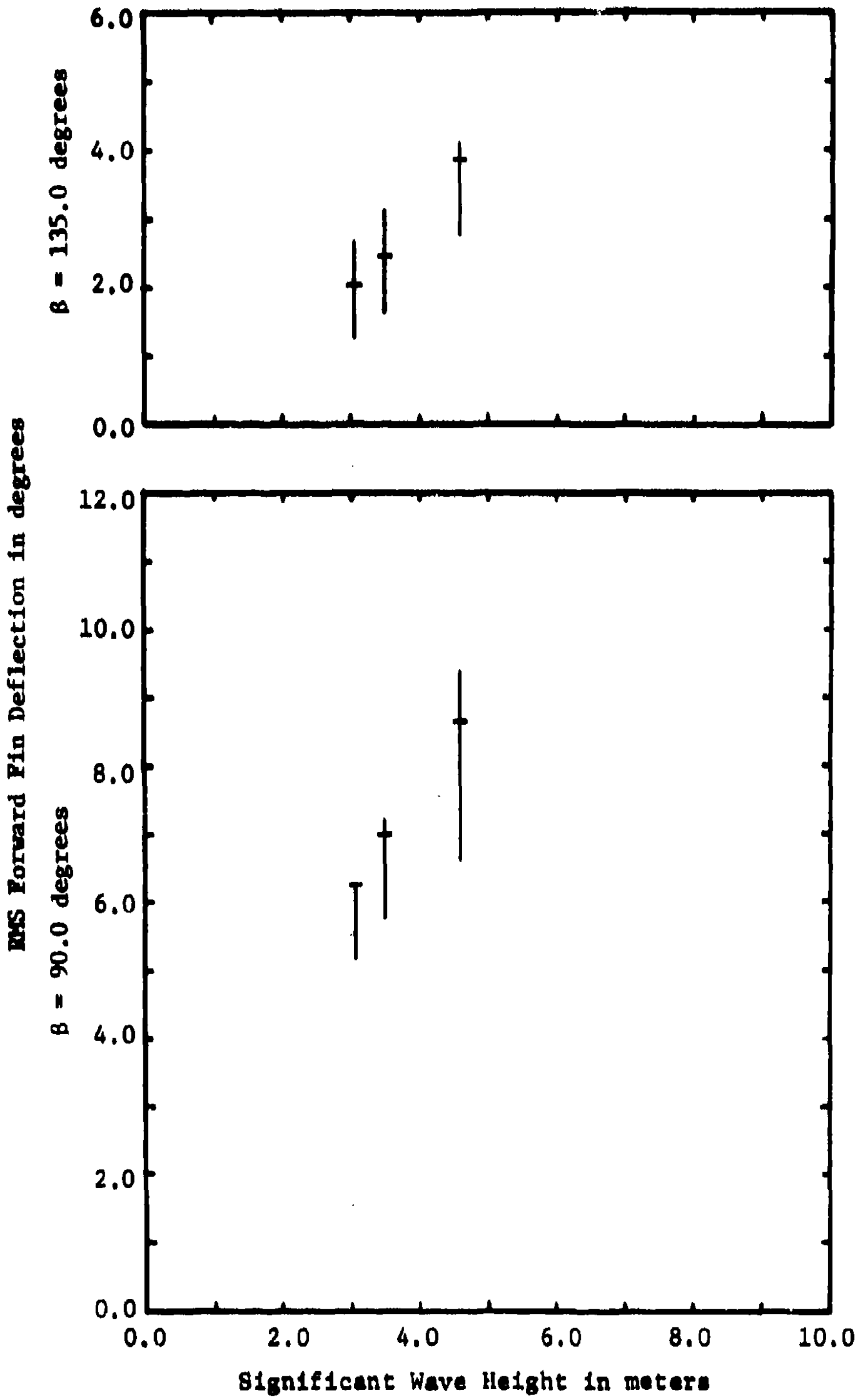

Figure 4 - RMS Values of Deflection Angles of All-Movable Main Foils at 21.0 knots and 9.0 m (29.5 ft) Draft

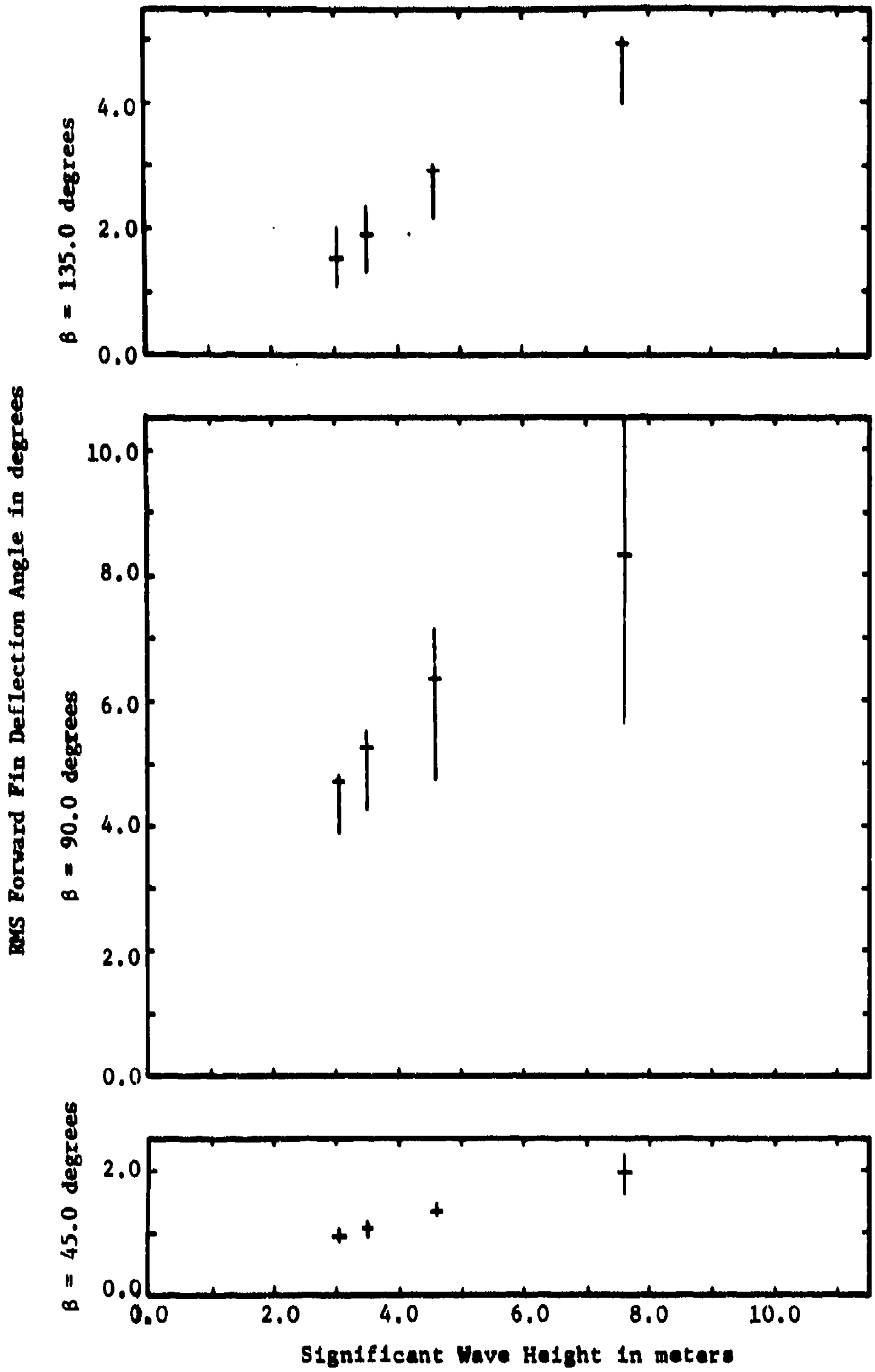

Figure 5 - RMS Values of Deflection Angles of All-Movable Main Foils at 23.0 knots and 8.23 m (27 ft) Draft

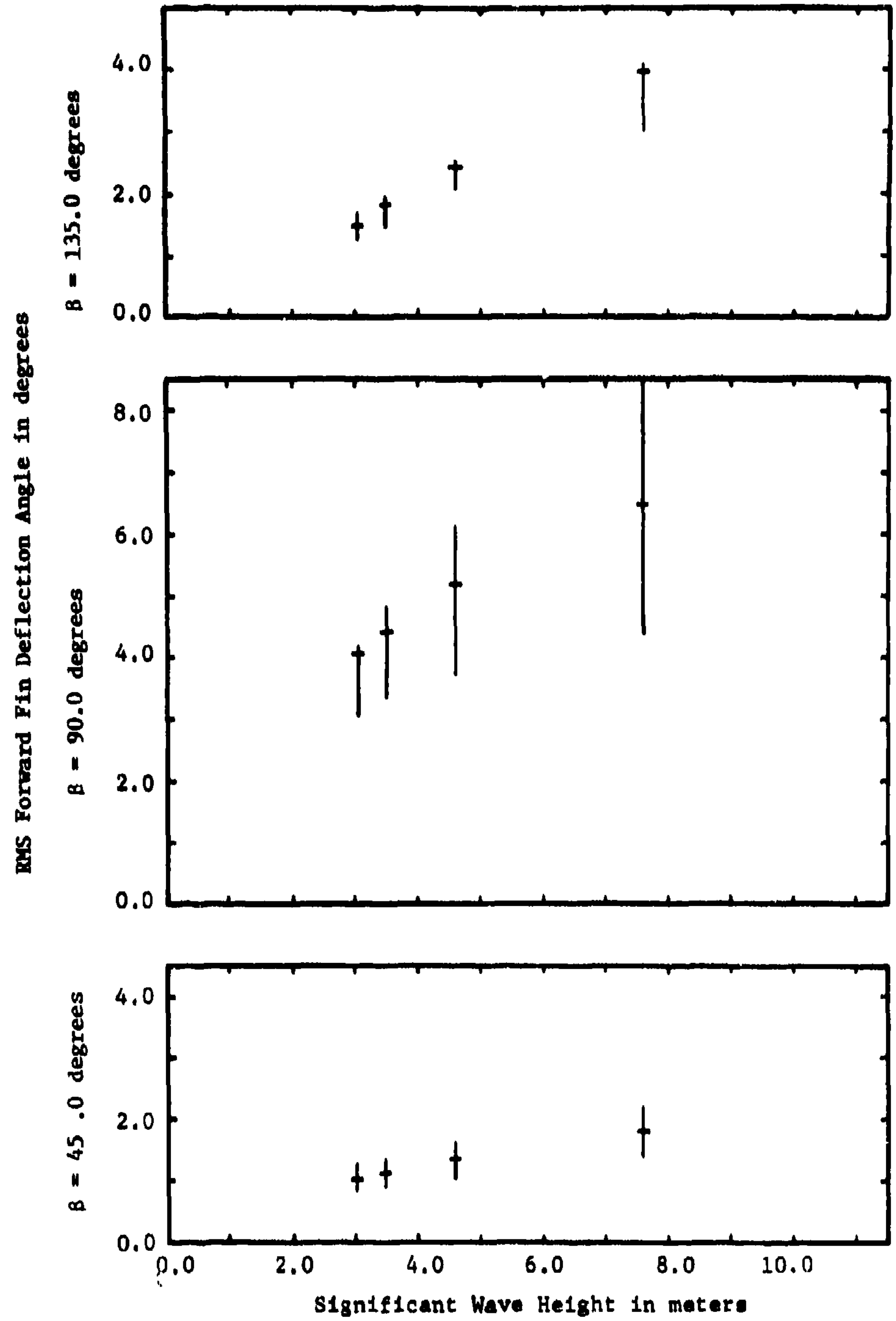

Figure 6 - RMS Values of Deflection Angles of All-Movable Main Foils at 23.0 knots and 7.04 m (23.1 ft) Draft

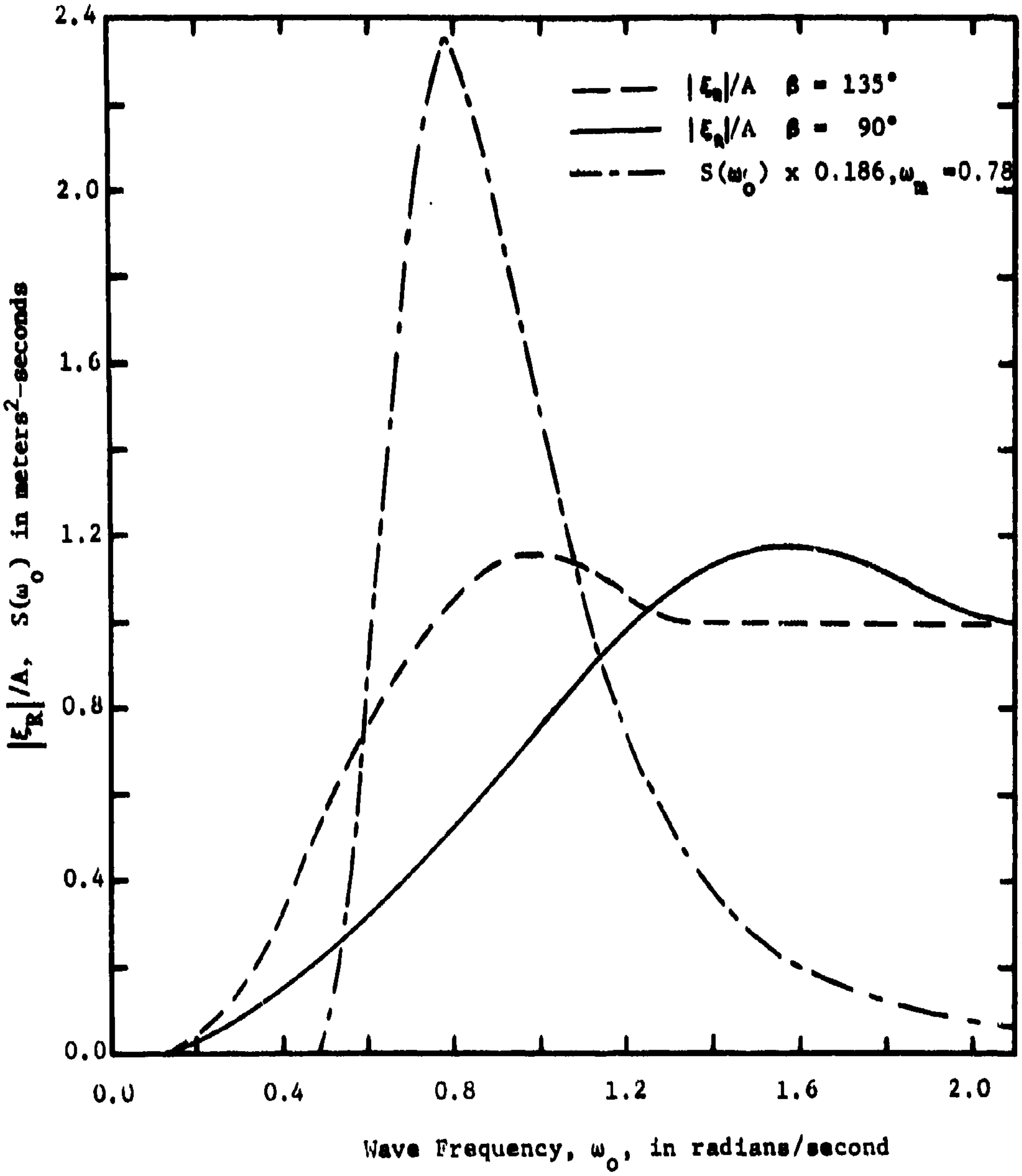

Figure 7 - Relative Motion Amplitudes at Bow for U = 23 knots and Sea Spectral Density (Modal Freq. = 0.78 rad/sec) versus Wave Frequency

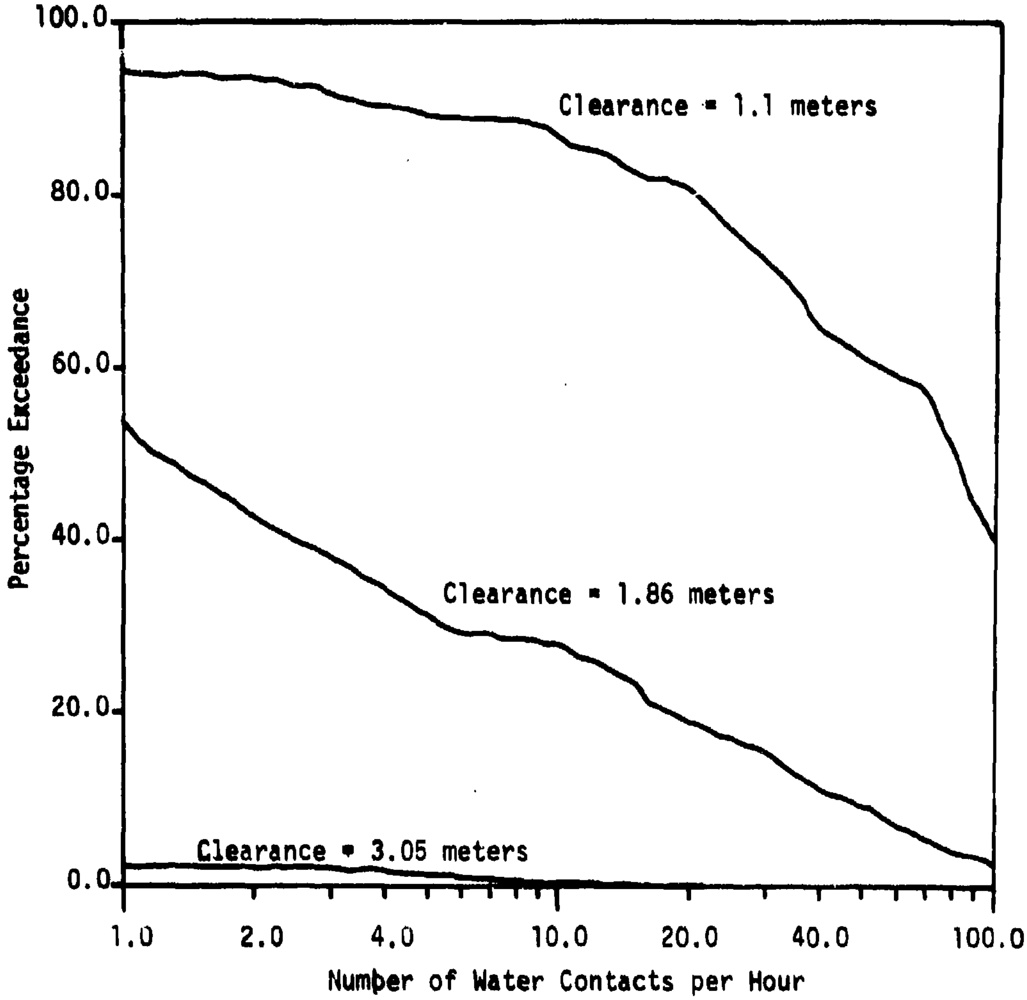

Figure 8 - Percentage Exceedance of Probable Number of Water Contacts per Hour in the North Atlantic Ocean for Various Upper-Hull Clearances at Bow for β = 90 degrees and U = 23 knots

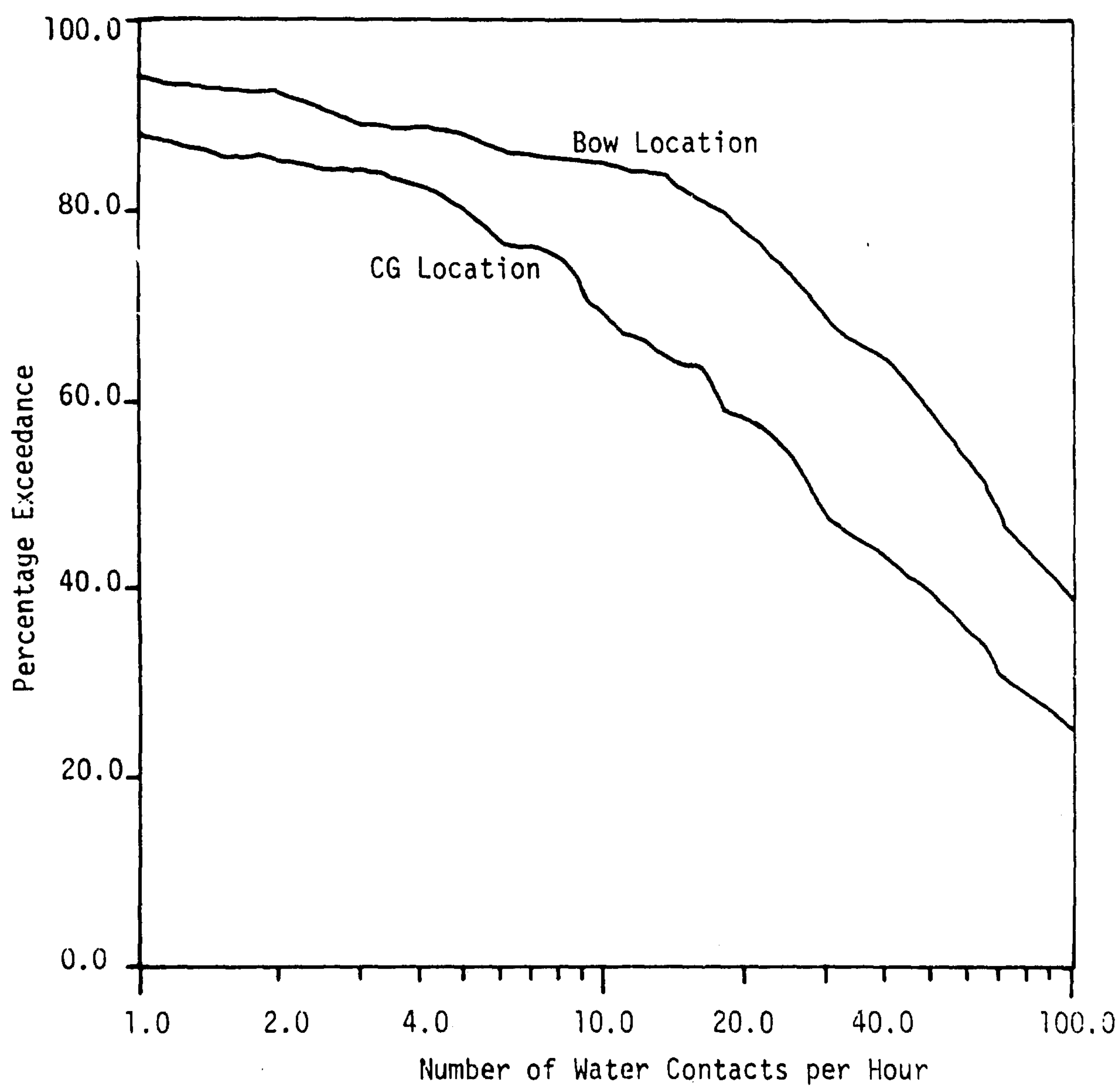

Figure 9 - Percentage Exceedance of Probable Number of Water Contacts per Hour in the North Atlantic Ocean for Various Longitudinal Locations of Ship for $\beta = 135$ degrees, $U = 23$ knots and $C_o = 1.86$ m

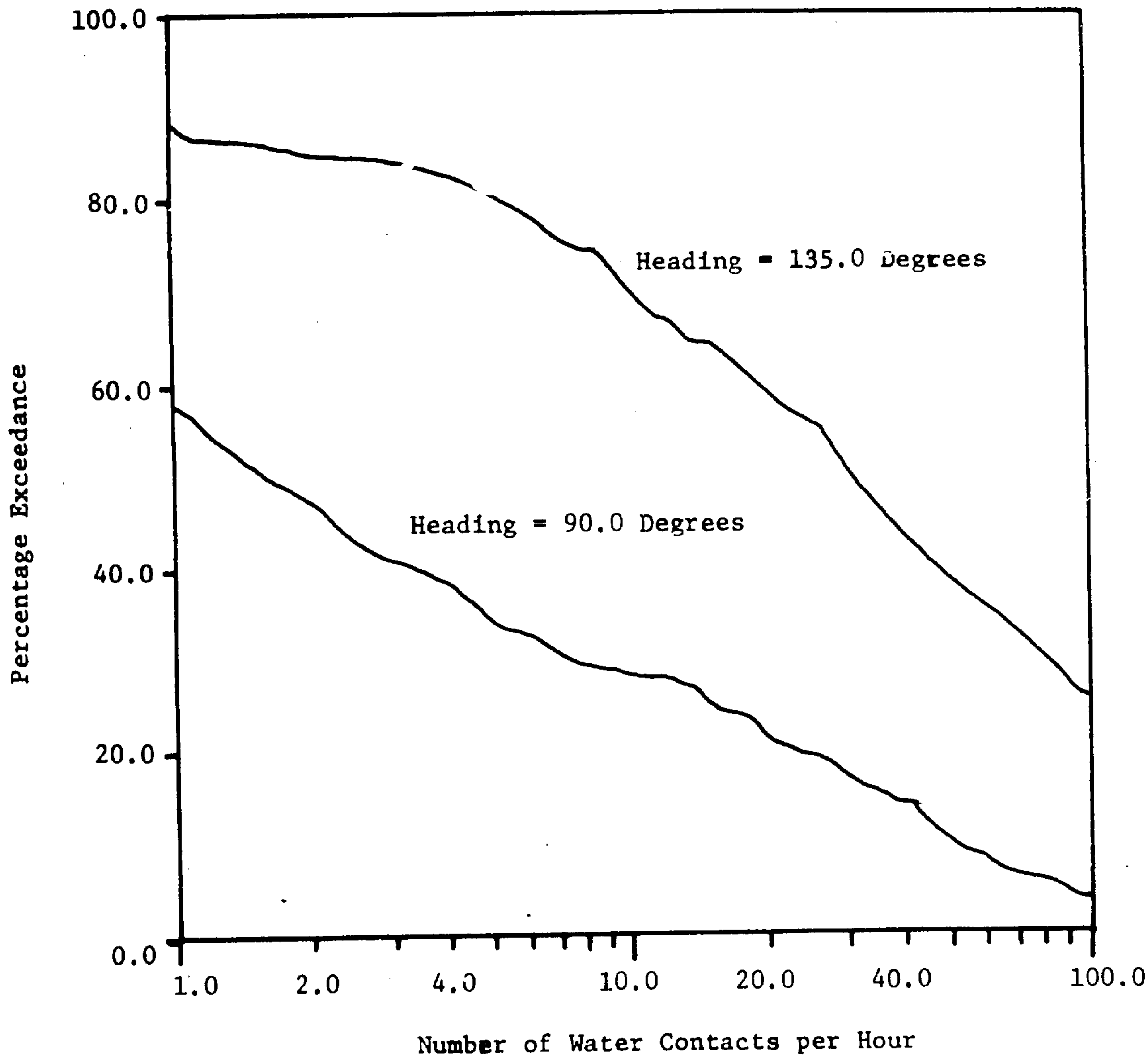

Figure 10 - Percentage Exceedance of Probable Number of Water Contacts per Hour in the North Atlantic Ocean for Various Wave Headings at Bow for U = 25 knots and C_o = 1.86 m

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