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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084-5000

THE EFFECT OF STRUT SHAPE ON SWATH SHIP MOTION

by

Young S. Hong

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SHIP PERFORMANCE DEPARTMENT
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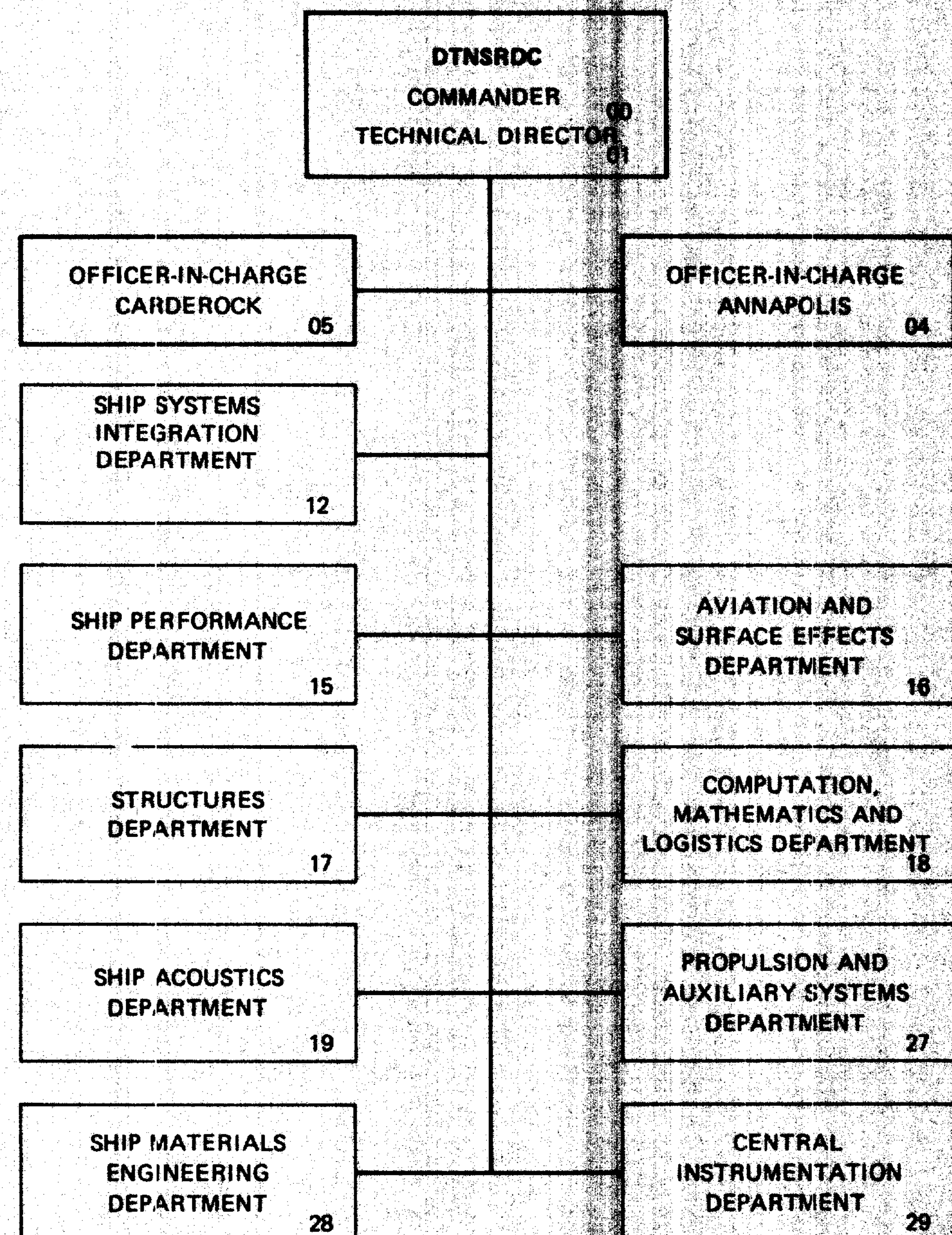

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Three different strut shapes have been investigated to determine the effect of shape on the heave motion of SWATH ships at heave resonance. A time-domain analysis has been developed to include the nonlinear effect of large motion amplitude. A two-dimensional model, in which the ship forward speed is assumed to be zero, has been investigated to simplify the problem. The results show that a proper choice of strut shape can reduce the ship heave motion substantially at resonance.

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NOTATION

A	Added mass
A'	Wave amplitude
a	Radius of submerged lower hull
B	Damping force
b_1	Half width of section at free surface
b_2	Half width of strut at lower hull
C	Hydrostatic force
C_D	Viscous damping coefficient
D	Viscous damping force
F_1, F_2	Cosine and sine terms of exciting force
F	$(F_1^2 + F_2^2)^{1/2}$
f	Location of centroid of lower hull relative to free surface
g	Gravitational acceleration
h	Draft
KG	Locaton of center of gravity above baseline
ℓ	Distance between centroid of lower hull and strut
m	Mass
S	Sectional area
s	Waterplane area
v	Vertical velocity of the SWATH section
Y	Amplitude of heave motion
$\bar{y}$	Complex amplitude of heave motion
ω	Frequency of incoming wave
ξ	Absolute value of $\bar{y}$
ρ	Water density

ABSTRACT

Three different strut shapes have been investigated to determine the effect of shape on the heave motion of ships at resonance. A time-domain analysis has been developed to include the nonlinear effect of large motion amplitude. A two-dimensional model, in which the ship forward speed is assumed to be zero, has been investigated to simplify the problem. The results show that a proper choice of strut shape can reduce ship heave motion substantially at reonance.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The concept of a small-waterplane-area twin-hull (SWATH) ship has been introduced by the Navy to improve the seakeeping characteristics of naval ships in waves. A SWATH ship consists of two submerged hulls, and struts that connect the wet deck and these lower hulls.[1*] The struts are usually vertical-wall sided.

The purpose of the present study is to investigate the effect of strut shape on the heave motion of SWATH ships near the resonance region. In particular, we wish to determine if a proper selection of strut configuration will decrease the peak value of heave. An existing analytical method frequently used to predict the motions of SWATH ships is based on a frequency-domain approach. Since the motion amplitude is large at resonance, the frequency-domain analysis may be unable to treat the nonlinear effect of this large-amplitude motion. In this study, a time-domain analysis has been developed to include the nonlinear effect of large-motion amplitude. To simplify the problem, a two-dimensional ship model in which the ship forward speed is assumed to be zero, has been investigated. Extending the investigation to a three-dimensional SWATH ship is beyond the scope of the present study and should be considered in the future.

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*References are listed on page 21.

The procedure of the present analysis starts with computation of the hydrodynamic and hydrostatic forces for three different ship drafts and for a given wave frequency. The equations of motion are integrated numerically at each time step. Also, at each time step, the instantaneous ship draft is computed, and the hydrodynamic and hydrostatic forces are interpolated for that draft. In this analysis it is assumed that the wave frequency itself is constant but that the wave amplitude increases from a small value to a larger steady-state value. This study, thus, attempts to analytically duplicate a tank test.

Three different strut shapes have been investigated, and the results are compared with those obtained using the frequency-domain method. The computed results show that a proper choice of strut shape can reduce the heave motion results substantially at resonance.

EQUATIONS OF MOTION

We define an oxy coordinate system with origin 0 at the free surface. The x axis is in the plane of the free surface and the y axis directed vertically upward along the SWATH section centerline (see Figure 1).

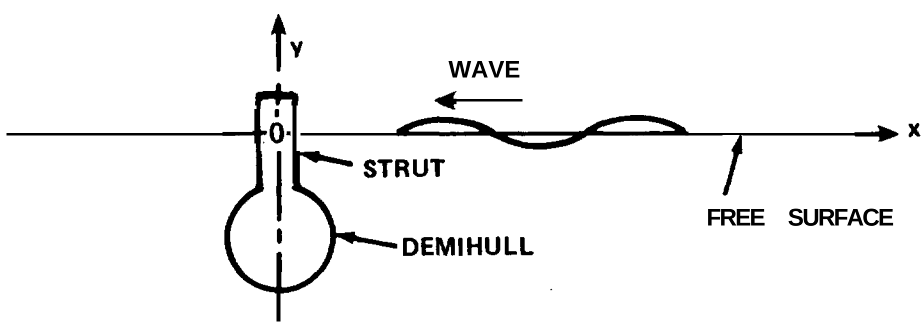

Figure 1 - Coordinate System Used in SWATH Section Study

Let us assume that a two-dimensonal SWATH section is floating at the origin, and that a train of waves is approaching this section from the positive x axis. During the transient period, the amplitude of the wave is initially very small, and it increases to that of the regular wave in some finite time, say about 15 s. Furthermore, it is assumed that the wave period is constant during the transient period. The incoming wave sets the SWATH section into a harmonic motion and the equation for the heave motion can be written

$$(m+A(t))\, y'' + B(t)y' + C(t)y + D(t)y'^2$$

$$= F_1(t) \cos \omega t + F_2(t) \sin \omega t \qquad (1)$$

where m is the mass of the section, A the added mass, B the damping force, and F_1 and F_2 are exciting forces. In addition, y is the amplitude of heave motion and ω is the frequency of the incoming wave. The prime and double prime indicate first and second derivatives of y with respect to time, respectively. The time dependency of A, B, C, D, F_1, and F_2 is due to the change of ship draft at a given ω as the wave passes.

The following computational procedure is employed for obtaining the hydrostatic and hydrodynamic forces. The sectional contour is divided into segments, and a constant source of unknown strength is computed using the body boundary condition which states that the normal velocity of the body is the same as that of the fluid at the boundary. This method is sometimes called the Frank-close-fit method.[2,3]

If we assume that A, B, C, Fl, and F_2 are frequency dependent but independent of time, and that D is zero, then the solution of Equation (1) is simply in the form

$$y = Re(\bar{y}\, e^{-i\omega t}) \qquad (2)$$

where $\bar{y}$ is given by

$$\bar{y} = \frac{Fl + iF_2}{c - \omega^2 (m+A) - i\omega B} \qquad (3)$$

Equation (3) can be easily obtained by substitution of Equation (2) into Equation (1).

NUMERICAL INTEGRATION OF EQUATION (1)

When the coefficients in Equation (1) are dependent on time, it is impossible to find a solution such as Equation (3). The solution of Equation (1) is possible, however, through a step-by-step numerical integration. The Adams-Moulton method can be used to integrate Equation (1) numerically. (The details of this method are given in the Appendix.) In order to utilize the Adams-Moulton method, we rewrite Equation (1) as

$$y'' = ay + by' + cy'^2 + f_1 \cos \omega t + f_2 \sin \omega t \tag{4}$$

where

$$a = -\frac{C}{m + A}$$

$$b = -\frac{B}{m + A}$$

$$c = -\frac{D}{m + A}$$

$$f_1 = \frac{F_1}{m + A}$$

and

$$f_2 = \frac{F_2}{m + A}$$

If we let

$$\frac{dy}{dt} \equiv y' = v, \tag{5}$$

then

$$\frac{dv}{dt} = v' = y''$$

and Equation (4) can be expressed as

$$\frac{dv}{dt} = y'' = ay + bv + cv^2 + f_1 \cos \omega t + f_2 \sin \omega t \tag{6}$$

With $v = z$ these equations can be expressed as a system of linear equations

$$y' = z$$

and

$$z' = ay + bz + cz^2 + f_1 \cos \omega t + f_2 \sin \omega t \tag{7}$$

With substitution of x for t we can now apply the Adams-Moulton method explained in the Appendix to solve Equation (7).

Before we start the numerical integration of Equation (7), we make the following assumptions:

1. The displacement and KG of each SWATH section are constant.
2. The draft varies as the wave passes.
3. The water-plane and beam areas at the free surface are a function of the draft.
4. The added mass, and damping and exciting forces are a function of the draft at a given frequency ω.

In the present method, the coefficients A, B, C, F_1, and F_2 in Equation (1) are computed for three different drafts at a given frequency using the frequency-domain ship motion program; one of these is the calm-water draft. At the initial stage, the values of these coefficients are for the calm-water draft. When the incoming wave approaches the body, an instantaneous draft is computed, and these coefficients are interpolated for that draft.

NUMERICAL RESULTS

Three two-dimensional SWATH-ship-like sections (Figure 2) have been selected as a numerical test in the present study. SWATH Section A is almost the same as the midship section of one hull of SWATH 6A.[1] The strut of this section is

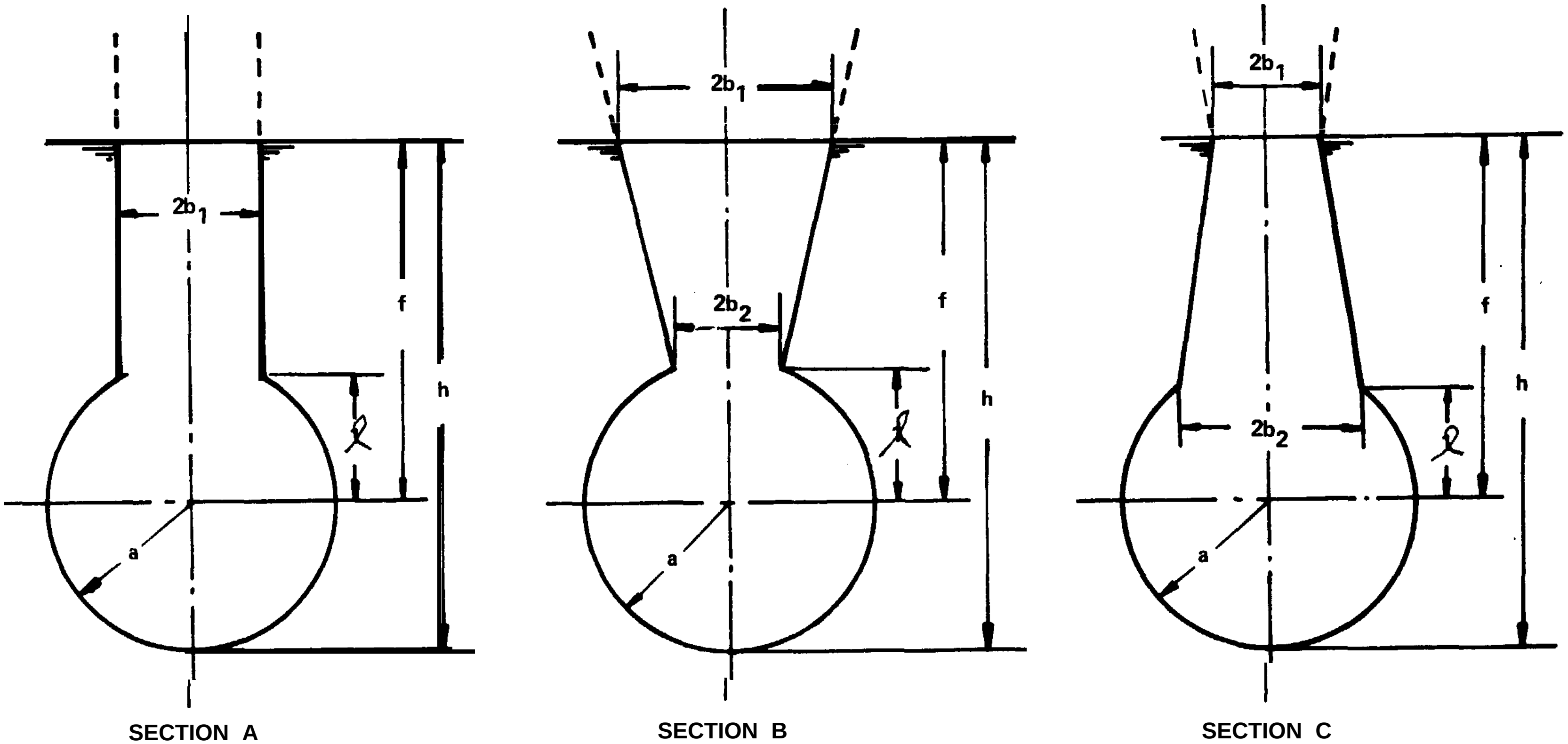

Figure 2 - SWATH Sections Chosen for Two-Dimensional Numerical Test

vertical-wall-sided. SWATH Section B has a flare-type strut with minimum width at the intersection with the lower hull. SWATH Section C has a maximum width at the intersection with the lower hull and a minimum width at the free surface. All three sections have the same radius a for the submerged circular hull. The principal dimensions of these sections are indicated in Figure 2 and tabulated in Table 1.

The numerical computation has been performed for two cases: (a) constant draft (the results of this case are the same as for those of the frequncy-domain computation), and (b) the draft varies as the wave passes. For each case the computation was done with and without inclusion of the viscous damping force D. The viscous damping force is computed as

$$D = (\rho C_D s v^2)/2$$

where s is the waterplane area and v is the instantaneous vertical velocity of the SWATH section. Whenever this damping force was included in the computation, it was assumed that the coefficient C_D is 0.715.

Figure 3 shows the heave motion results for the three sections selected. These results are compared with responses predicted by the frequency-domain motion program. Since SWATH Section A has a vertical strut, there is no change in the response function.

In the plots for SWATH Sections B and C the peak values obtained by time-domain analysis (present method) are substantially smaller than the value for Section A. This is true because the struts of Sections B and C provide greater damping than the wall-sided strut does. Table 2 shows the results of heave motion at resonance. The results obtained for constant draft with CD = 0 should be the same as those of the frequency-domain computation. However, there is a substantial difference in the results for SWATH Section C. This difference is caused by the fact that in the present method the total integration time of the differential equation is of too short a duration. Throughout the computations this time was taken as 400 s. If a total integration time of 1000 s is used, the results obtained for SWATH Section C are the same for both the time-domain and frequency-domain computations.

TABLE 1 - PRINCIPAL DIMENSIONS OF SWATH SECTIONS

Principal Dimensions (m)	SWATH Section A	SWATH Section B	SWATH Section C
a	2.3	2.3	2.3
h	8.1	8.1	8.1
f	5.8	5.8	5.8
ℓ	2.02	2.16	1.90
b_1	1.1	1.41	0.45
b_2		0.4	1.3
KG	3.01	3.01	3.01
S*	24.52	24.52	24.52

*Sectional area (m^2).

TABLE 2 - NONDIMENSIONAL AMPLITUDE (ξ/A') AT HEAVE RESONANCE

		SWATH Section A	SWATH Section B	SWATH Section C
Resonant Frequency ω (rad/s)		0.780	0.855	0.705
Constant Draft C_D	0.0	17.56	13.13	21.73
	0.715	3.53	3.31	3.74
Variable Draft C_D	0.0	17.52	3.24	2.23
	0.715	3.53	2.79	2.11
Frequency-Domain Method		18.84	13.64	32.78

Note: the values for the Constant Draft and Variable Draft rows are ξ/A'.

The motion results for variable draft for SWATH Sections B and C at resonance are substantially reduced compared to Section A. Furthermore, for the present method, the location of resonance is slightly shifted towards the lower frequencies (see Figures 3(b) and (c)). As shown in Figures 4 and 5, the added mass, damping, hydrostatic and exciting-force coefficients for Sections B and C vary significantly with draft change.

Figures 6 to 11 show heave motion time histories for the three sections at resonance with $C_D = 0$. For each SWATH section, the motions for constant draft and variable draft are computed. For the case of constant draft, the values of added mass, damping, exciting, and hydrostatic forces are taken when -the draft h is 8.1 m; this is true throughout the total time of 400 s. As mentioned earlier, the results of the present method when assuming constant draft should be the same as those of the frequency-domain approach. Figures 6 to 8 show the results for constant draft. The heave amplitudes have not reached a steady-state value by t = 400 s. When t is taken as 1000 s (which is not shown in these plots), heave becomes steady state, and the amplitudes are then the same as the frequency-domain results. Most runs were not made for 1000 s, however, because of excessive computer time and cost.

Figures 9 to 1% show the results for variable draft. Since SWATH Section A has a vertical-wall sided strut, there is no change in the heave time history compared to the constant-draft case. For SWATH Sections B and C, however, the amplitudes at resonance become much smaller than those for constant draft. The rapid reduction of the resonance value of heave motion for SWATH Sections B and C is caused by the fact that the hydrostatic and hydrodynamic force coefficients (Figures 4 and 5) change greatly as a function of draft. These same coefficients for SWATH Section A are less dependent on the draft.

It is worth noting that the heave amplitudes for variable draft for SWATH Sections B and C are not symmetric with respect to the undisturbed free surface. For SWATH Section B, the positive amplitude (heave up) tends to be larger than the negative one as the motion continues (Figure 10). The hydrostatic and hydrodynamic force coefficients for Section B, conversely, become smaller for upward heave (Figure 4). Thus, even though the motion is a function of the force coefficients according to Equation (3), it appears that small coefficients result in large heave, and vice versa.

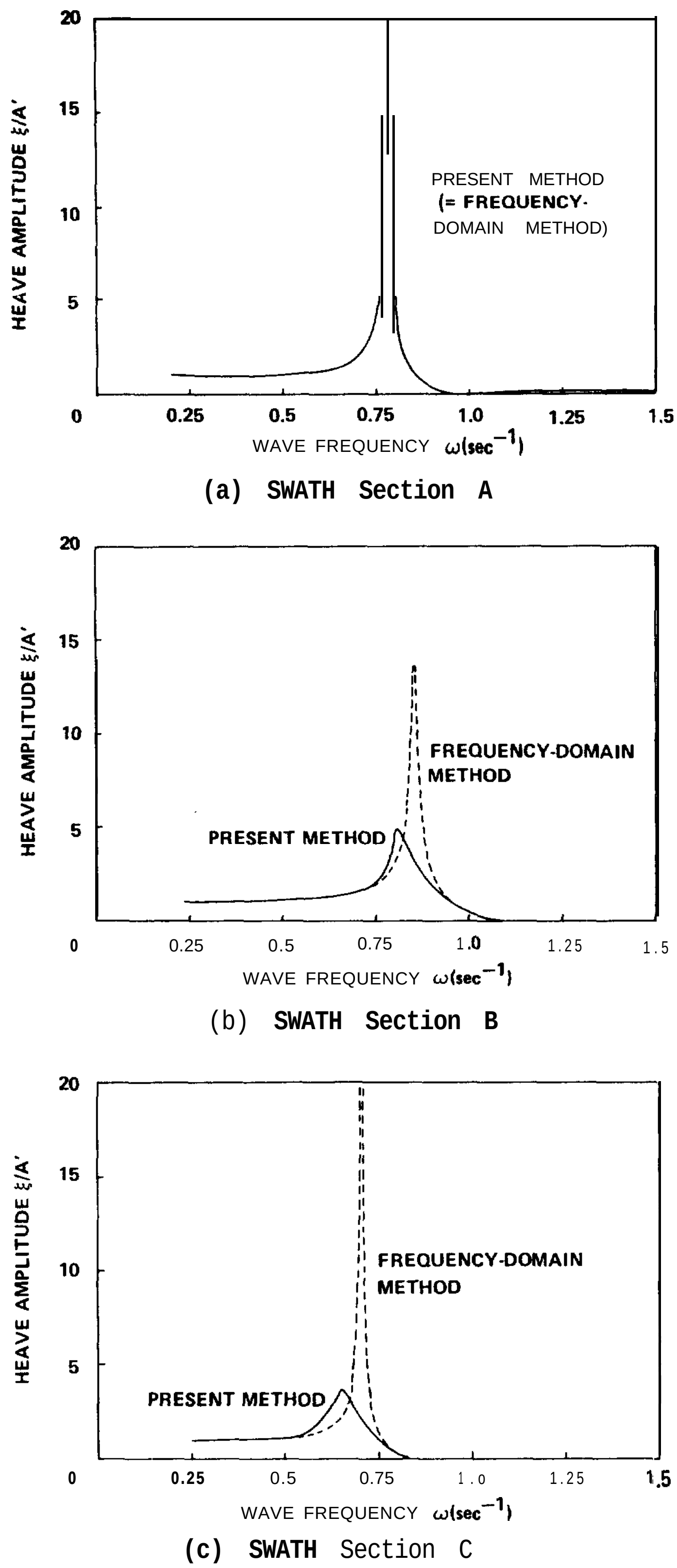

Figure 3 - Heave Motion of the Three SWATH Sections Studied

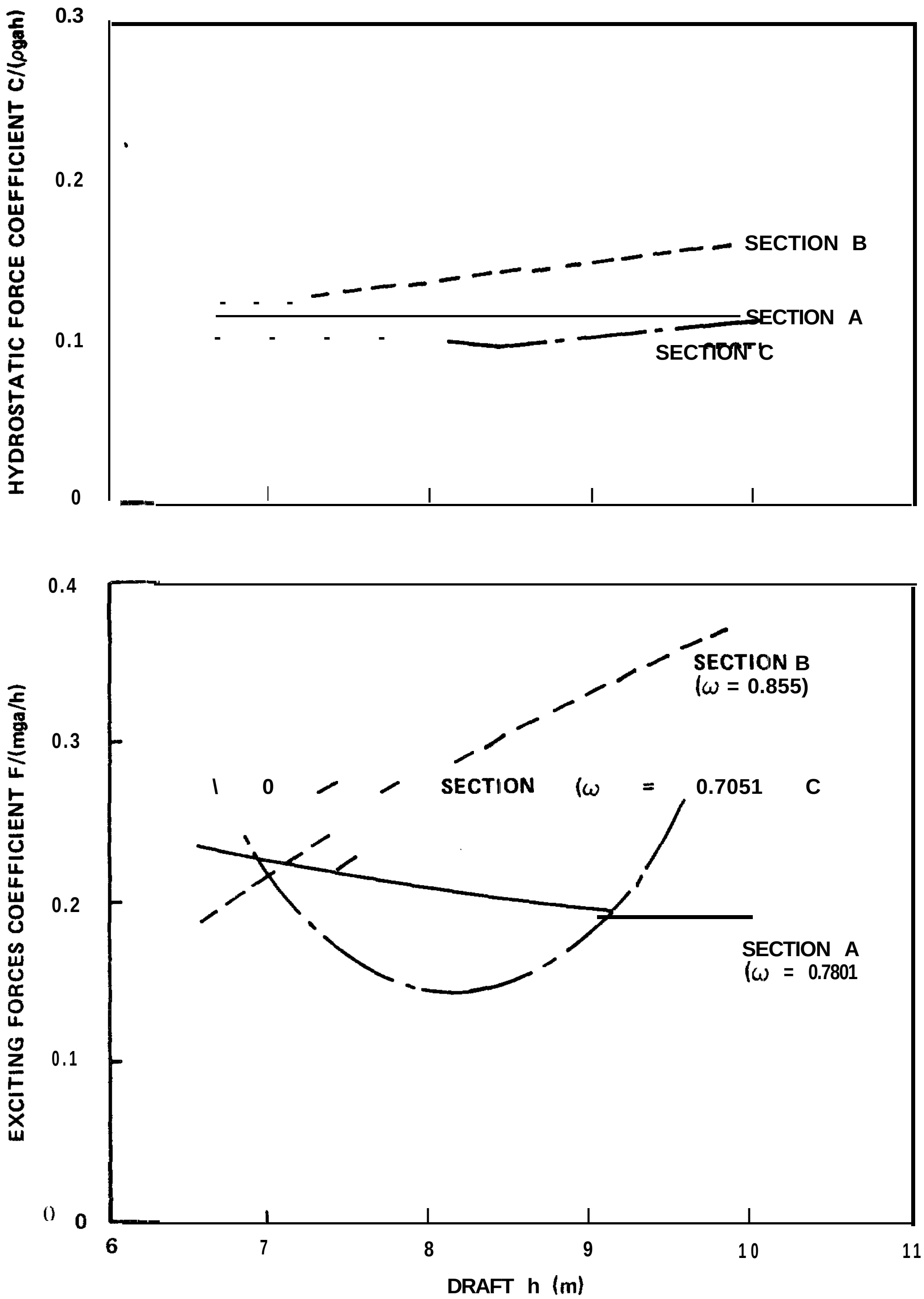

Figure 4 - Hydrostatic and Exciting Forces Coefficients of SWATH Sections for Heave Resonance as a Function of Draft

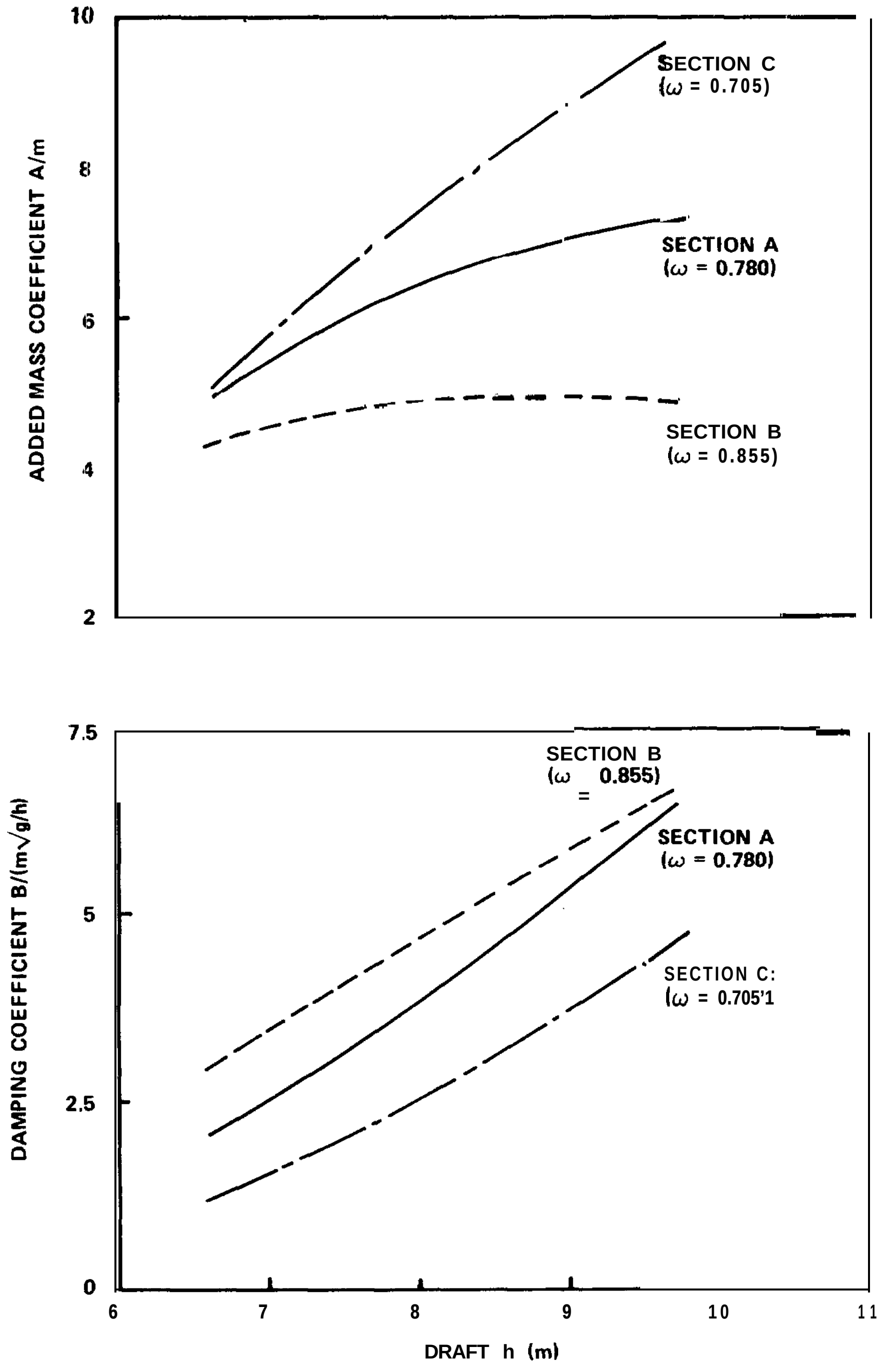

Figure 5 - Added Mass and Damping Coefficients of SWATH Sections for Heave Resonance as a Function of Draft

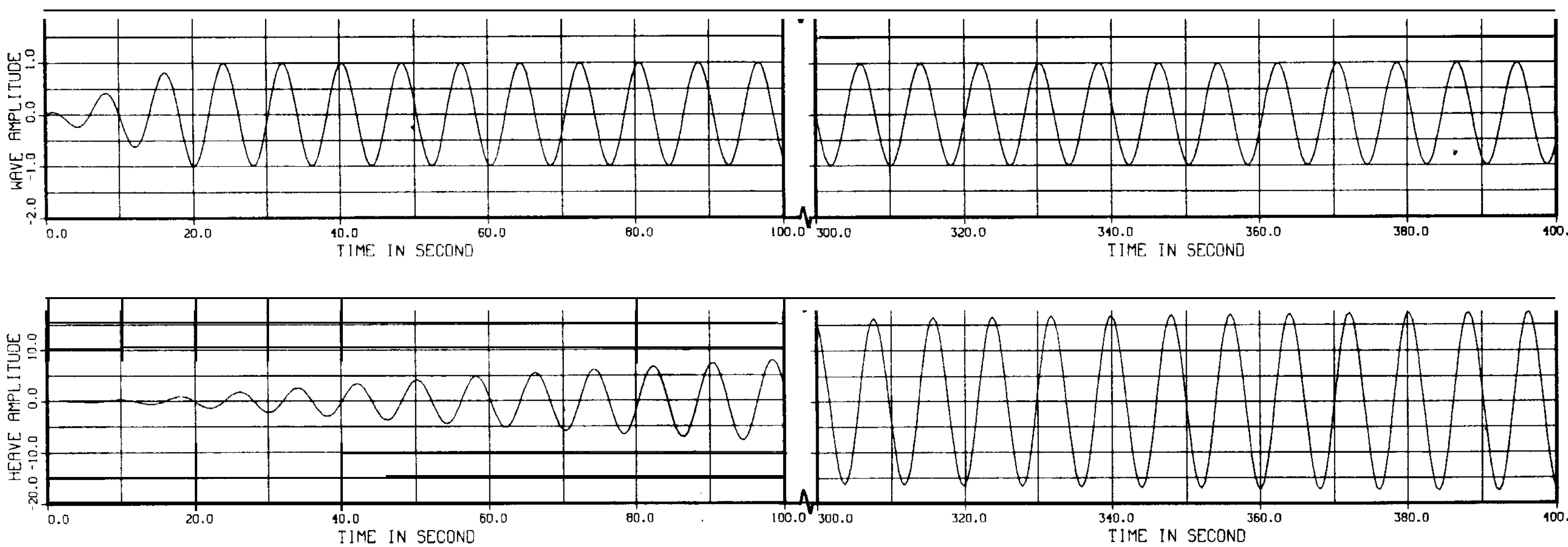

Figure 6 - Heave Motion of SWATH Section A in Time Domain for Constant Draft and ω = 0.780

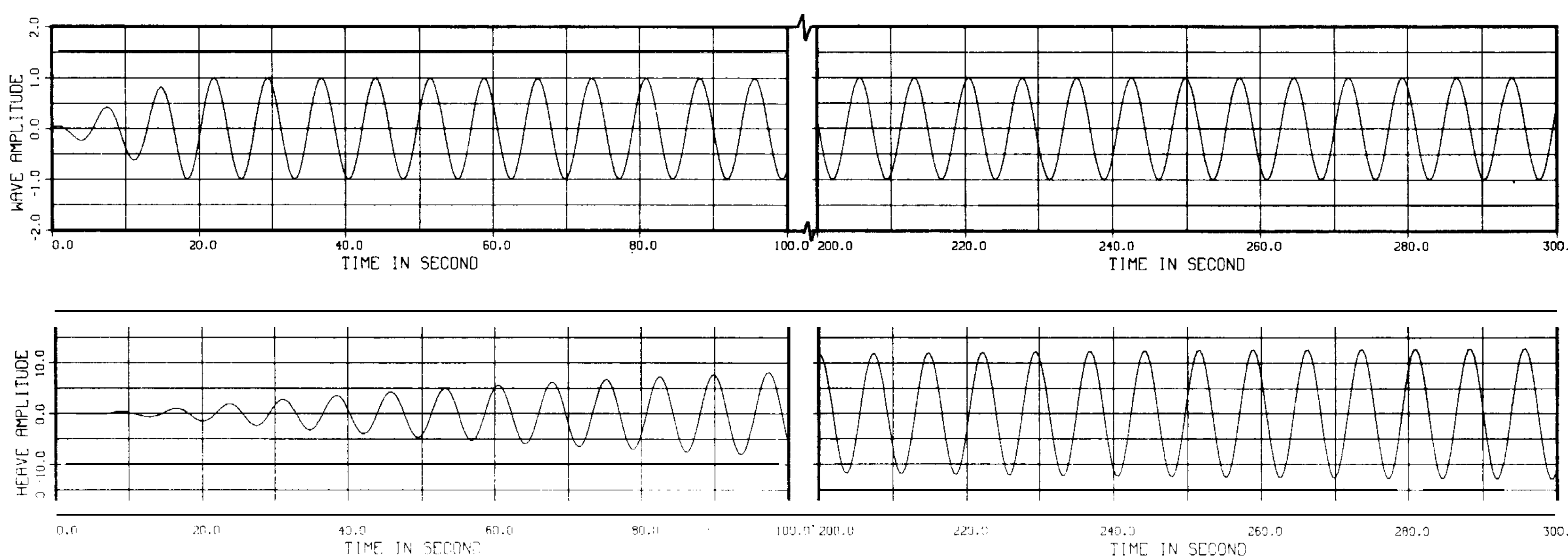

Figure 7 - Heave Motion of SWATH Section B in Time Domain for Constant Draft and ω = 0.855

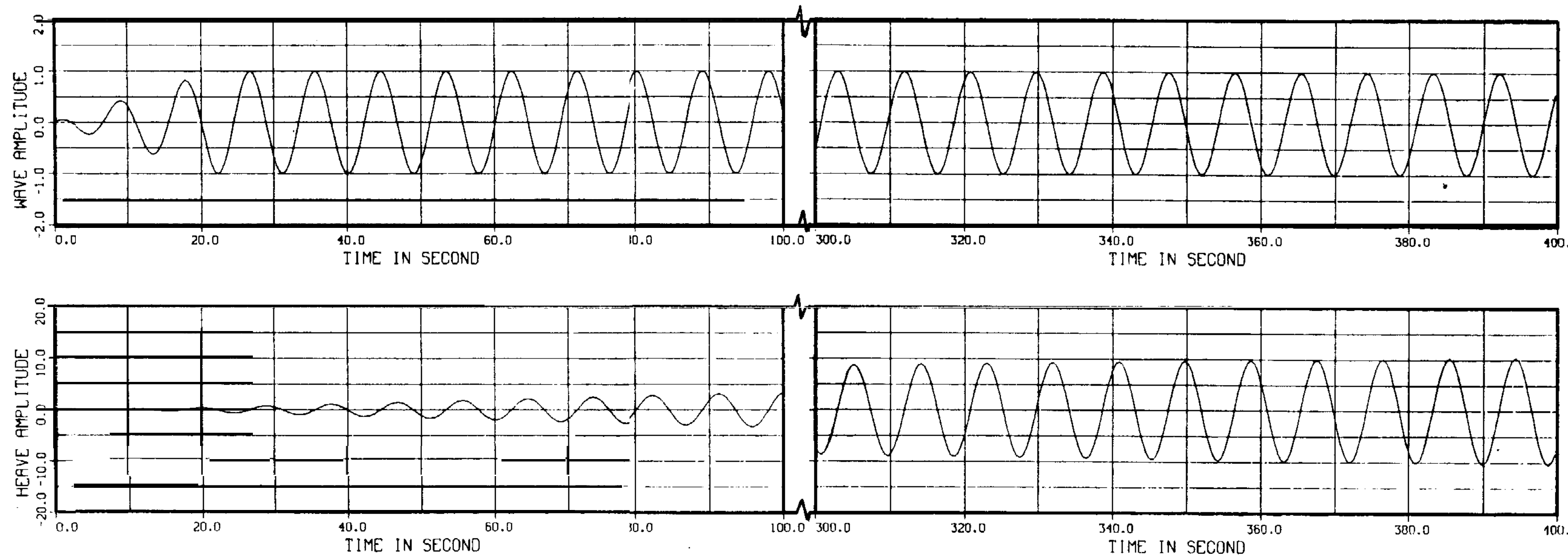

Figure 8 - Heave Motion of SWATH Section C in Time Domain for Constant Draft and ω = 0.705

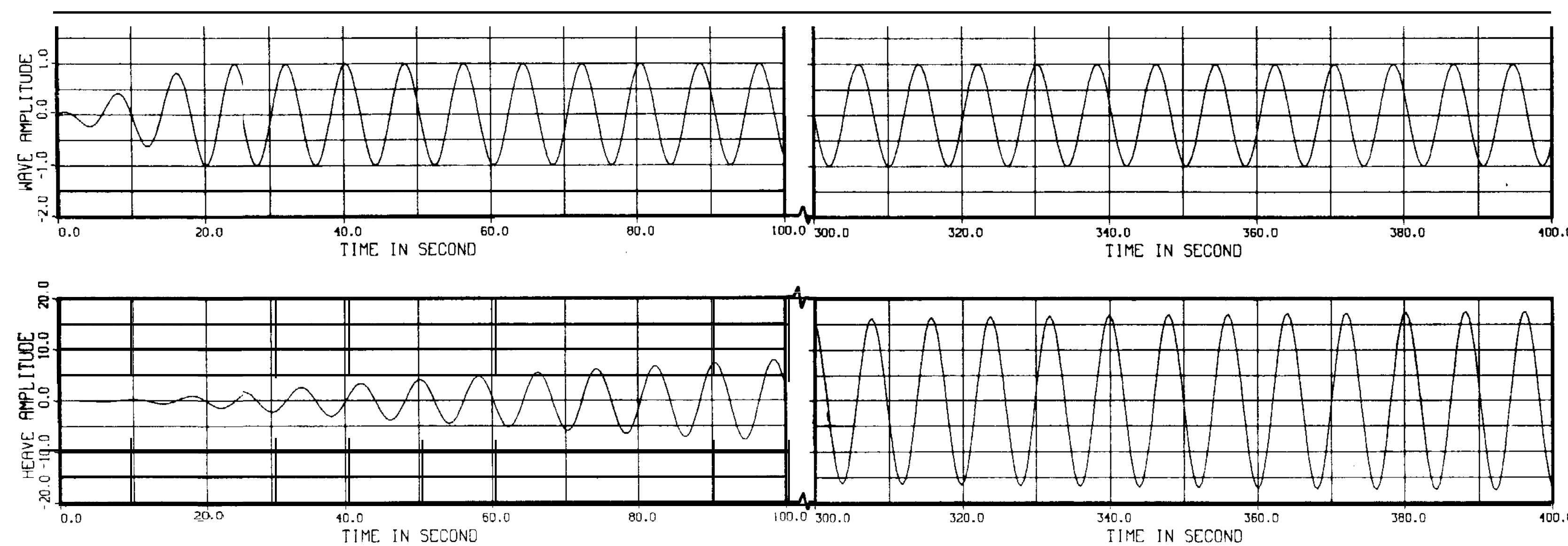

Figure 9 - Heave Motion of SWATH Section A in Time Domain for Variable Draft and ω = 0.780

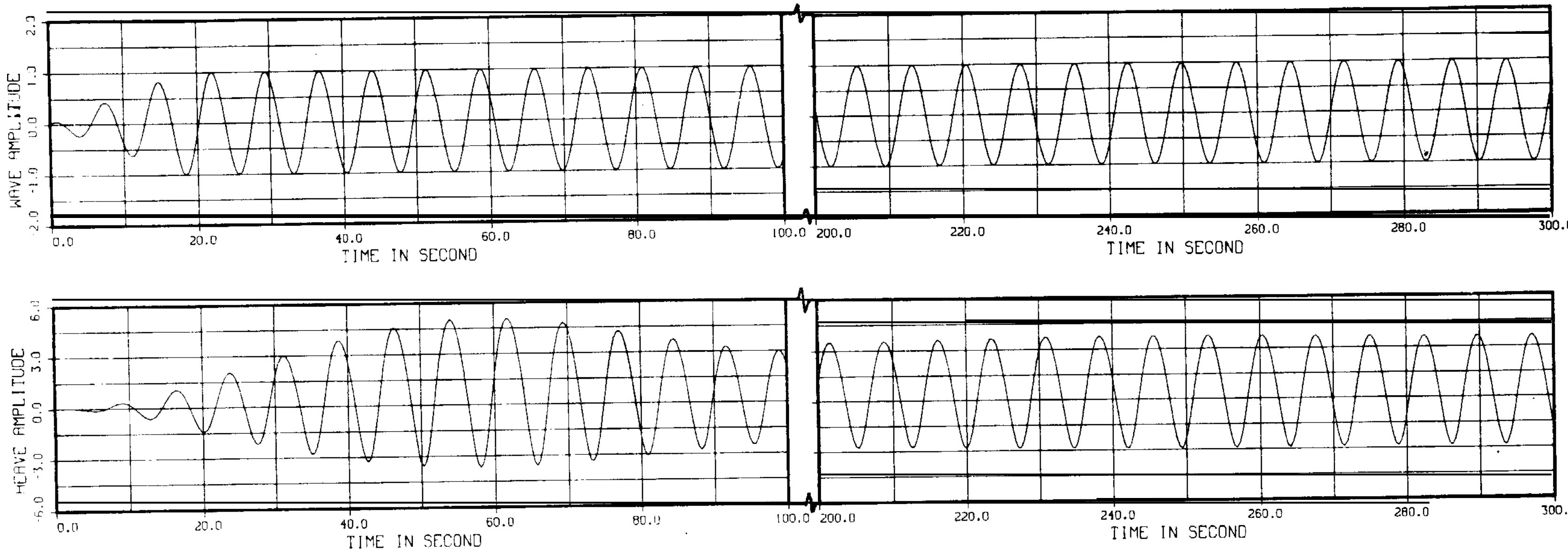

Figure 10 - Heave Motion of SWATH Section B in Time Domain for Variable Draft and ω = 0.855

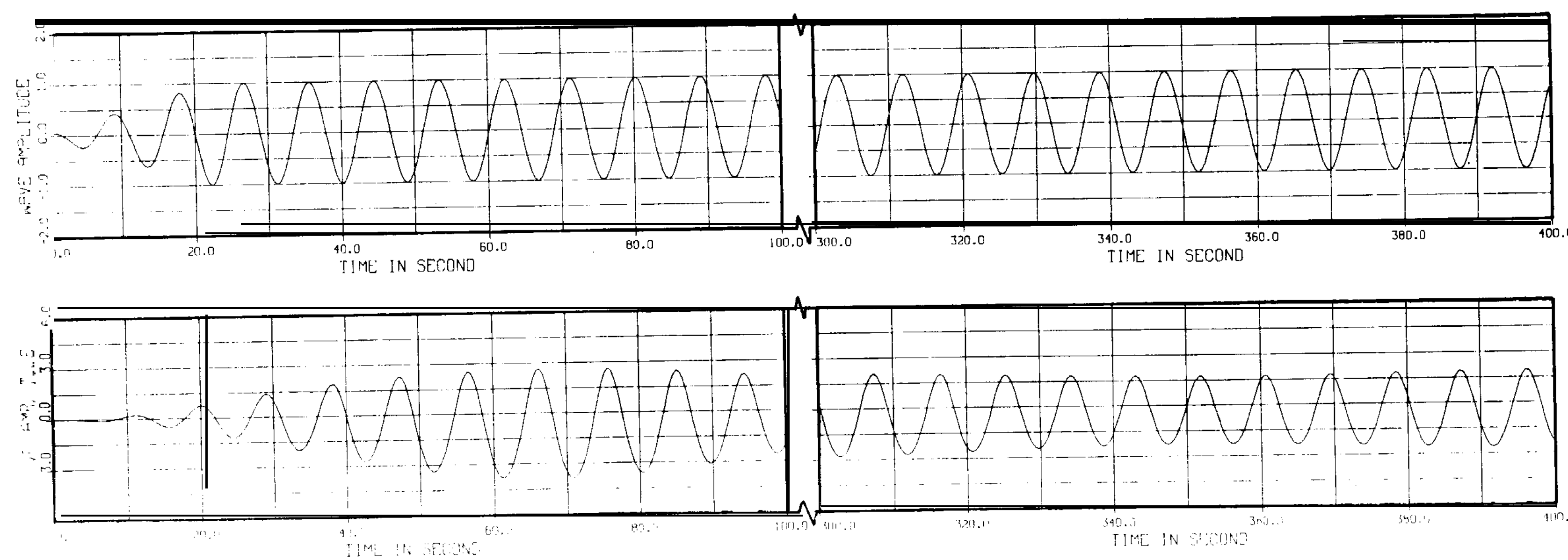

Figure 11 - Heave Motion of SWATH Section C in Time Domain for Variable Draft and ω = 0.705

As shown in Figure 11, the heave characteristic for Section C is opposite that of Section B in that positive amplitude is generally smaller than the negative one. In addition, the Section C hydrostatic and exciting force coefficients also exhibit a different trend.

Table 2 shows that if we introduce viscous damping (CD = 0.715 instead of 0), a further reduction of heave motion is obtained.

SUMMARY AND CONCLUSIONS

Time-domain analysis is applied to investigate the effect of SWATH ship strut shape on heave motion at heave resonance. The computed results show a strong dependence of the heave motion on strut shape. A substantial reduction in motion is achievable by proper strut selection for SWATH ships. The following conclusions may be drawn from the present study:

1. Heave motion at resonance can be reduced substantially by a proper choice of strut shape. Furthermore, there is an additional reduction of the ship motion amplitude when viscous damping forces are incorporated.

2. The present study was carried out only for two-dimensional sections. It is of interest to conduct a similar investigation for existing SWATH ship models, such as SWATH 6A, 6B, 6C, and 6D. We can then compare the results with experimental data obtained in regular waves.

ACKNOWLEDGMENTS

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APPENDIX

ADAMS-MOULTON METHOD

When a differential equation is given as

$$\frac{dy}{dx} \equiv y' = f(x,y) \qquad \text{(A1)}$$

with initial values $x = x_0$ and $y = y_o$, the approximate solution can be expressed with the backward difference as

$$y_{n+1} = y_n + h[y'_n+(1/2)\nabla y'_n+(5/12)\nabla^2 y'_n+(3/8)\nabla^3 y'_n+(251/720)\nabla^4 y'_n+\dots] \qquad \text{(A2)}$$

where h is the step increase of x, and the backward difference operator ∇ is defined as

$$\nabla y'_n = y'_n - y_{n-1}$$

$$\nabla^2 y'_n = \nabla y'_n - \nabla y'_{n-1} = y'_n - 2y'_{n-1} + y'_{n-2}$$

$$\nabla^3 y'_n = \nabla^2 y'_n - \nabla^2 y'_{n-1} = y'_n - 3y'_{n-1} + 3y'_{n-2} - y'_{n-3} \qquad \text{(A3)}$$

and so on. The computational scheme of the backward difference is given in tabular form as

x	y	y'	$\nabla y'$	$\nabla^2 y'$	$\nabla^3 y'$	$\nabla^4 y'$
x_{n-3}	y_{n-3}	y'_{n-3}		$\nabla^2 y'_{n-2}$		$\nabla^4 y'_{n-1}$
			$\nabla y'_{n-2}$		$\nabla^3 y'_{n-1}$	
x_{n-2}	y_{n-2}	y'_{n-2}		$\nabla^2 y'_{n-1}$		$\nabla^4 y'_n$
			$\nabla y'_{n-1}$		$\nabla^3 y'_n$	
x_{n-1}	y_{n-1}	y'_{n-1}		$\nabla^2 y'_n$		
			$\nabla y'_n$			
x_n	y_n	y'_n				

The numerical procedure of the Adams method* is

1. Use Equation (A2) to compute y_{n+1}
2. From the given differential equation Equation (A1), calculate y'_{n+1}
3. Complete the difference table for the (n+1)th line
4. Using the (n+1)th line in place of the nth line, repeat the three steps.

Equation (A2) computes y_{n+1} without using y'_{n+1}. Moulton's method, however, computes y_{n+1} using y'_{n+1} more accurately. The solution of Equation (A1) by Moulton's method is given by

$$y_{n+1} = y_n + h[y'_{n+1} - (1/2)\nabla y'_{n+1} - (1/24)\nabla^3 y'_{n+1}$$

$$-(19/270)\nabla^4 y'_{n+1} - (27/1440)\nabla^5 y'_{n+1} + \ldots] \qquad \text{(A4)}$$

*Details of this method are given in W.E. Milne, "Numerical Solution of Differential Equations," Dover Publications, Inc., New York (1970).

At the start of computation (or n = o) the values of the backward difference are not available. We apply the Taylor series method to calculate these tabular values. The Taylor series fior y is given by

$$y = y_o + y'_o(x-x_o) + \frac{y''_o}{2!}(x-x_o)^2 + \frac{y'''_o}{3!}(x-x_o)^3 + \ldots \qquad \text{(A5)}$$

where y'_o is the value of Equation (Al) at $x = x_o$, y''_o the value of y'' at $x = x_o$, and so on. y''_o can be obtained after differentiating Equation (Al) and substituting $x = x_o$, $y = y_o$, and $y' = y'_o$. In order to compute y_{-1} or y_{n-1} for n = 0, we compute y'_o, y''_o, y'''_o, ... with initial values, and then calculate y_{-1} by means of Equation (A5) with an assumed value for $(x_{-1} - x_o)$. With a known value of y_{-1} we calculate the derivatives y'_{-1}, y''_{-1}, y'''_{-1}, --- , and y_{-2} can be calculated with substitution of $(x_{-2} - x_{-1})$ for $(x_{-1} - x_o)$. Once y_{-1}, y'_{-1}, y'_{-2}, . . . are known, the backward differences of y' are easily computed.

When a system of first-order differential equations is given as

$$y' = f(x,y,z)$$

$$z' = g(x,y,z)$$

with initial values of $x = x_o$, $y = y_o$, and $z = z_o$, the solution can be obtained by the Adams-Moulton method. In this case we need two tables of backward differences, one each for y and z. Equation (A5) is used to calculate the values at the start of the computation for y and z. Once the tables are ready, y_{n+1} and z_{n+1} are computed with an equation having the form of Equation (AZ), and we call these the first results. A new table of backward differences is computed with the first results. That is, the second results for y_{n+1} and z_{n+1} are computed with Equation (AZ) and this yields a new table of backward differences. These values are compared with the first results. If the convergence is not within the desired limit, the procedure is repeated using the second results to compute third results, and so on, until the convergence is satisfactory.

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