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Forward Speed Effects on the Sway, Roll, and Yaw Motion Coefficients

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ABSTRACT

The added mass and damping coefficients for sway, roll and yaw are formulated for a ship with forward speed. The theory is similar to that given by Ogilvie and Tuck (1969) for the heave and pitch coefficients of a slender ship. Numerical results are presented for the cross-coupling coefficients.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

A substantial amount of effort has gone into predicting the added mass and damping coefficients of an oscillating ship. Historically, a large part of this effort has been concentrated on the vertical plane motions of heave and pitch with some interest shown in the horizontal motion of roll. Korvin-Kroukovsksy and Jacobs (1957) emphasized the importance of coupling coefficients in the vertical plane motions, i.e. the pitch force due a heave motion and vice versa. Their method of calculating these coefficients was based on strip theory with some adjustments made to include forward speed and three-dimensional effects. However, their method for finding these "dynamic coupling" terms appears to be incomplete in that these terms do not satisfy the symmetry relations established by Timman and Newman (1962).

Salvesen, Tuck and Faltinsen (1970) applied a more consistant approach to the problem of ship motions and developed a theory for both the vertical and horizontal modes of motion. Their cross-coupling coefficients did satisfy the Timman-Newman (1962) relations and gave improved results when theory was compared with experiment.

Ogilvie and Tuck (1969) found the added mass and damping coefficients for heave and pitch by using a systematic application of matched asymptotic expansions. Their results satisfied the Timman-Newman (1962) symmetry relations but differed from the coefficients given by Salvesen, Tuck and Faltinsen (1970) in a number of ways. The Ogilvie-Tuck coefficients included a term which represented the integral of the square of the velocity potential evaluated on the free surface. They did not include a velocity-squared term which they considered to be of higher order. In an effort to determine the relative importance of the free surface integral terms, Faltinsen (1974) evaluated them and compared them with both experiments and the terms given by Salvesen, Tuck and Faltinsen. The results indicate that the Ogilvie-Tuck heave-pitch coupling coefficients are important and compare better with experiment than previous theories.

Timman and Newman (1962) included the horizontal motions in their symmetry relations. Specfically they reported that the cross-coupling terms between roll and yaw and yaw and sway were antisymmetric with respect to forward velocity. Inspection of the Salvesen, Tuck and Faltinsen coefficients show that they satisfy these conditions.

One motion coefficient in the horizontal plane that has received some attention is the roll damping coefficient. Typically the damping coefficient is composed of a velocity independent part, calculated from potential theory, and a correction factor used to account for viscous effects. In an effort to more clearly understand these various effects on roll motion, Sugai and Yamanouchi (1963) conducted a series of experiments using a self-propelled model with opposing gyroscopes to provide a rolling moment. One of the results of these experiments was the indication that rolling motion becomes more linear as forward speed is increased. In other words, the non-dimensional quantity of roll motion divided by roll exciting moment (multiplied by the appropriate constant to correct for the units) becomes less a function of the actual magnitude of the rolling moment. This implies that roll damping is speed dependent and that this dependency may be at least as important as the viscous damping. Watanabe (1977) applied the principle of thin ship theory to this problem and produced results that show a speed dependency on the roll damping coefficient. However, he did not conclusively state what effects a non-thin ship would have on his theory.

Using the same assumptions made by Ogilvie and Tuck (1969) for the vertical plane motions, we will consider in this paper the following two questions: First, will a consistant slender body theory produce roll damping coefficients that reduce roll motions as the speed of the ship increases? And second, will the theory produce numerically significant terms to the ones derived by Ogilvie and Tuck.

STATEMENT OF THE PROBLEM WITH RESULTS

EQUATIONS OF MOTION

Similar to that shown by Salvesen, Tuck and Faltinsen (1970), the coupled equations of motions for sway, roll, and yaw may be given as follows:

$$(A_{22}+M)\ddot{\eta}_2 + B_{22}\dot{\eta}_2 + (A_{24}-Mz_c)\ddot{\eta}_4 + B_{24}\dot{\eta}_4 + (A_{26}+x_cM)\ddot{\eta}_6 + B_{26}\dot{\eta}_6 = F_2e^{i\omega t} \tag{1}$$

$$(A_{42}-Mz_c)\ddot{\eta}_2 + B_{42}\dot{\eta}_2 + (A_{44}+I_4)\ddot{\eta}_4 + B_{44}\dot{\eta}_4 + C_{44}\eta_4 + (A_{46}-I_{46})\ddot{\eta}_6 + B_{46}\dot{\eta}_6 = F_4e^{i\omega t} \tag{2}$$

$$(A_{62}+x_cM)\ddot{\eta}_2 + B_{62}\dot{\eta}_2 + (A_{64}-I_{46})\ddot{\eta}_4 + B_{64}\dot{\eta}_4 + (A_{66}+I_6)\ddot{\eta}_6 + B_{66}\dot{\eta}_6 = F_6e^{i\omega t} \tag{3}$$

where

M is the mass of the ship

A_{jk}, B_{jk} are the added mass and damping coefficients respectively

I_j is the moment of inertia about the j-th axis

I_{jk} is the product of inertia

z_c is the vertical location of the center of gravity

$F_je^{i\omega t}$ is the force or moment in the j-th mode due to waves

C_{44} is the hydrostatic roll restoring moment

x_c is the longitudinal location of the center of gravity

ω is the frequency of encounter

η_j for j=2,4,6 is the sway, roll, and yaw displacement, respectively. (The dots denote time derivatives, i.e. $\ddot{\eta}_4$ is the roll acceleration.)

The coordinate system used is a right hand one with the origin located in the plane of the undisturbed free surface and the z axis passing through midship. See Figure 1 for definitions of positive sway, roll, and yaw.

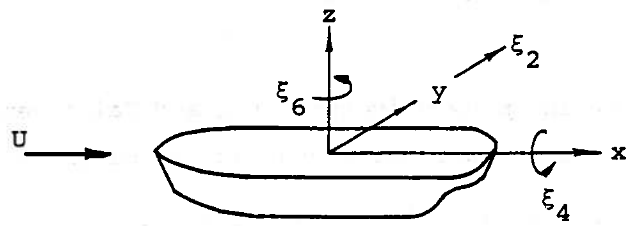

Figure 1 Coordinate System

Consider the coordinate system as fixed in an incident stream with velocity U flowing in the positive x direction and the ship swaying, rolling, and yawing about that system. We now desire to find the added mass and damping coefficients, A_{jk} and B_{jk}, for sway, roll, and yaw using assumptions similar to the ones used by Ogilvie and Tuck (1969).

If we define the motion of the ship in a two parameter expansion, ε, a slenderness parameter related to the beam to length ratio, and δ, a motion-amplitude parameter related to the smallness of motion, we can require that the motion be smaller than the beam of the ship even as $\varepsilon \to 0$. Specifically, assume that

displacements resulting from $\eta_j = O(\delta\varepsilon)$

where η_j is the motion in the j-th mode. Also assume that the frequency of encounter is of the following order:

$$\omega = O(\varepsilon^{-1/2}).$$

Then the velocity potential for the complete (linearized) solution can be represented as follows:

$$\phi(x,y,z,t) = Ux + U\chi(x,y,z) + \psi(x,y,z,t) \qquad (4)$$

where the first two terms give the solution of the steady-motion problem as shown by Tuck (1965) and the last term represents everything that must be added in order to satisfy the boundary conditions. We assume that $\psi(x,y,z,t)$ has a time dependence of $e^{i\omega t}$ and the velocity U is of order one.

As shown by Ogilvie and Tuck (1969), we may put equation (4) into the governing equations describing the boundary value problem of the oscillating ship. We next linearize the problem with respect to the amplitude motion, but keep higher order terms of the slenderness parameter expansion. The time-dependent part of the potential then is found to satisfy the following equations:

$$\psi_{yy} + \psi_{zz} \tilde{=} 0 \quad \text{in the fluid domain,} \tag{5}$$

$$-\omega^2\psi + g\psi_z \tilde{=} -i\omega U(2\psi_x + 2\chi_y\psi_y + \chi_{yy}\psi) \quad \text{on} \quad z=0, \tag{6}$$

and on the hull

$$\begin{aligned} \frac{\partial\psi}{\partial n} \tilde{=}\ & i\omega n_2(\eta_2 + x\eta_6) + i\omega\eta_4(yn_3 - zn_2) + Un_2\eta_6 \\ & -U(\eta_2 + x\eta_6)(n_2\chi_{yy} + n_3\chi_{yz}) + U\eta_4\Big[(n_3\chi_y - n_2\chi_z) \\ & + z(n_2\chi_{yy} + n_3\chi_{yz}) - y(n_2\chi_{yz} + n_3\chi_{zz})\Big] \end{aligned} \tag{7}$$

where n is the unit normal directed out of the fluid, n_2 and n_3 are the components of the unit normal in the y and z direction respectively and varibles subscripted with y and/or z denote partial differentiation with respect to that coordinate.

The form of the above equations (5) - (7) can only be correct if the formal rules of matched asymptotic expansions are followed. In other words, the far field expansion of the $\psi(x,y,z,t)$ potential must match, to an appropriate order, an inner expansion of a potential representing a line of pulsating sources and dipoles. To show that this is indeed the case, we could use a method similar to that used by Troesch (1975), where he applied the theory of Fourier Transforms or use the method of complex variables as shown by Ogilvie (1974). In both cases, the authors were solving anti symmetric problems, which are applicable to the sway, roll, and yaw potential discussed in this paper.

A solution for the complete $\psi(x,y,z,t)$ problem can now be given in much the same manner as shown by Troesch (1975) for the case of an anti symmetric pressure distribution on the free surface. The actual solution is fairly complex and it is not necessary to repeat it here. Rather, we note that since a solution exists, we may find the pressure from Bernoulli's equation and subsequently the hydrodynamic force acting on an oscillating ship. The details are given in the appendix.

ADDED MASS AND DAMPING COEFFICIENTS

Following Ogilvie and Tuck (1969), the generalized hydrodynamic force,

F_j , may be related to the added mass and damping coefficients in the following manner

$$F_j(t) = \sum_k \left[\omega^2 A_{jk} - i\omega B_{jk}\right]\eta_k(t) \equiv \sum_k \left[T_{jk}^{(0)} + T_{jk}^{(1)} + T_{jk}^{(2)}\right]\eta_k(t)$$

where the superscript (0) denotes the usual zero speed strip theory terms. The velocity dependent terms, which are of higher order are found in $T^{(1)}$ and $T^{(2)}$. These coefficients can then be given in terms of the steady motion potential, χ , and the usual zero speed forced oscillation potential, ϕ_j , defined in the following manner:

$$\phi_{j_{yy}} + \phi_{j_{zz}} = 0 \quad \text{in the fluid domain}$$

$$\frac{\partial \phi_j}{\partial N} = N_j \ , \ j = 2,4,6, \quad \text{on the hull}$$

$$-\omega^2 \phi_j + g\phi_{j_z} = 0 \quad \text{on } z = 0$$

and

$$\phi_j \rightarrow \pm A_j e^{-i\nu|y|} \quad \text{as} \quad y \rightarrow \pm\infty$$

where N is now the two dimensional normal in the y-z plane and N_j is given as follows:

$$N_2 = n_2$$

$$N_4 = n_3 y - n_2 z$$

$$N_6 = x n_2$$

The complete expressions for the complex factors T_{jk} are given in the Appendix. If we make two assumptions, we can simplify the expressions for $T_{24}^{(1)}$, $T_{24}^{(2)}$, $T_{46}^{(1)}$, and $T_{46}^{(2)}$ considerably. First assume that the ship is symmetrical. (For a symmetrical ship the half-beam at the waterline, $y_0(x)$, is an even function with respect to x and the y and z derivatives of the steady motion potential, $\chi(x,y,z)$, are odd functions with respect to x .) Next assume that the ship in question has long sections of parallel mid-body, that is, long relative to its end section. (This has the effect of making the end contributions to $T_{jk}^{(1)}$ and $T_{jk}^{(2)}$ higher order than the mid-body contributions.) The complete factors T_{jk} may then be written in the following manner:

$$T_{22}^{(0)} = -\rho(i\omega)^2 \int_L dx \int_{C(x)} d\ell\, n_2\phi_2 \equiv \int_L dx\, t_{22}^{(0)}$$

$$T_{44}^{(0)} = -\rho(i\omega)^2 \int_L dx \int_{C(x)} d\ell(n_3y - n_2z)\phi_4$$

$$T_{66}^{(0)} = \int_L dx\, x^2 \quad t_{22}^{(0)}$$

$$T_{24}^{(0)} = T_{42}^{(0)} = -\rho(i\omega)^2 \int_L dx \int_{C(x)} d\ell\, n_2\phi_4$$

$$T_{26}^{(0)} = T_{62}^{(0)} = \int_L dx\, x \quad t_{22}^{(0)}$$

$$T_{46}^{(0)} = T_{64}^{(0)} = -\rho(i\omega)^2 \int_L dx\, x \int_{C(x)} d\ell\, n_2\phi_4$$

$$T_{jj}^{(1)} = 0 \ , \ j = 2,4,6$$

$$T_{26}^{(1)} = -T_{62}^{(1)} = \frac{U}{i\omega} T_{22}^{(0)}$$

$$T_{24}^{(1)} = T_{42}^{(1)} = 0$$

$$T_{64}^{(1)} = -T_{46}^{(1)} = \frac{U}{i\omega} T_{42}^{(0)}$$

$$T_{jj}^{(2)} = 0 \ , \ j = 2,4,6$$

$$T_{24}^{(2)} = T_{42}^{(2)} = 0$$

$$T_{26}^{(2)} = -T_{62}^{(2)} = \rho(i\omega)^3 \frac{2U}{g} \int_L dx \Big[\int_{y_0}^{\infty} dy(\phi_2^2 - A_2^2 e^{-2i\nu y}) - \frac{i}{2\nu} A_2^2\, e^{-2i\nu y_0} \Big]$$

and

$$T_{46}^{(2)} = -T_{64}^{(2)} = \rho(i\omega)^3 \frac{2U}{g} \int_L dx \Big[\int_{y_0}^{\infty} dy(\phi_2\phi_4 - A_2A_4 e^{-2i\nu y} - \frac{i}{2\nu} A_2A_4 e^{-2i\nu y_0} \Big]$$

where

ρ is the water density

$C(x)$ is the hull contour at station x

L is the ship length

ν is the wave number found from $\omega^2 = \nu g$

g is the gravitational constant

$y_0(x)$ is the half-beam at station x

and

$A_j e^{-i\nu y}$ is the behavior of ϕ_j as $y \to \infty$.

The added mass and damping coefficients are then given by the relations

$$A_{jk} = \frac{1}{\omega^2} Re \{T_{jk}^{(0)} + T_{jk}^{(1)} + T_{jk}^{(2)}\} \tag{8}$$

and

$$B_{jk} = \frac{-1}{\omega} Im \{T_{jk}^{(0)} + T_{jk}^{(1)} + T_{jk}^{(2)}\} \tag{9}$$

where *Re* and *Im* denote the real and imaginary parts of the complex expression respectively.

Before we compare these coefficients with those derived by Salvesen, Tuck and Faltinsen (1970), write $T_{26}^{(2)}$ and $T_{46}^{(2)}$ following a notation established by Ogilvie and Tuck (1969) and used by Faltinsen (1974). Let

$$\rho(i\omega)^3 \frac{2U}{g} ⨍_F ds\ \Phi_2^2 \equiv T_{26}^{(2)}$$

and

$$\rho(i\omega)^3 \frac{2U}{g} ⨍_F ds\ \Phi_2 \Phi_4 \equiv T_{46}^{(2)}$$

where a bar has been drawn through the integral sign to indicate that the integral does not really exist as written, and F denotes that the limits of integration extend on the free surface from the body to infinity.

The added mass and damping coefficients derived by the two different methods are given in Table 1. The ship is assumed to be pointed at both ends so that the end terms given in the Salvesen, Tuck, and Faltinsen (1970) coefficients do not appear. Also a_{jk} and b_{jk} represent the usual two dimensional sectional added mass and damping coefficients.

NUMERICAL RESULTS

Recall that we are addressing ourselves to two questions. First, will this theory show a speed dependence for the roll damping coefficient and, second, are the extra terms, $T_{jk}^{(2)}$, numerically significant? In order to answer the first question, set F_2 in equation (1) and F_6 in equation (3) equal to zero and let F_4 in equation (2) be some constant. This corresponds to the experiments described by Sugai and Yamanouchi (1963) where they applied a pure roll moment to a moving model. A computer program was written that solved equation (1) - (3) using the added mass and damping coefficients given in equations (8) and (9). The hull offsets used were from a Series 60, $C_B = .70$ hull and the model was assumed to have the following additional characteristics:

$$z_c \cong -0.2d$$

$$I_4 \cong M\left[(0.397B)^2 + (z_c)^2\right]$$

$$C_{44} = MgGM$$

$$GM \cong -z_c$$

$$I_6 \cong M(0.25L)^2$$

$$I_{46} \cong 0.0$$

where d is the draft of the ship, B is the beam, and L is the length.

The computer program that calculated the horizontal plane coefficients also returned the ones for the vertical plane, i.e., the Ogilvie-Tuck added mass and damping coefficients for heave and pitch. The Series 60 hull form was selected in order to compare the results returned for heave and pitch with those reported by Faltinsen (1974). (The comparison was satisfactory.) While the hull form selected is not truly symmetrical and does not have large sections of parallel mid-body, it should satisfy the conditions of symmetry and relatively constant cross sections to a sufficient degree to answer the two questions posed in the Introduction.

The method used for evaluating the free surface integrals is described in the Appendix. The results of the forced rolling tests for three different Froude numbers (F_n = .15,.20,.30) are shown in Figures 2,3, and 4. Inspection of Table 1 shows that B_{44} is independent of speed. Therefore, the only way that the roll motion at resonance will be influenced by speed is through

Table 1 Comparison of Added Mass and Damping Coefficients

Coefficient	Salvesen, Tuck and Faltinsen (1970) (1)	As given by the theory in this paper
A_{22}	$\int a_{22} d\xi$	$\int a_{22} d\xi$
B_{22}	$\int b_{22} d\xi$	$\int b_{22} d\xi$
A_{44}	$\int a_{44} d\xi$	$\int a_{44} d\xi$
B_{44}	$\int b_{44} d\xi + B^*_{44}$ (2)	$\int b_{44} d\xi$
A_{66}	$\int \xi^2 a_{22} d\xi + A_{22} U^2/\omega^2$	$\int \xi^2 a_{22} d\xi$
B_{66}	$\int \xi^2 b_{22} d\xi + B_{22} U^2/\omega^2$	$\int \xi^2 b_{22} d\xi$
A_{24}	$\int a_{24} d\xi$	$\int a_{24} d\xi$
B_{24}	$\int b_{24} d\xi$	$\int b_{24} d\xi$
A_{42}	$\int a_{24} d\xi$	$\int a_{24} d\xi$
B_{42}	$\int b_{24} d\xi$	$\int b_{24} d\xi$
A_{26}	$\int \xi a_{22} d\xi - B_{22} U/\omega^2$	$\int \xi a_{22} d\xi - B_{22} U/\omega^2 + Im\left[(\rho\omega 2U/g) \int_F ds \Phi_2^2\right]$
B_{26}	$\int \xi b_{22} d\xi + A_{22} U$	$\int \xi b_{22} d\xi + A_{22} U + Re\left[(\rho\omega^2 2U/g) \int_F ds \Phi_2^2\right]$

Table 1 (cont.)

Coefficient	Salvesen, Tuck and Faltinsen (1970) [1]	As given by the theory in this paper
A_{62}	$\int \xi a_{22} d\xi + B_{22} U/\omega^2$	$\int \xi a_{22} d\xi + B_{22} U/\omega^2 - Im\left[(\rho\omega 2U/g) \int_F ds\Phi_2^2\right]$
B_{62}	$\int \xi b_{22} d\xi - A_{22} U$	$\int \xi b_{22} d\xi - A_{22} U - Re\left[(\rho\omega^2 2U/g) \int_F ds\Phi_2^2\right]$
A_{46}	$\int \xi a_{24} d\xi - B_{24} U/\omega^2$	$\int \xi a_{24} d\xi - B_{24} U/\omega^2 + Im\left[(\rho\omega 2U/g) \int_F ds\Phi_4\Phi_2\right]$
B_{46}	$\int \xi b_{24} d\xi + A_{24} U$	$\int \xi b_{24} d\xi + A_{24} U + Re\left[(\rho\omega^2 2U/g) \int_F ds\Phi_4\Phi_2\right]$
A_{64}	$\int \xi a_{24} d\xi + B_{24} U/\omega^2$	$\int \xi a_{24} d\xi + B_{24} U/\omega^2 - Im\left[(\rho\omega 2U/g) \int_F ds\Phi_4\Phi_2\right]$
B_{64}	$\int \xi b_{24} d\xi - A_{24} U$	$\int \xi b_{24} d\xi - A_{24} U - Re\left[(\rho\omega^2 2U/g) \int_F ds\Phi_4\Phi_2\right]$

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(1) The end effects in the Salvesen, Tuck and Faltinsen (1970) theory were dropped.

(2) B_{44}^* is a quasi-linear viscous-damping coefficient. Viscous effects are ignored in the theory presented in this paper.

the coupling between roll and sway and roll and yaw. Figure 3 indicates that this effect is negligible. Only the motion of yaw, in Figure 4, shows any speed effects. We can conclude that slender body theory, as derived in this paper, will not show an increase in the roll damping coefficient as forward speed increases. This result can be contrasted with the results given by Watanabe (1977) where an application of thin-ship theory did produce larger roll damping coefficients as the forward speed increased. It should be noted, however, that the theory of that paper included a trailing vortex sheet and consequently differed fundamentally from the theory presented here. In a recent paper by Ikeda, Himeno and Tanaka (1978), it is suggested that the "wave damping component" of a moving, rolling ship is, to a large extent, independent of speed for values of τ greater than 0.5. Here τ equals $U\omega/g$. The "wave damping component" corresponds to the damping coefficient B_{44} presented in this paper. Our assumptions make $\tau=O(\varepsilon^{-1/2})$, which represents high speed and/or high frequency of rolling. Thus it appears that B_{44} is consistant with the results presented by Ikeda, et.al. (1978).

To demonstrate the difference between the added mass and damping coefficients as derived by the theory presented in this paper and those coefficients derived by Salvesen, Tuck and Faltinsen (1970), Figures 5 through 8 are presented. The coupled sway-yaw added mass and damping coefficients are non-dimensionalized by $\rho\forall L$ and $\rho\forall L\sqrt{g/L}$ respectively. Here $\forall$ is the volume displacement of the ship. The coupled roll-yaw added mass and damping coefficients are non-dimensionalized by $\rho\forall L^2$ and $\rho\forall L^2\sqrt{g/L}$ respectively. They are all plotted as functions of $\omega\sqrt{L/g}$. The results are shown for a $F_n=0.2$ only. Froude numbers of 0.15 and 0.30 showed similar tendencies. From the figures, it is clear that there are some differences. Figure 5 which shows the added mass coupling coefficient A_{62} of sway into yaw also has included results of experiments conducted by Vugts (1970). The experiments were forced motion tests on a 10 foot segmented model. The sectional added mass components were added to give the results shown in the figure. The comparison between theory and experiment, at least for the coefficient of A_{62} , seems reasonable. (Recall that the expressions A_{62} and B_{62} are unaffected by the antisymmetry and constant mid body assumptions. Consequently, they should be more applicable to ship shapes than any of the coefficients resulting from a coupling with roll.)

In Figures 9 and 10, the ratios of $T_{jk}^{(2)}$ to $T_{jk}^{(1)}$ are plotted as functions of $\omega\sqrt{L/g}$. These ratios are speed independent since both $T_{jk}^{(2)}$ and $T_{jk}^{(1)}$ vary linearly with velocity. From Table 1, it is clear that the real part of $T_{jk}^{(1)}$ corresponds to the velocity dependent part of the Salvesen, Tuck and Faltinsen added mass and the imaginary part of $T_{jk}^{(1)}$ corresponds to the velocity dependent part of their damping coefficient. Since $T_{jk}^{(2)}$ represents the free surface integrals, we can see from these plots the relative importance of these terms to the usual forward speed terms as given by Salvesen, Tuck, and Faltinsen (1970). For some frequency ranges, $T_{ij}^{(2)}$, the free surface integral, is equal to or larger than the usual forward speed term.

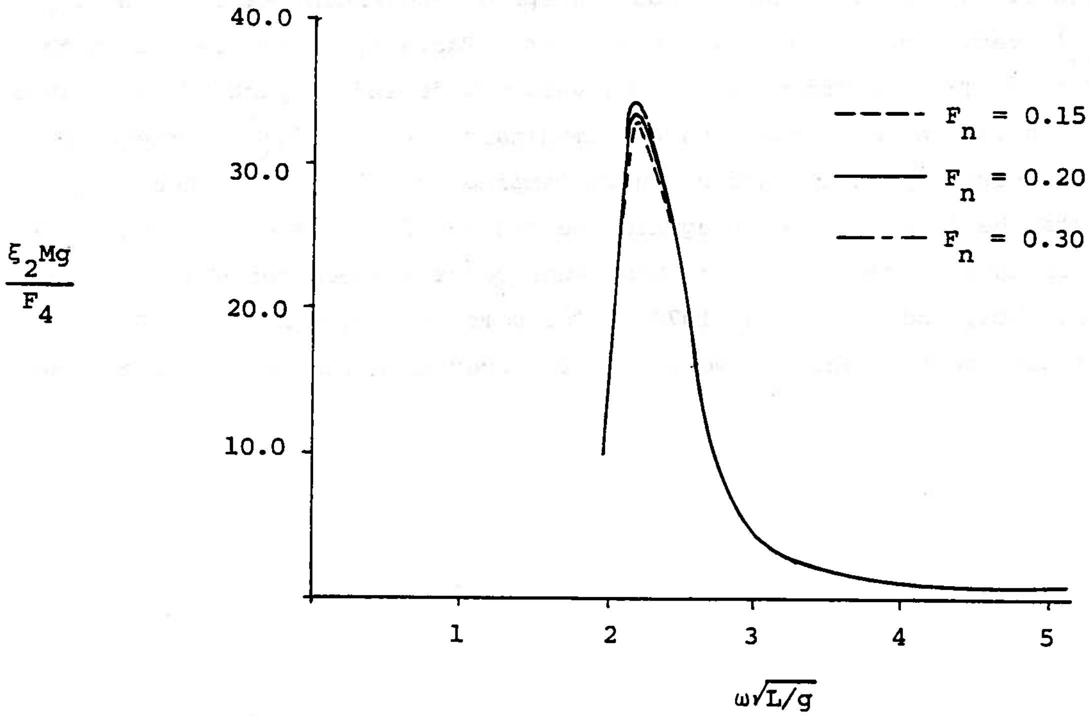

Figure 2 Sway response to unit roll moment

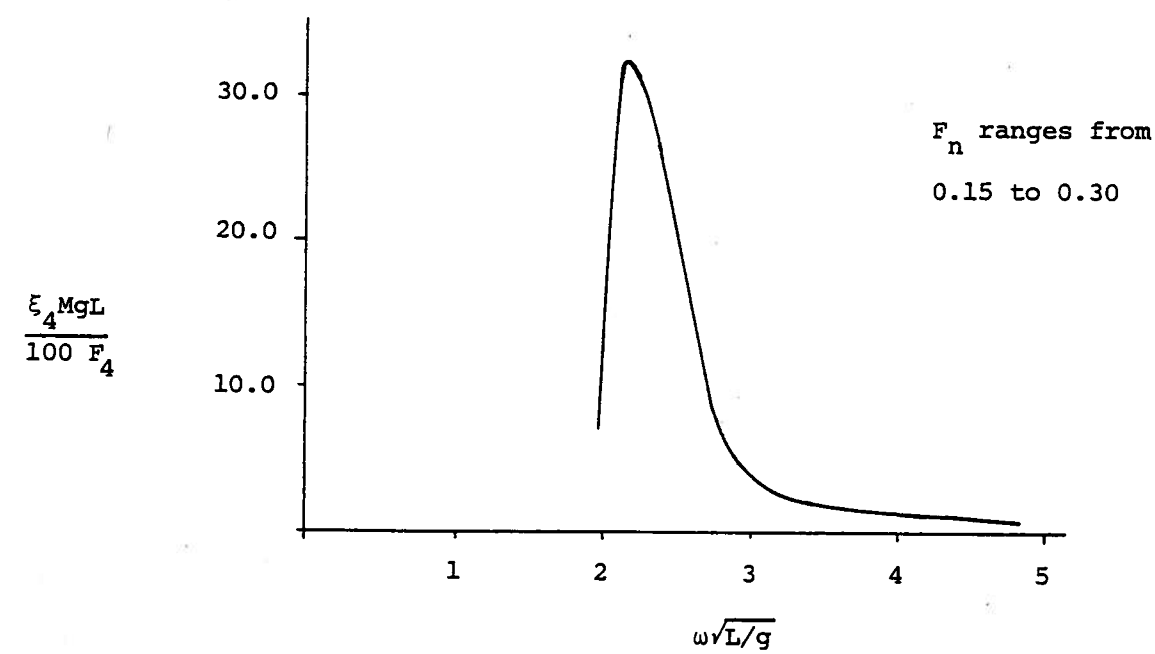

Figure 3 Roll response to unit roll moment

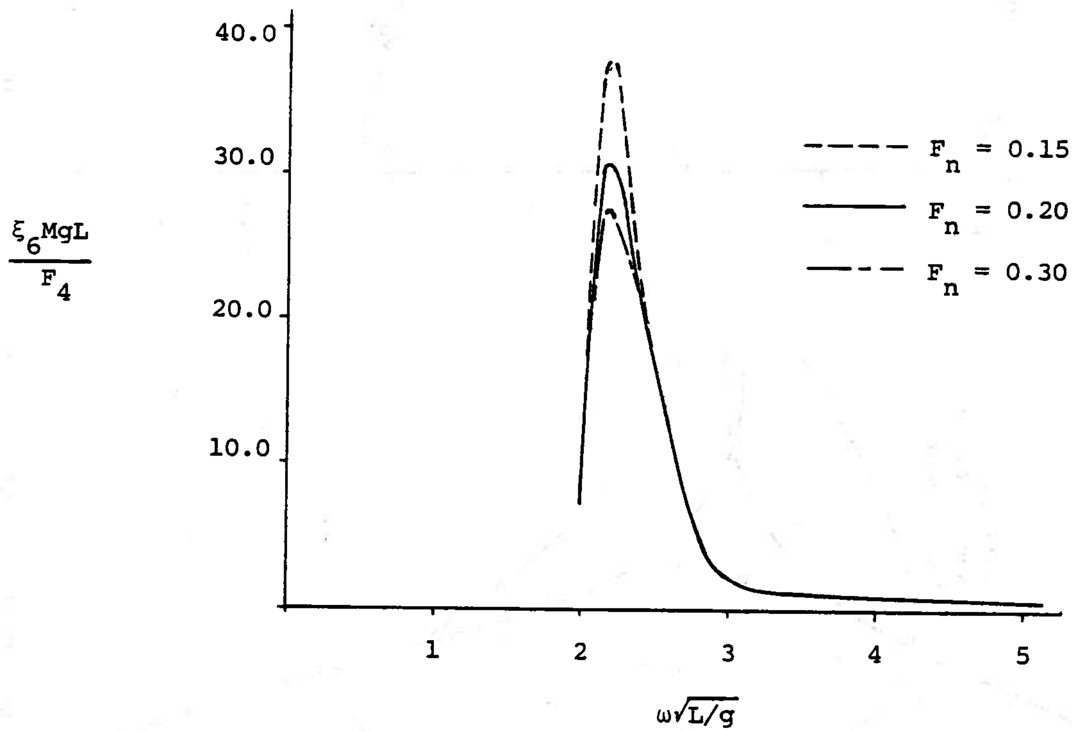

Figure 4 Yaw response to unit roll moment

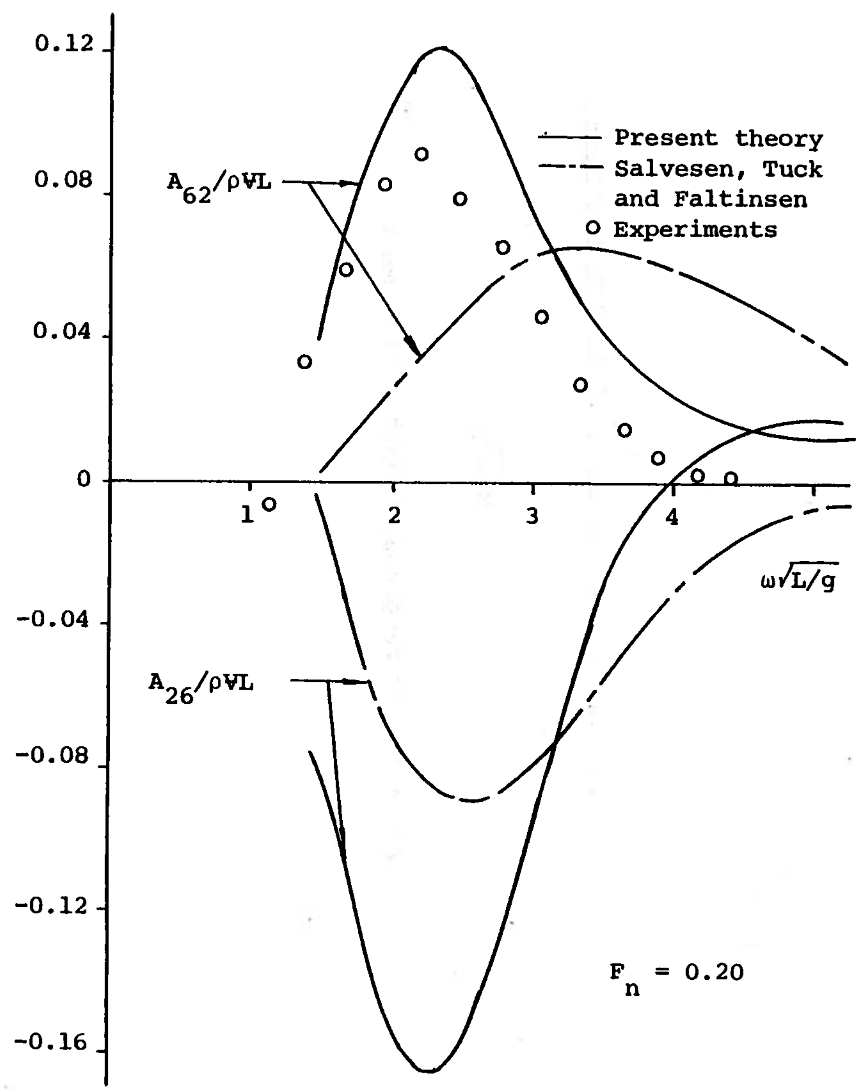

Figure 5 Added mass coefficients A_{62} and A_{26}

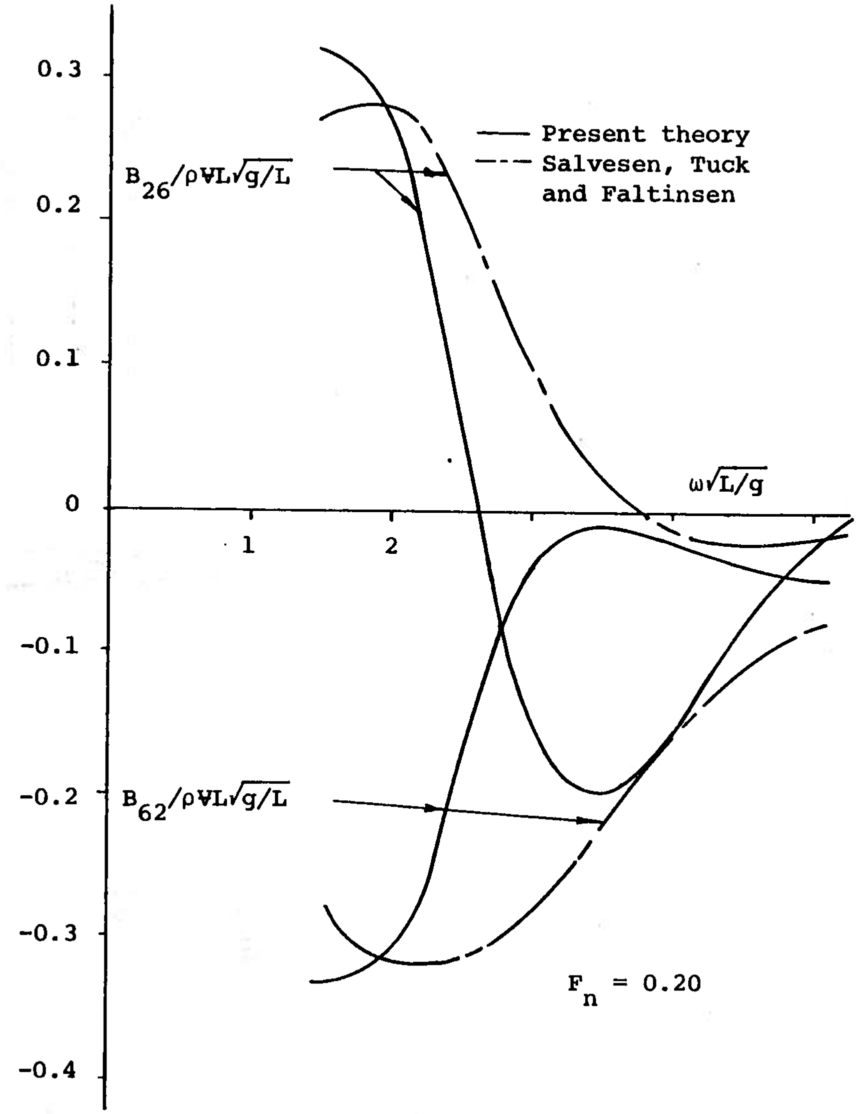

Figure 6 Damping coefficients B_{62} and B_{26}

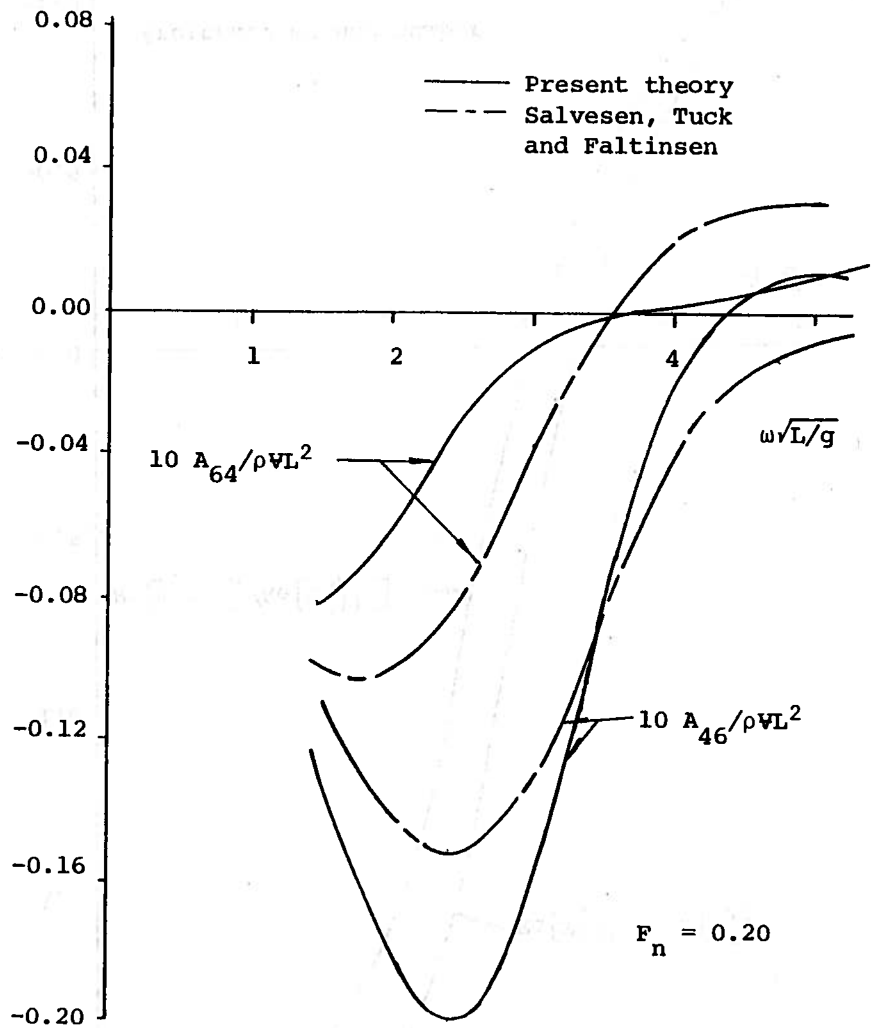

Figure 7 Added mass coefficients A_{64} and A_{46}

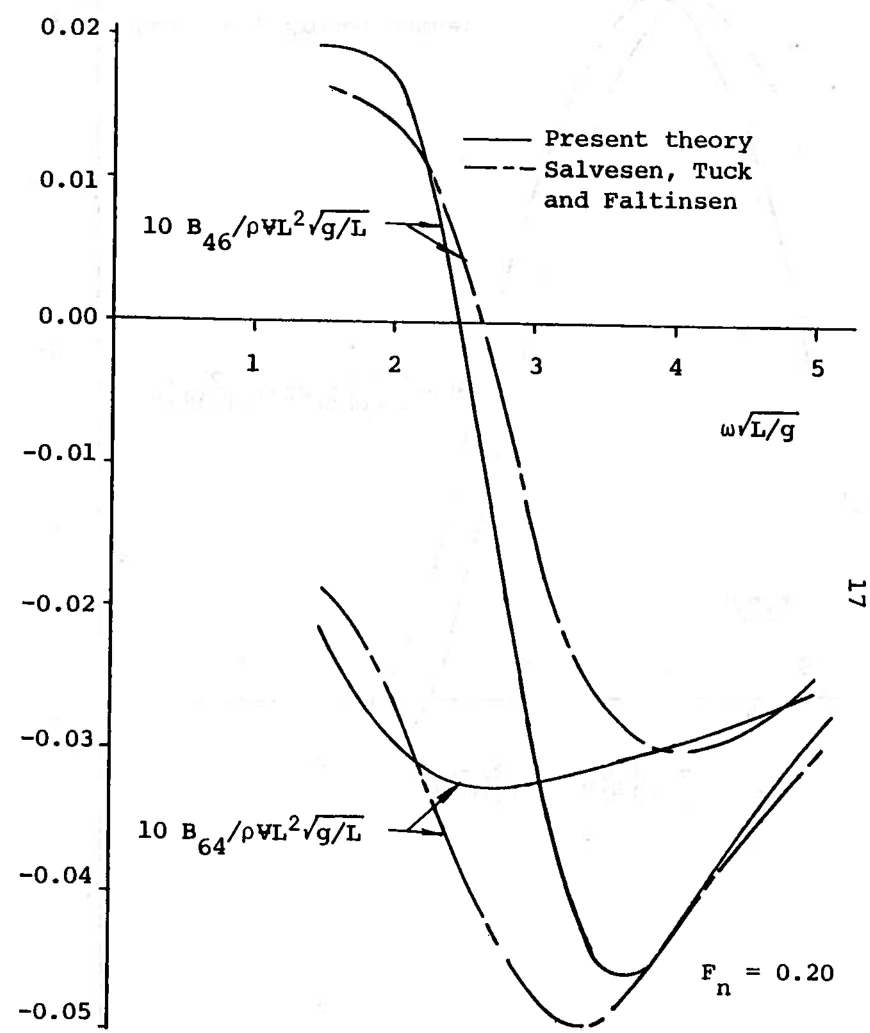

Figure 8 Damping cofficients B_{46} and B_{64}

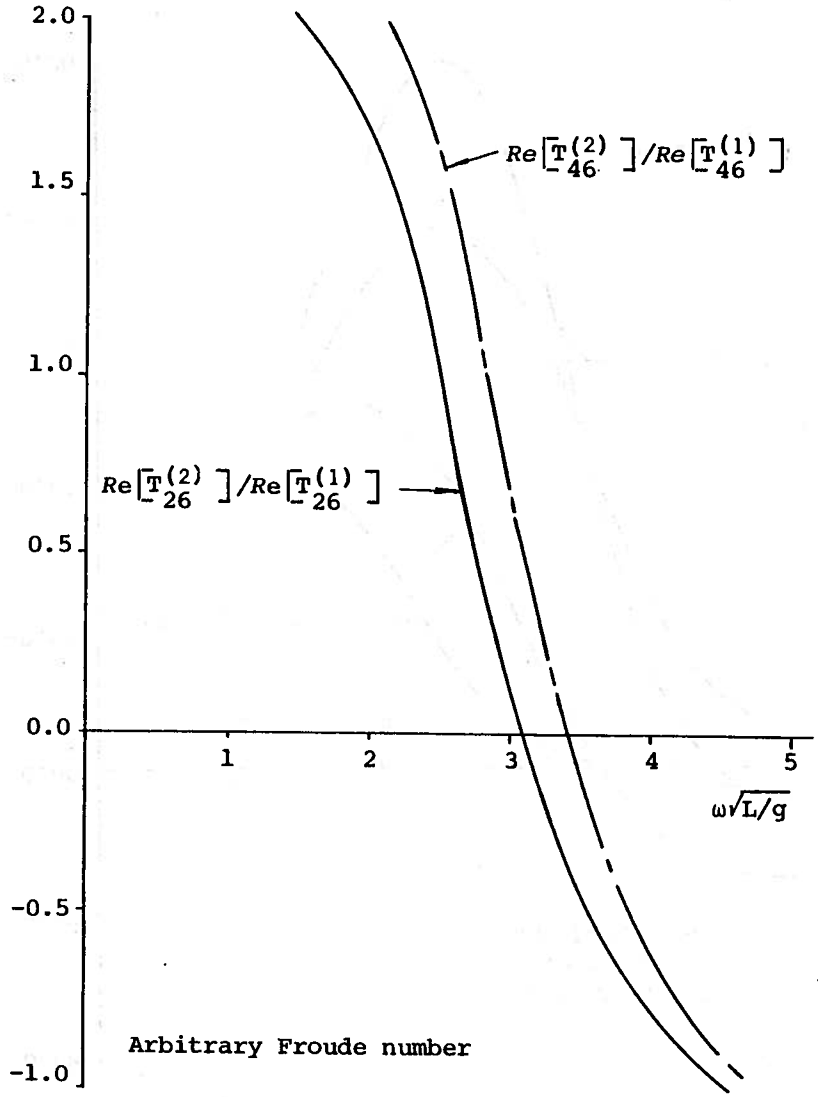

Figure 9 Relative importance of free surface integrals

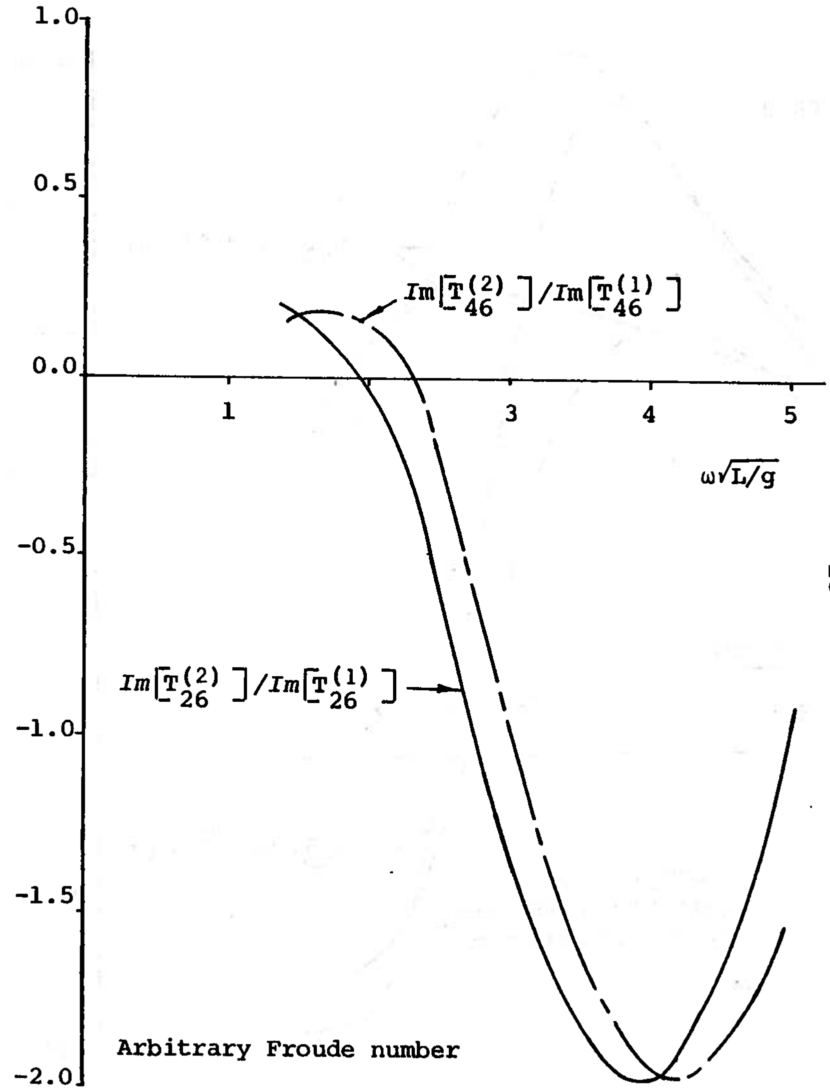

Figure 10 Relative importance of free surface integrals

APPENDIX

FORCE AND MOMENT ON THE HULL

Since most of the details for finding the force and moment on the hull due to horizontal motions are similar to those for vertical motions as presented by Ogilvie and Tuck (1969), only a brief summary of the derivation will be given here.

The time dependent solution is given by the $\psi(x,y,z,t)$ potential. It must satisfy equations (5) - (7) which are repeated here for convenience

$$\psi_{yy} + \psi_{zz} \doteq 0 \quad \text{in the fluid domain} \tag{5}$$

$$-\omega^2\psi + g\psi_z \doteq -i\omega U(2\psi_x + 2\chi_y\psi_y + \chi_{yy}\psi) \quad \text{on} \quad z=0 \tag{6}$$

and on the hull

$$\begin{aligned}\frac{\partial\psi}{\partial n} \doteq\ & i\omega n_2(\eta_2 + x\eta_6) + i\omega\eta_4(yn_3 - zn_2) + Un_2\eta_6 \\ & -U(\eta_2 + x\eta_6)(n_2\chi_{zz} + n_3\chi_{yz}) + U\eta_4\big[(n_3\chi_y - n_2\chi_z) \\ & + z(n_2\chi_{yy} + n_3\chi_{yz}) - y(n_2\chi_{yz} + n_3\chi_{zz})\big]\end{aligned} \tag{7}$$

There is also a radiation condition that must be satisfied. More will be said about this later.

In order to simplify the solution of the forced oscillation potentials, Ogilvie and Tuck (1969) defined the following quantities:

n_j and m_j for $j=2,4,6$ where

$$n_2 = n_2$$

$$n_4 = yn_3 - zn_2$$

$$n_6 \doteq xn_2$$

$$m_2 \doteq -n_2\chi_{yy} - n_3\chi_{yz}$$

$$m_4 \doteq \chi_y n_3 - \chi_z n_2 + z(n_2\chi_{yy} + n_3\chi_{yz}) - y(n_2\chi_{yz} + n_3\chi_{yz})$$

$$m_6 \doteq n_2 - xm_2$$

Let the mean hull surface be defined by the equation

$$S_0(x,y,z) = 0.$$

Then define a potential ϕ_j where

$$\phi_{j_{yy}} + \phi_{j_{zz}} = 0 \qquad \text{in the fluid}$$

$$\frac{\partial \phi_j}{\partial N} = n_j \quad \text{on} \quad S_0 = 0$$

and

$$-\omega^2\phi_j + g\phi_{j_z} = 0 \quad \text{on} \quad z=0 .$$

Note that $\phi_6 \tilde{=} x\,\phi_2$

Next define a potential Ψ_j where

$$\Psi_{j_{yy}} + \Psi_{j_{zz}} = 0 \quad \text{in the fluid}$$

$$\frac{\partial \Psi_j}{\partial N} = m_j \quad \text{on} \quad S_0 = 0$$

and

$$-\omega^2\Psi_j + g\Psi_{j_z} = 0 \quad \text{on } z=0$$

Finally define a potential Ω_j where

$$\Omega_{j_{yy}} + \Omega_{j_{zz}} = 0 \quad \text{in the fluid}$$

$$\frac{\partial \Omega_j}{\partial N} = 0 \quad \text{on} \quad S_0 = 0$$

and

$$-\omega^2\Omega_j + g\Omega_{j_z} = -(2\phi_{j_x} + 2\chi_y\phi_{j_y} + \chi_{yy}\phi_j) \quad \text{on} \quad z=0 .$$

Then $\psi = \sum_j (i\omega\phi_j + U\Psi_j - \omega^2 U\Omega_j)\eta_j$ satisfies all the equations in the boundary value problems (equations (5) - (7)) to the order considered. The radiation conditions for the ϕ_j and Ψ_j problems are the usual ones which require out going waves. The Ω_j potential represents an anti-symmetric pressure distribution on the free surface, and as shown by Troesch (1975), its radiation condition is represented by linearly growing, anti-symmetric out-going waves.

As shown by Ogilvie and Tuck (1969), the pressure can be found from Bernoulli's equation and then integrated over the mean position of the ship's hull to give a total force consistent to an order of $O(\varepsilon^{3/2}\delta)$. It has the following form:

$$F_j(t) \cong -\rho \int_{S_0} ds\{\sum_k [n_j(i\omega)^2 - Um_j(i\omega)]\phi_k\eta_k + Un_j\sum[(i\omega)\Psi_k + (i\omega)^3\Omega_k]\eta_k\}$$

As done in the main text, let us define several quantities as follows:

$$F_j(t) \equiv \sum_k [T_{jk}^{(0)} + T_{jk}^{(1)} + T_{jk}^{(2)}]\eta_k(t) \ .$$

Then

$$T_{jk}^{(0)} = -\rho(i\omega)^2 \int_{S_0} ds\ n_j\phi_k$$

$$T_{jk}^{(1)} = -\rho i\omega U \int_{S_0} ds(n_j\Psi_k - m_j\phi_k)$$

and

$$T_{jk}^{(2)} = -\rho(i\omega)^3 U \int_{S_0} ds\ n_j\Omega_k \ .$$

See the main text for the complete expressions for $T_{jk}^{(0)}$ when $j=2,4,6$ and $k=2,4,6$.

Consider now $T_{jk}^{(1)}$. The far field behavior of ϕ_j and Ψ_j are given as

$$i\omega\phi_j n_j \rightarrow \mathrm{sgn}(y)A_j(x)e^{\nu z}e^{i(\omega t - \nu|y|)}$$

and

$$U\Psi_j n_j \rightarrow \mathrm{sgn}(y)B_j(x)e^{\nu z}e^{i(\omega t - \nu|y|)}$$

as $y \rightarrow \infty$. Here ν is the wave number given by $\omega^2=\nu g$. Using this fact and Green's theorem for two dimensions, we can follow the method used by Ogilvie and Tuck (1969) to easily show that

$$T_{jj}^{(1)} = 0$$

and

$$T^{(1)}_{jk} = -\rho i\omega U \int_{S_0} ds(\phi_j m_k - \phi_k m_j)$$

The following expressions are given for specific modes of motion:

$$T^{(1)}_{26} = -T^{(1)}_{62} = -\rho i\omega U \int_{S_0} ds\ n_2\phi_2$$

$$T^{(1)}_{24} = -T^{(1)}_{42} = -\rho i\omega U \int_{S_0} ds(\phi_2 m_4 - \phi_4 m_2)$$

and

$$T^{(1)}_{46} = -T^{(1)}_{64} = -\rho i\omega U\left[\int_{S_0} ds\, x(m_2\phi_4 - m_4\phi_2) + \int_{S_0} ds\, n_2\phi_4\right]$$

To simplify $T^{(2)}_{jk}$, we need the far field behavior of the Ω potential. Using the method shown by Troesch (1975) for a anti-symmetric pressure distribution on the free surface we can write

$$-\omega^2 U\Omega_j n_j \to \mathrm{sgn}(y)e^{\nu z+i(\omega t-\nu|y|)}\left[C_j(x) - \frac{2i\omega U}{g} A_{j_x}(x)(z-i|y|)\right]$$

as $y \to \infty$.

Then we can show, using a method similar to that used by Ogilvie and Tuck (1969), that

$$T^{(2)}_{jj} = 0$$

$$T^{(2)}_{26} = -T^{(2)}_{62} = \rho(i\omega)^3 \frac{2U}{g}\int_L dx\left[\int_{y_0}^{\infty} dy(\phi_2^2 - A_2^2 e^{-2i\nu y}) - \frac{i}{2\nu} A_2^2 e^{-2i\nu y_0}\right]$$

and for roll, when either j=4 or k=4 and the other subscript equals 2 or 6

$$T_{jk}^{(2)} = -T_{kj}^{(2)} = \rho(i\omega)^3 \frac{2U}{g} \int_L dx \left\{ \int_{y_0}^{\infty} dy \Big[(\phi_j \phi_{k_x} - A_j A_{k_x} e^{-2i\nu y}) - (\phi_{j_x}\phi_k - A_{j_x} A_k e^{-2i\nu y}) + \chi_y (\phi_j \phi_{k_y} + \phi_{j_y} \phi_k) \Big] + \frac{i}{2\nu} e^{-2i\nu y_0} (A_{j_x} A_k - A_j A_{k_x}) \right\}$$

where the subscript of x means the derivative of the subscripted variable with respect to x.

Note the following:

i) For symmetric hull forms m_2, m_4 and χ_y are odd functions with respect to x.

ii) In regions of constant cross sections, m_2, m_4, χ_y, ϕ_{j_x} and A_{j_x} are equal to zero.

iii) In the end sections the beam of the hull becomes higher order than the beam at mid ships. As a result the oscillation potentials ϕ_2 and ϕ_4, also are higher order there than in the mid sections.

NUMERICAL METHOD FOR DETERMINING THE ADDED MASS AND DAMPING COEFFICIENTS

The added mass and damping coefficients were found in two steps. First, the potential valid on the hull surface was determined. Next, a multipole expansion, valid outside some radius R which inclosed the body, was matched to the first potential. Using this scheme significantly lowered the computing time of evaluating the free surface integrals.

The potential in the near field was given by an integral representation of sources distributed over the hull surface. The source strength, $\sigma_j(\zeta,\eta)$, was found by solving the following integral equation:

$$\frac{\partial\phi_j(y,z)}{\partial n} = -\pi\sigma_j(y,z) + \int_{C_H} d\ell\,\sigma_j(\zeta,\eta)\,\frac{\partial G}{\partial n}\,(y,z,;\zeta,\eta)$$

on the hull, where $\frac{\partial\phi_j}{\partial n}$ is the normal velocity on the hull and $G(y,z,;\zeta,\eta)$ is a Green's function given by

$$G(y,z;\zeta,\eta) = \log\sqrt{(y-\zeta)^2 + (z-\eta)^2} - \log\sqrt{(y-\zeta)^2 + (z+\eta)^2}$$
$$-2e^{\nu(z+\eta)}\operatorname{Re}\left\{e^{i\nu|y-\zeta|}E_1\left[\nu(z+\eta) + i\nu|y-\zeta|\right]\right\}$$
$$+2\pi i e^{\nu(z+\eta) - i\nu|y-\zeta|}$$

and $E_1(x+iy)$ is the complex exponential integral. The method for solving the integral equation is given in Troesch (1975).

Once the source distribution, $\sigma_j(\zeta,\eta)$ was known, a circle of radius R, where R enclosed the entire station being considered, was found. Then the potential given by the source distribution on the hull was matched to a multi-pole expansion consisting of a dipole and wave free potentials that were odd with respect to the x-z plane. The matching took place on the circle. The multi-pole expansion had the following form:

$$\phi_j(y,z) = A_j\left[-\frac{1}{\pi}e^{\nu z}\operatorname{sgn}(y)\operatorname{Re}\left\{ie^{i\nu|y|}E_1(\nu z+i\nu|y|)\right\}\right.$$
$$\left.+\frac{1}{\pi\nu}\frac{y}{r^2} + \operatorname{sgn}(y)e^{\nu z - i\nu|y|}\right]$$
$$+\sum_{m=1}^{N-1} A_{jm}(\nu R)^{2m+1}\left[\frac{\sin(2m+1)\theta}{(\nu r)^{2m+1}} + \frac{\sin 2m\theta}{2m(\nu r)^{2m}}\right]$$

where A_j and A_{jm} are coefficients determined from the matching processes, r equals $\sqrt{y^2+z^2}$, and θ is the angle between r and the negative z axis.

The free surface integrals, defined as

$$\int_{y_0}^{\infty} dy(\phi_2^2 - A_2^2 e^{-2i\nu y})$$

and

$$\int_{y_0}^{\infty} dy(\phi_2\phi_4 - A_2A_4e^{-2i\nu y})$$

have integrands that oscillate with a period of π. The subroutine that evaluated the integrals used Simpson's rule on 25 points for each interval of π. The integration was terminated when a given interval made no significant contribution to the total integral.

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