DRA/TM(AWMH)9234
OCTOBER 1992
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THE FREE DECAY OF COUPLED HEAVE AND PITCH MOTIONS OF A MODEL FRIGATE

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DRA/TM(AWMH)92340

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by
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Approved for release

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....
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SUMMARY

The PAT-91 ship program has been found to over predict damping especially at resonant frequencies, resulting in there being no significant peak in the transfer function of pitch at resonance. This memorandum presents the results of a series of experiments that measured the decay time histories of a model frigate free to move in the vertical plane, in an attempt to identify where the problems might be occurring.

Judgements are made concerning the components in the heave and pitch motions using the terms in the full two dimensional strip theory heave and pitch motion equations to explain the trends shown.

The investigation has shown that the sectional damping coefficient appears to be over predicted. This results in a relatively poor prediction of heave decay curves at low speed and over estimates the damping in the pitch decay curves. It appears that the discrepancies seen in the heave and pitch transfer functions could be due to the wave excitation being predicted incorrectly.

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THE FREE DECAY OF COUPLED HEAVE AND PITCH MOTIONS OF A MODEL FRIGATE

1. OBJECTIVES

This technical memorandum provides a comparison of the heave and pitch motion decay time histories together with the analytical decay time histories synthesised using the hydrodynamic coefficients predicted by PAT-91 (Reference 1).

The objective is to investigate the reasons for the poor prediction of pitch amplitude at pitch resonance.

The work was carried out for DOR(Sea) as part of the Research Package number P15e912x and marks the completion of milestone MS No 6999.

2. INTRODUCTION

The way that a ship responds in an ocean environment is an important consideration in its design especially if the vessel is required to operate in areas where rough weather is likely. The capability to predict reliably the behaviour of a ship in realistic wave conditions is important for the naval architect to assess the relative merits of different designs.

Work at the Defence Research Agency at Haslar has concentrated on developing such a capability which has culminated in the formation of the PAT suite of ship motion programs. PAT-80 was the first version to be implemented and has been subsequently updated over the last decade to the present version PAT-91 (Reference 1). The strip theory program SCORES (Reference 2) is used to predict the vertical plane transfer functions. The two dimensional properties used by SCORES are calculated using Lewis forms.

Experiments have been carried out over the years in an attempt to validate the suite or identify if there are problems in the suite. This report concentrates on the vertical plane motions. References 3-5 show that the vertical motions are predicted with acceptable accuracy.

However, Reference 6 shows an error in the prediction of the absolute motion spectrum for a container ship in head seas. This suggests errors in the prediction of pitch and heave motion. The predicted transfer functions of pitch and heave tend not to have significant peaks suggesting a heavily damped system. Yet experiments carried out by Gerritsma on two 3 metre models of the Wigley Hull forms (Reference 7) shows marked resonance in the pitch and heave transfer functions.

Reference 8 shows a comparison on predictions of vertical plane transfer functions from a variety of computer programs worldwide. One conclusion is that the prediction of pitch is suspect at resonance. Reference 8 shows the predictions of the motions of a S-175 container throughout the world. The comparisons are favourable at frequencies other than those at or around resonance.

Reference 9 describes a series of experiments aimed at determining the non-linearities of pitch and heave in waves of increasing amplitude. The pitch transfer function had to be found in order to determine the frequency at which pitch resonance occurs. The transfer functions are shown in Figure 1. The pitch transfer function shows a marked resonance at forward speed, whereas the theory predicts little or no resonance. Thus, the PAT suite predicts the transfer function satisfactorily except at the resonant frequencies. Unfortunately the most interesting point is at and around resonance. Therefore the cause of the discrepancies between the predicted and the measured transfer function should be addressed.

Included in the experiments reported in Reference 9 were a series of experiments that measured the decay time histories of pitch and heave in calm water. This eliminated the forcing terms from the equations of motion and any source of errors in the programs will be attributed to the hydrodynamic coefficients.

3. EXPERIMENTS

These experiments were part of a larger set of experiments designed to investigate the non linearities of vertical motion in waves of increasing steepness. The experiments were carried out in No 1 Ship Tank at Haslar. The model was a scale model of the narrow beam LEANDER class frigate.

The free decay tests were carried out at varying speeds in calm water. The bow of the model was lifted and then released, the subsequent decaying motion being recorded. The model was free to heave and pitch, but it was not allowed to surge, roll, sway or yaw.

4. GENERAL THEORY

When a ship responds in waves the vertical plane motions (heave and pitch) are coupled together and therefore influence each other. Heave motion x_5 is taken to be positive downwards. Pitch motion x_5 is positive bow up.

Using the notation adopted by Lloyd (Reference 10) but neglecting end effects, the full set of equations for heave and pitch is given by:

$$(m + a_{33})\ddot{x}_3 + b_{33}\dot{x}_3 + c_{33}x_3 + a_{35}\ddot{x}_5 + b_{35}\dot{x}_5 + c_{35}x_5 = F_{30}\sin(\omega_e t + \gamma_3) \tag{1}$$

and

$$a_{53}\ddot{x}_3 + b_{53}\dot{x}_3 + c_{53}x_3 + (I_{55} + a_{55})\ddot{x}_5 + b_{55}\dot{x}_5 + c_{55}x_5 = F_{50}\sin(\omega_e t + \gamma_5) \tag{2}$$

The problems lie in determining the added mass terms (a_{ij}), the damping terms (b_{ij}), the stiffness terms (c_{ij}) and the excitation terms (F_i).

Gerritsma and Beukelman (Reference 11), amongst others, developed a theoretical method for determining these individual terms.

The total downward vertical force on a strip require to sustain heave and pitch motions of the ship is given by:

$$\delta F_3 = \left[a'_{33}(\ddot{x}_3 - x_{BI}\ddot{x}_5 + 2\dot{U}x_5) + \left(b'_{33} - \frac{Uda'_{33}}{dx_{BI}}\right)(\dot{x}_3 - x_{BI}\dot{x}'_5 + Ux_5) + c_{33}(x_3 - x_{BI}x_5)\right]\delta x_{BI} \tag{3}$$

and integrating these forces over the ship's hull, the total heave force and pitch moment required to balance the hydrodynamic reaction and sustain heave and pitch motions of the ship are given by:

$$F_3 = \int dF_3 \tag{4}$$

and

$$F_5 = -\int x_{BI} dF_3 \tag{5}$$

Equations (4) and (5) must be compared with (1) and (2) and by equating coefficients of like terms the following can be derived:

$$a_{33} = \int a'_{33} dx_{B1}$$

$$b_{33} = \int b'_{33} dx_{B1}$$

$$c_{33} = \int c'_{33} dx_{B1}$$

$$a_{35} = -\int x_{B1} a'_{33} dx_{B1}$$

$$b_{35} = 2U \int a'_{33} dx_{B1} - \int x_{B1} b'_{33} dx'_{B1}$$

$$c_{35} = U \int b'_{33} dx_{B1} - \int x_{B1} c'_{33} dx_{B1}$$

$$a_{53} = -\int x_{B1} a'_{33} dx_{B1}$$

$$b_{53} = -\int x_{B1} b'_{33} dx_{B1}$$

$$c_{53} = \int x_{B1} c'_{33} dx_{B1}$$

$$a_{55} = \int x_{B1}^2 a'_{33} dx_{B1}$$

$$b_{55} = -2U \int x_{B1} a'_{33} dx_{B1} + \int x_{B1}^2 b'_{33} dx_{B1}$$

$$c_{55} = -U \int x_{B1} b'_{33} dx_{B1} + \int x_{B1}^2 c'_{33} dx_{B1}$$

So, the coefficients of equations (1) and (2) are determined except for the forcing terms F_3, F_5 and the sectional coefficients.

$$a'_{33},\ b'_{33},\ c'_{33}$$

In the examples shown here the two dimensional properties (TDPs) a'_{33}, b'_{33}, were calculated using Lewis forms only. An initial study also looked at calculating the TDPs using a multi-parameter fit such as that described in Reference 12. The two techniques showed virtually no differences in the final results and so only one case is reported here.

The way the forces on the strip is calculated has remained virtually unchanged since the Froude-Kriloff hypothesis. Under this hypothesis the force due to waves is found from the buoyancy change due to the wave profile, and the pressure gradient existing within the wave. The total exciting force is taken from the difference between the buoyancy force and the force due to the change in pressure gradient. However, the effect of the ship on the pressure distribution within the wave is not considered.

In a routine seakeeping calculation, the forcing terms on the right hand side of equations (1) and (2) are non zero. In a decay experiment the excitation due to the waves is not present and the forcing terms are zero.

So, setting equations (1) and (2) to zero, they can be solved simultaneously to eliminate either heave x_3 or pitch x_5. For simplicity, using the D-operator notation where

$$D = \frac{d}{dt}$$

$$(c_1D^4 + c_2D^3 + c_3D^2 + c_4D + c_5)x_3 = 0 \tag{6a}$$

$$(c_1D^4 + c_2D^3 + c_3D^2 + c_4D + c_5)x_5 = 0 \tag{6b}$$

where

$$c_1 = a_{33}a_{55} - a_{35}a_{53}$$

$$c_2 = a_{33}b_{55} + a_{55}b_{33} - a_{35}b_{53} - a_{53}b_{35}$$

$$c_3 = a_{33}c_{55} + b_{33}b_{55} + a_{55}c_{33} - a_{53}c_{35} - b_{35}b_{53} - a_{35}c_{53}$$

$$c_4 = b_{33}c_{55} + b_{55}c_{33} - b_{35}c_{53} - b_{53}c_{35}$$

$$c_5 = c_{33}c_{55} - c_{35}c_{53}$$

Equations (6a) and (6b) are fourth order homogeneous linear ordinary differential equations. Reference 13 shows a method of treating homogeneous linear ODEs.

So, both equations (6a) and (6b) can be solved algebraically by treating them as quartic equations in the D-operator.

All four roots of the equations are of the form

$$\alpha \pm \beta i,\ \gamma \pm \delta i \qquad with\ \alpha,\ \beta,\ \gamma,\ \delta\ \in \mathbf{R}$$

giving a general solution of the form

$$x_3(t)=Ae^{\alpha t}\sin(\beta t+\epsilon)+Be^{\gamma t}\sin(\delta t+\zeta) \tag{7}$$

$$x_5(t) = Ce^{\alpha t}\sin(\beta t + \eta) + De^{\gamma t}\sin(\delta t + \theta) \tag{8}$$

These equations each represent two free decay motions with the unknown terms.

A, B, C, D - *motion amplitudes*

$\epsilon, \zeta, \eta, \theta$ - *motion phase-shifts*

These unknowns are found using initial conditions taken from experimental data which are then substituted into equations (7) and (8) and their first three derivatives.

5. INITIAL CONDITIONS

The datum t = 0 was not taken at the point of release of the model. Strip theory is a steady state motion calculation and it was felt prudent to allow at least one cycle of the decay time histories to pass to allow any unsteady characteristics to settle out. Therefore t = 0 corresponds to the maximum or minimum immediately following the point of release.

The unknowns are unique for each set of different initial conditions.

For $x_3(t)$ and their respective derivatives at t=0 we have the following system of equations:

$$x_3(0) = A\sin\epsilon + B\sin\zeta$$

$$\dot{x}_3(0) = A(\alpha\sin\epsilon + \beta\cos\epsilon) + B(\delta\sin\zeta + \gamma\cos\zeta)$$

$$\ddot{x}_3(0) = (\alpha^2 - \beta^2)A\sin\epsilon + 2\alpha\beta A\cos\epsilon + (\gamma^2 - \delta^2)B\sin\zeta + 2\gamma\delta B\cos\zeta$$

$$\dddot{x}_3(0) = (\alpha^3 - 3\alpha\beta^2)A\sin\epsilon + (3\alpha^2\beta - \beta^3)A\cos\epsilon + (\gamma^3 - 3\gamma\delta^2)B\sin\zeta + (3\gamma^2\delta - \delta^3)B\cos\zeta$$

Taking measured values of initial heave and pitch at a maximum point of the heave and the pitch amplitude time histories (so heave and pitch velocities are both zero), the initial conditions for heave and pitch are as follows:

$$x_3(0) = z_0 \text{ (initial heave) } ; x_5(0) = \theta_0 \text{ initial pitch)}$$

$$\dot{x}_3(0) = 0 ; \dot{x}_5(0) = 0$$

$$\ddot{x}_3(0) = -\frac{c_{35}}{a_{33}}\theta_0 - \frac{c_{33}}{a_{33}}z_0 ; \ddot{x}_5(0) = -\frac{c_{55}}{a_{55}}\theta_0 - \frac{c_{53}}{a_{55}}z_0$$

$$\dddot{x}_3(0) = 0 ; \dddot{x}_5(0) = 0$$

Using a matrix system the eight equations above can be solved for both heave and pitch. The following example is for heave. Substituting the following into the first four equations:

$$p_1 = A\sin\epsilon;\ p_2 = B\sin\zeta;\ p_3 = A\cos\epsilon;\ p_4 = B\cos\zeta$$

and then use the initial conditions to give the following matrix system:

$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ \alpha & \gamma & \beta & \delta \\ \alpha^2 - \beta^2 & \gamma^2 - \delta^2 & 2\alpha\beta & 2\gamma\delta \\ \alpha^3 - 3\alpha\beta^2 & \gamma^3 - 3\gamma\delta^2 & 3\alpha^2\beta - \beta^3 & 3\gamma^2\delta - \delta^3 \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{pmatrix} = \begin{pmatrix} x_3(0) \\ \dot{x}_3(0) \\ \ddot{x}_3(0) \\ \dddot{x}_3(0) \end{pmatrix}$$

Then solving this system using any suitable method values for the P_i's can be found and thus the particular solution required can be determined by:

$$\epsilon = \tan^{-1}\left(\frac{p_1}{p_3}\right);\quad \zeta = \tan^{-1}\left(\frac{p_2}{p_4}\right);\quad A = p_1\operatorname{cosec}\epsilon;\quad B = p_2\operatorname{cosec}\zeta$$

An identical method can be used for pitch, but different initial conditions are used. The general theory is easily applied for a particular set of hydrodynamic coefficients. The hydrodynamic coefficients are speed and encounter frequency dependent. PAT-91 outputs coefficients for a specified speed and a wide range of discrete wave encounter frequencies. We are concerned with coefficients at a wave encounter frequency (ω_e) corresponding to heave and pitch damped natural frequencies.

Lloyd (9) gives these as:

$$\omega_{z3}^{d} = \sqrt{\frac{c_{33}}{a_{33}}}\sqrt{1 - \frac{b_{33}^{2}}{4a_{33}c_{33}}}$$

$$\omega_{z5}^{d} = \sqrt{\frac{c_{55}}{a_{55}}}\sqrt{1 - \frac{b_{55}^{2}}{4a_{55}c_{55}}}$$

for uncoupled motions.

Both damped natural frequencies were calculated analytically from hydrodynamic coefficients which are themselves frequency dependent. The problem was solved by an iterative scheme. Initial estimates of heave and pitch damped frequencies from within the wave encounter frequency range (ie 1.5 rads/s) were taken and new estimates for the damped frequencies from the above equations were calculated. Eventually the iterative scheme converged to required values of pitch and heave damped frequencies and their corresponding hydrodynamic coefficients.

A particular problem arose because PAT-91 outputs coefficients for discrete wave encounter frequencies and these did not necessarily match the heave and pitch damped frequencies. A simple linear interpolation routine estimated the hydrodynamic coefficients each time new heave and pitch natural frequencies were found.

As the experimental data had been digitised and was therefore discrete in nature other problems also had to be compensated for. Both initial heave amplitude and pitch angle (model scale converted to ship scale) were taken from this discrete data when calculating the initial conditions. As explained earlier the maxima from the experimental heave and pitch data were chosen as initial conditions, but this did not necessarily correspond to one of the discrete points in the experimental data. Therefore a least squares mini-max fit to the experimental data, to approximate the true maxima, was used. The least squares fit was for a parabola to guarantee that the third derivatives were zero at the maximum, thus matching the third derivatives of the initial conditions.

Since the hydrodynamic coefficients are generated by PAT-91 using ship scale, the general theory above is applied to generate ship scale time histories, whereas the initial conditions are taken from experimental data for the scale model. Both time histories are non-dimensionalised before being output as a set of discrete points.

6. DISCUSSION

Decay tests were carried out at nine different Froude Numbers ranging from zero to 0.40. Having solved the quartics shown in equations (6a) and (6b), it can be seen that two terms are attributed to the decay of the time histories and two terms are attributed to the frequency of the time histories. All these terms were obtained at each Froude Number.

Table 1 shows how these four terms vary with Froude Number. The difference in the two frequency terms gets larger whilst the difference in the two decay terms becomes smaller for increasing Froude number.

Figure 2 shows a heave decay time history at high Froude number. It shows that the PAT suite can predict the decay time history very well. Both the frequency and decay appear to be accurately estimated. Small differences may be attributed to the fact that the initial condition may not be quite correct, for instance perhaps the heave velocity at the pitch maximum chosen to be the initial condition may not be exactly zero. Despite these differences, the results are encouraging.

Figure 3 shows a pitch decay time history at high Froude number. The differences are more marked. The frequency seems to be correct (apart from small differences initially which could be due to incorrect initial conditions), yet the motion is over damped. This mirrors the differences seen in Figure 1, where the predicted transfer function of pitch has no resonance and the experiments show marked resonance. Note that the decay time histories shown here are not at the speed at which the transfer function was found. One would expect the resonance to be more pronounced at higher Froude number (in head waves).

Figures 4 and 5 show heave and pitch decay time histories respectively at zero Froude number. The pitch frequency is predicted very well, with the small differences probably being attributed to slightly incorrect initial conditions. There is only a small difference in the amount of damping (shown by the number of oscillations before no motion is measured). There is certainly less of a difference between the predicted and measured decay curves than those compared at high Froude numbers.

Tables 2 and 3 show a comparison between the non-dimensional frequency and decay components of the curves, of both experimental and predicted, shown in Figures 2-9 and also for some cases not illustrated. The frequency has been non-dimensionalised by

$$\omega' = \omega\sqrt{\frac{L}{g}}$$

A non-linear least squares fit to the data was made using a function of the form:

$$y = a(e^{bt}\cos(ct + d) + f)$$

where a, b, c, d, f are constants determined by the least squares analysis.

The time histories shown in Figures 2-9 are non-dimensional and hence so are b and c.

Also shown in Tables 2 and 3 are the non-dimensional natural decay frequency (ω_d) and the decay coefficient (η) as calculated for a single degree of freedom system as shown by Lloyd (9). In order to compare the frequencies calculated for a single degree of freedom (directly from the hydrodynamic coefficients) the frequency (ω_d) was non-dimensionalised using $\sqrt{\frac{L}{g}}$. The constant b found from the least squares analysis was converted to a decay coefficient in the following way:

$$\eta_b = \frac{b}{\sqrt{b^2 + c^2}}$$

The asterisks shown in Tables 2 and 3 illustrate those results that appear in Figure 2-9.

The experimental and predicted heave damping frequencies are in good agreement, with differences not exceeding 6 per cent. The differences in pitch damping frequencies are higher, with differences of the order of 20 per cent. The differences appear to decrease with increasing speed. The heave frequencies found from the coefficients are in agreement with the experimental values but the pitch frequencies tend to be higher when calculated as an uncoupled system.

The heave and pitch decay coefficients tend to be under predicted at low speed. But, the trends suggested in the tables are all reproduced in the figures. That is, in Figure 3, the predicted pitch time decay coefficients predicted from the single degree of freedom model are larger than the fully coupled system.

According to Lloyd (Reference 10), if the model was only allowed to heave, the heave decay coefficient would be given by:

$$\eta = \frac{b_{33}}{2\sqrt{c_{33}a_{33}}}$$

and the heave damped natural frequency would be given by:

$$\omega^{d}_{33} = \omega_{e}\sqrt{1 - \eta^{2}}$$

with

$$\omega_{e} = \sqrt{\frac{c_{33}}{a_{33}}}$$ the natural frequency

So the frequency component is dependent upon the damping term for a single degree of freedom system, yet the decay term is more dependent upon the damping term. This could suggest that the differences observed in Figures 2-5 are attributed to the ship motion suite predicting damping incorrectly. It should be re-called that the experiments described here are a fully coupled system, it is difficult to isolate the terms from equations (1) and (2) that make up the constituent parts of the general equations (7) and (8).

Furthermore, at zero and high Froude numbers the prediction of the heave decay curves is very good.

Thus, if it was b'_{33} that was not predicted correctly, then does this reflect the results of the decay experiments and the transfer functions shown in Figure 1?

The heaving motion of a ship is dominated at low frequency by the stiffness terms. The amount of damping at the low frequencies is negligible and even if these values were in error by a large percentage the effect of the heave response will be small. The actual values of damping predicted at heave resonance are virtually correct. However, because of the nature of the coupled equations of pitch and heave, the heave sectional damping b'_{33} has a magnified effect, in the equation for b_{55} for example. Thus the fact that the value of b'_{33} is in error, perhaps, will have a greater effect in pitch than in heave.

Also for pitch motion, at high Froude numbers the decay natural frequencies are good, but the decay coefficient is clearly over predicted by the PAT suite. The calculation of b_{55} involves a lever arm squared and this will exaggerate any inaccuracies in the sectional damping coefficients (b'_{33}). This, together with the increase in importance of the damping terms in pitch, makes the transfer functions at forward speed wrong. The fact that the prediction of pitch at zero speed appears to be very good could be due to the increased stiffness in pitch at zero speed.

Figures 6 and 7 show the decay curves at the Froude number used in the transfer function experiments in Figure 1. The heave decay time histories (Figure 6) compare very favourably with each other. It is difficult to assess the pitch time histories in Figure 7 because the motions are so small. However, it appears that the curves are closely matched with only slight differences in the damping.

Reference 14 describes a set of experiments that measured the added mass and damping of two dimensional bodies and compares them with sectional coefficients as predicted using Lewis forms and a three parameter fit. The report shows that there are slight discrepancies in damping prediction at low frequency from the two methods used.

Figures 8 and 9 show heave and pitch decay curves at low Froude number (Fn = 0.07). Here the prediction is not correct. Figures 5 and 6 show much better results for zero speed and the prediction deteriorates more than would be expected for such a small increase in forward speed.

Thus, what other differences should be taken into account?

The initial heave amplitude is approximately equal in both cases, yet the initial pitch angle at zero speed is about half of that at Fn = 0.07. So, the deterioration in pitch prediction at Fn = 0.07 could be related to the size of the initial pitch angle. The large pitch angle could be introducing some non-linearities which the simple decay equation can not cope with. In solving the decay equation, a few assumptions are made, one of which is that the stiffness terms (c_{ij}) remain constant for a given speed and frequency. However, for large pitch angles the stiffness terms will also be dependent upon pitch angle.

References 9 and 15 have reported that excessive non-linear pitch motions have been observed.

7. CONCLUSIONS

The investigation has shown that the sectional damping coefficient appears to be over predicted. This results in a relatively poor prediction of heave decay curves at low speed and over estimates the damping in the pitch decay curves. The heaving motion of a ship is dominated at low frequencies by the stiffness terms. The amount of damping at these frequencies is negligible and any errors in the damping terms have little effect on the transfer functions. The actual values of heave damping at resonance appear to be correct, but because of the nature of the coupled system of equations the heave sectional damping has a magnified effect in the pitch equation.

The comparisons between theory and experiments have shown that the sectional damping coefficient b'_{33} may not be theoretically predicted correctly at all frequencies. This has had no or little effect on the predictions of the heave motion transfer functions away from resonance. Furthermore, because of the nature of the coupled equations of pitch and heave, the heave sectional damping b'_{33} has a magnified effect in the pitch equations. This has an effect on the predictions of the pitch motion transfer functions.

Breaking down the time histories into the decay term and frequency term has shown that the heave damped frequencies are predicted very well at all speeds. Some differences are noted in the pitch frequency. The predictions of decay coefficients are less good for both heave and pitch.

The differences described above, however, do not appear sufficiently large to account for the discrepancies shown in Figure 1. Therefore, these discrepancies could be attributed to the way the forcing terms are evaluated in strip theory.

This TM has shown the importance of considering only low amplitude motions when using strip theory to make seakeeping predictions. Strip theory is still used widely in predicting the rough weather performance of a ship. The benefits are that it is quick and, in the vertical plane, fairly accurate. However this TM has emphasised the limitations of linear strip theory when it is used to make linear predictions of a ship behaving in a non-linear manner.

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Table 1

DECAY AND FREQUENCY TERMS OF THE SOLVED QUARTIC

Froude Number	α	γ	$\beta\sqrt{(L/g)}$	$\delta\sqrt{(L/g)}$
0.00	-0.324	-0.297	4.523	4.363
0.07	-0.358	-0.298	4.567	4.380
0.16	-0.376	-0.306	4.603	4.327
0.18	-0.375	-0.309	4.607	4.310
0.20	-0.375	-0.315	4.617	4.290
0.25	-0.371	-0.315	4.607	4.127
0.26	-0.378	-0.326	4.646	4.240
0.31	-0.380	-0.336	4.680	4.183
0.41	-0.385	-0.356	4.753	4.060

Table 2

EXPERIMENTAL AND PREDICTED NON-DIMENSIONAL DAMPED FREQUENCY OF DECAY CURVES

Froude Number	Experimental		Predicted			
			from Graphs		from Coefficients (Lloyd 1989)	
	Heave	Pitch	Heave	Pitch	Heave	Pitch
0.00*	4.180	4.234	4.325	4.340	4.280	4.630
0.07	4.177	3.796	4.346	4.570	4.313	4.670
0.16	4.166	3.384	4.360	4.318	4.307	4.660
0.18	4.279	4.355	4.353	4.320	4.307	4.663
0.20	4.159	3.774	4.268	4.521	4.307	4.653
0.25*	4.130	3.858	4.244	4.276	4.267	4.607
0.26	4.060	3.824	4.227	4.510	4.303	4.640
0.31	3.975	3.798	4.229	4.290	4.300	4.623
0.40*	3.877	3.705	4.090	4.466	4.293	4.583

* See Figures 2-9

Table 3

EXPERIMENTAL AND PREDICTED DECAY COEFFICIENT OF DECAY CURVES

Froude Number	Experimental		Predicted			
			from Graphs		from Coefficients (LLoyd 1989)	
	Heave	Pitch	Heave	Pitch	Heave	Pitch
0.00*	0.222	0.224	0.172	0.176	0.221	0.234
0.07	0.222	0.222	0.119	0.224	0.228	0.249
0.16	0.218	0.195	0.182	0.159	0.232	02.62
0.18	0.209	0.222	0.186	0.171	0.233	0.266
0.20	0.211	0.190	0.137	0.227	0.234	0.269
0.25*	0.191	0.215	0.186	0.197	0.231	0.273
0.26	0.165	0.195	0.146	0.230	0.236	0.277
0.31	0.177	0,208	0.200	0.233	0.238	0.285
0.40*	0.189	0.193	0.188	0.239	0.242	0.302

* See Figures 2-9

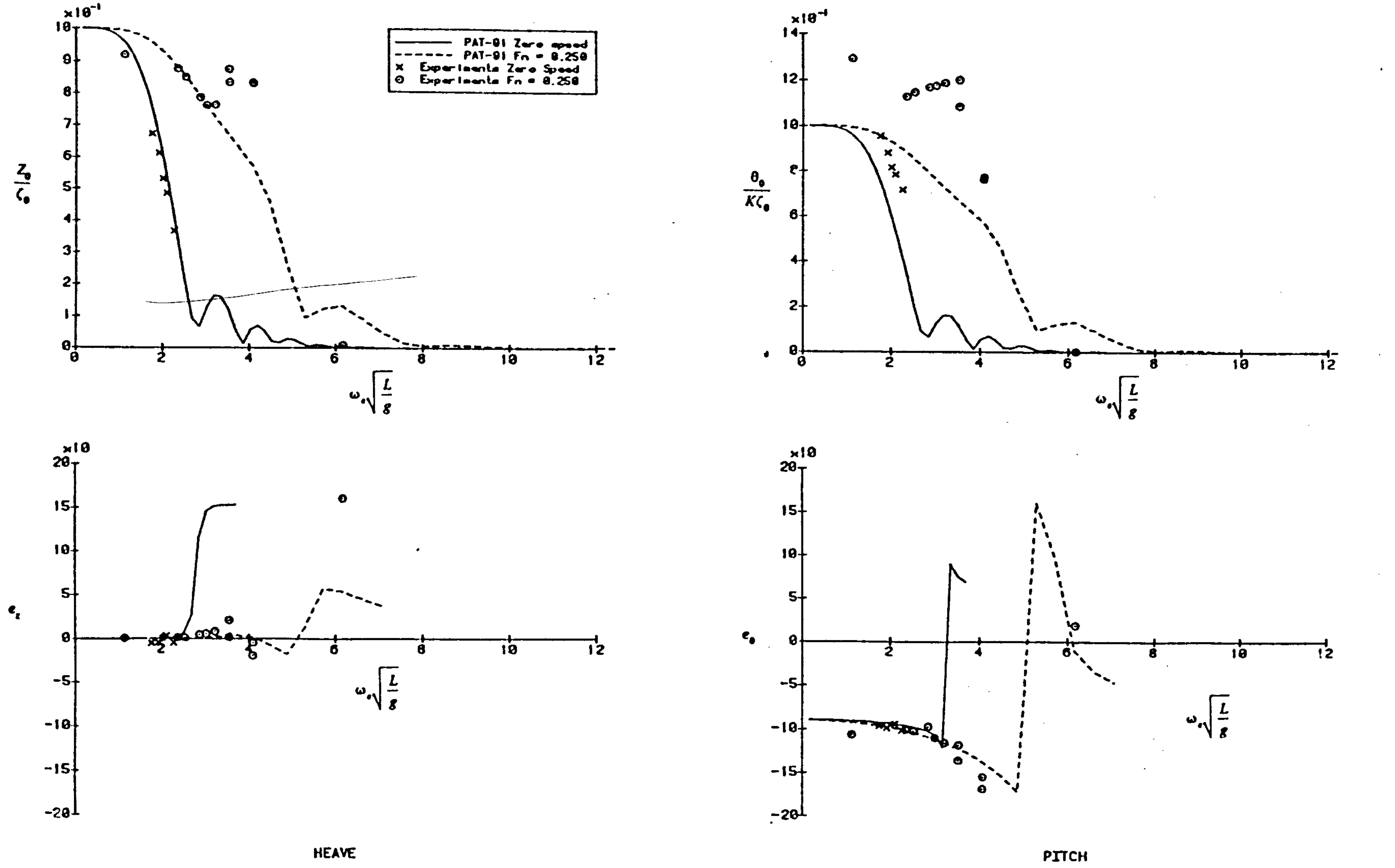

Figure 1

RIGID BODY MOTION TRANSFER FUNCTIONS

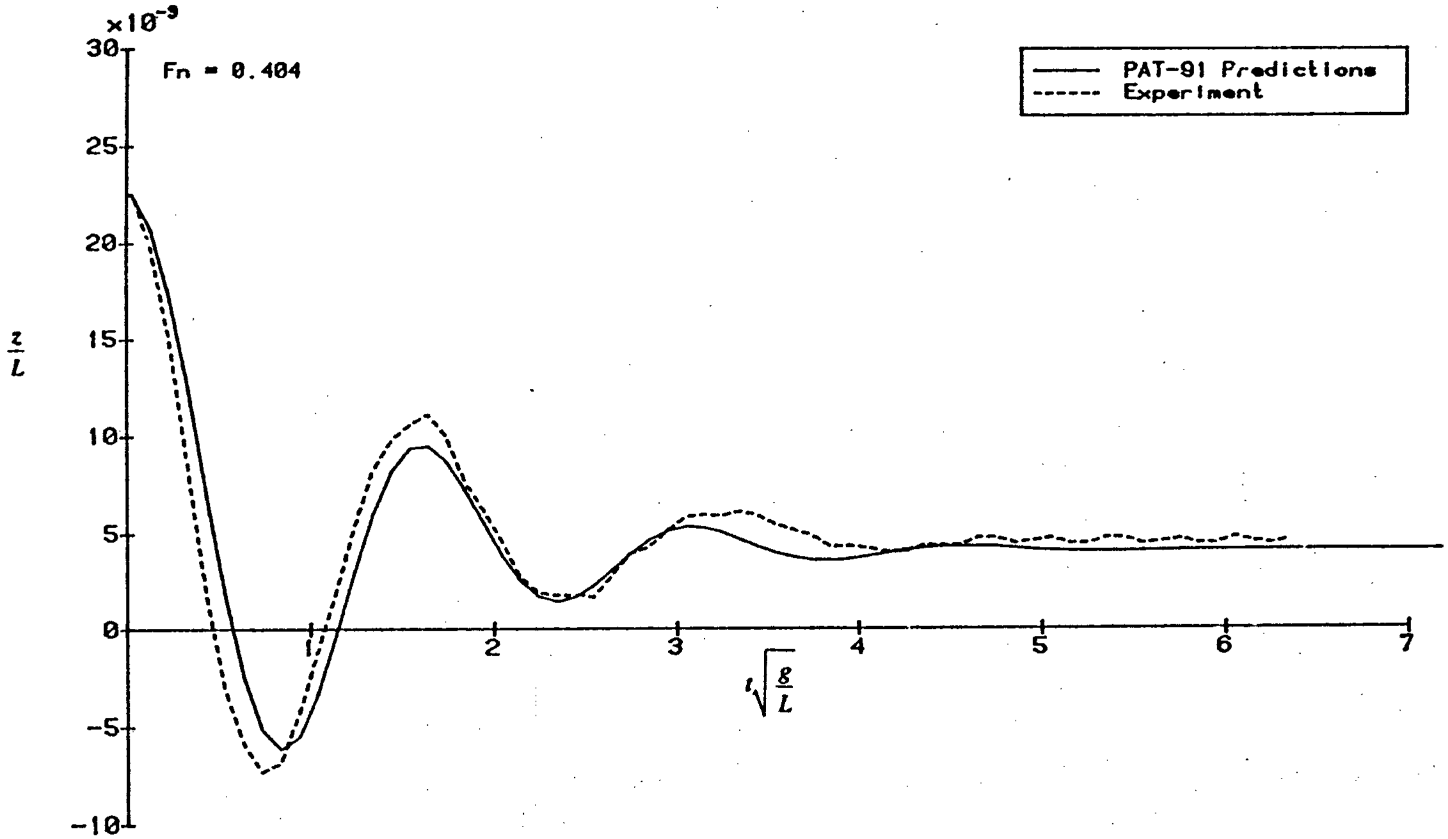

Figure 2

HEAVE DECAY TIME HISTORY

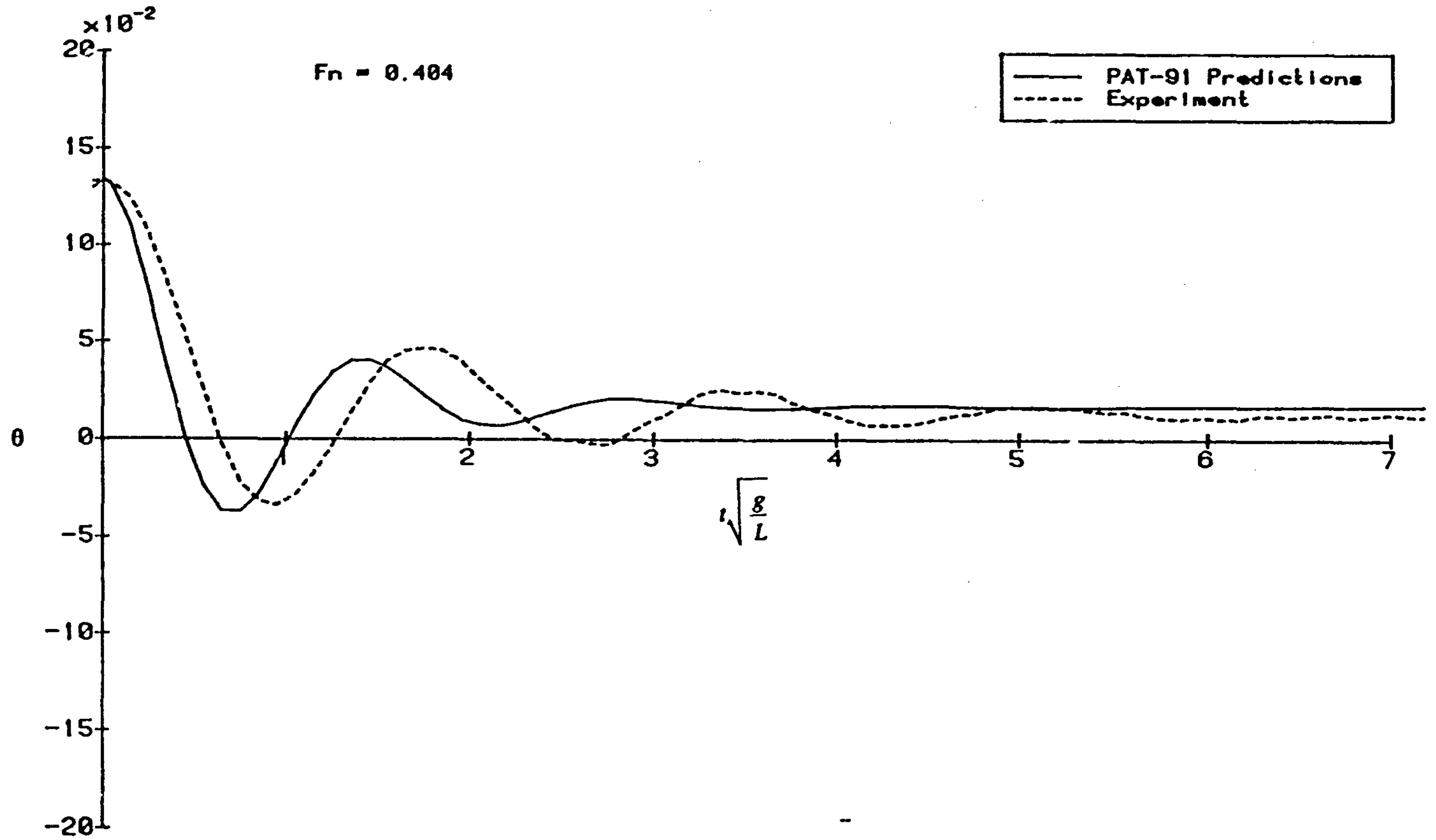

Figure 3

PITCH DECAY TIME HISTORY

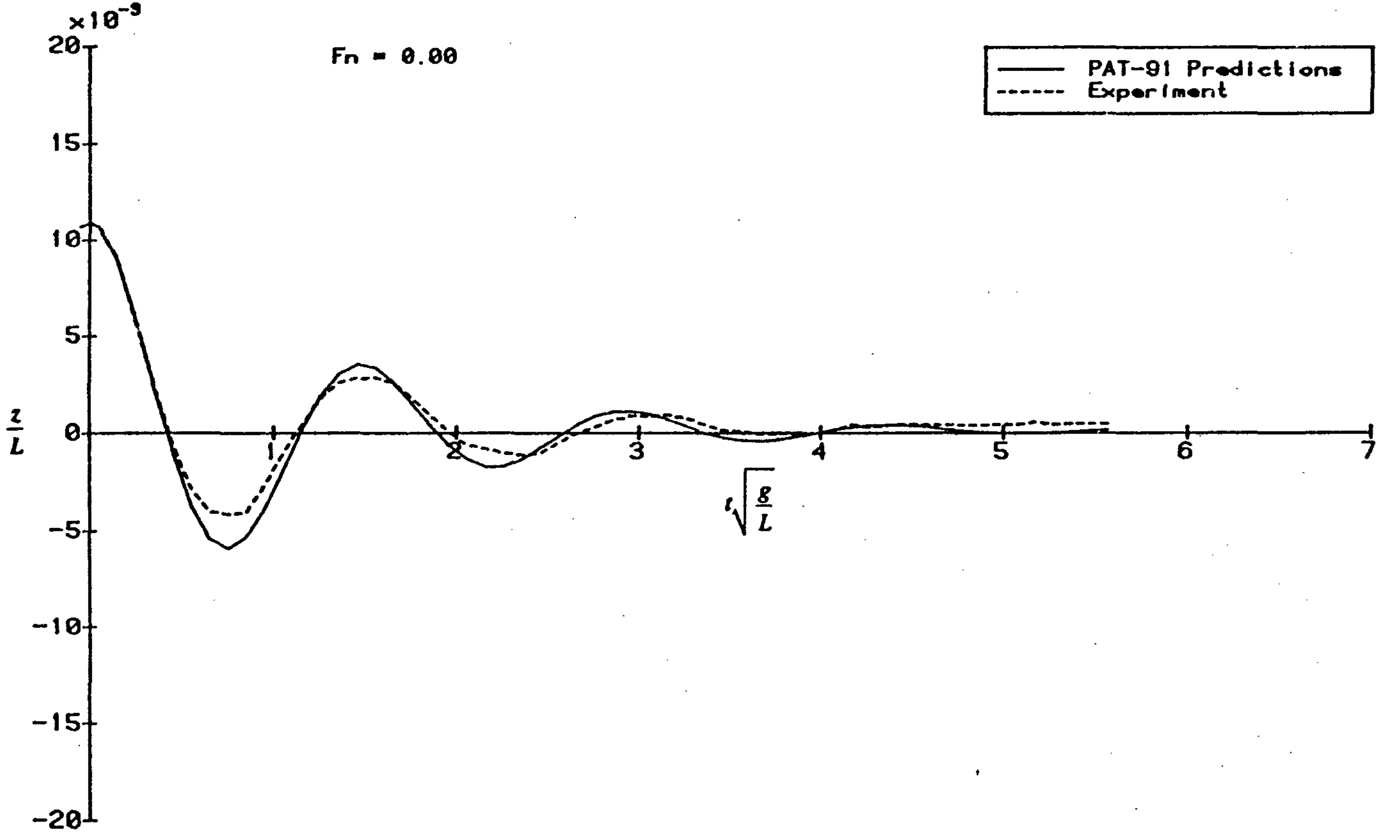

Figure 4

HEAVE DECAY TIME HISTORY

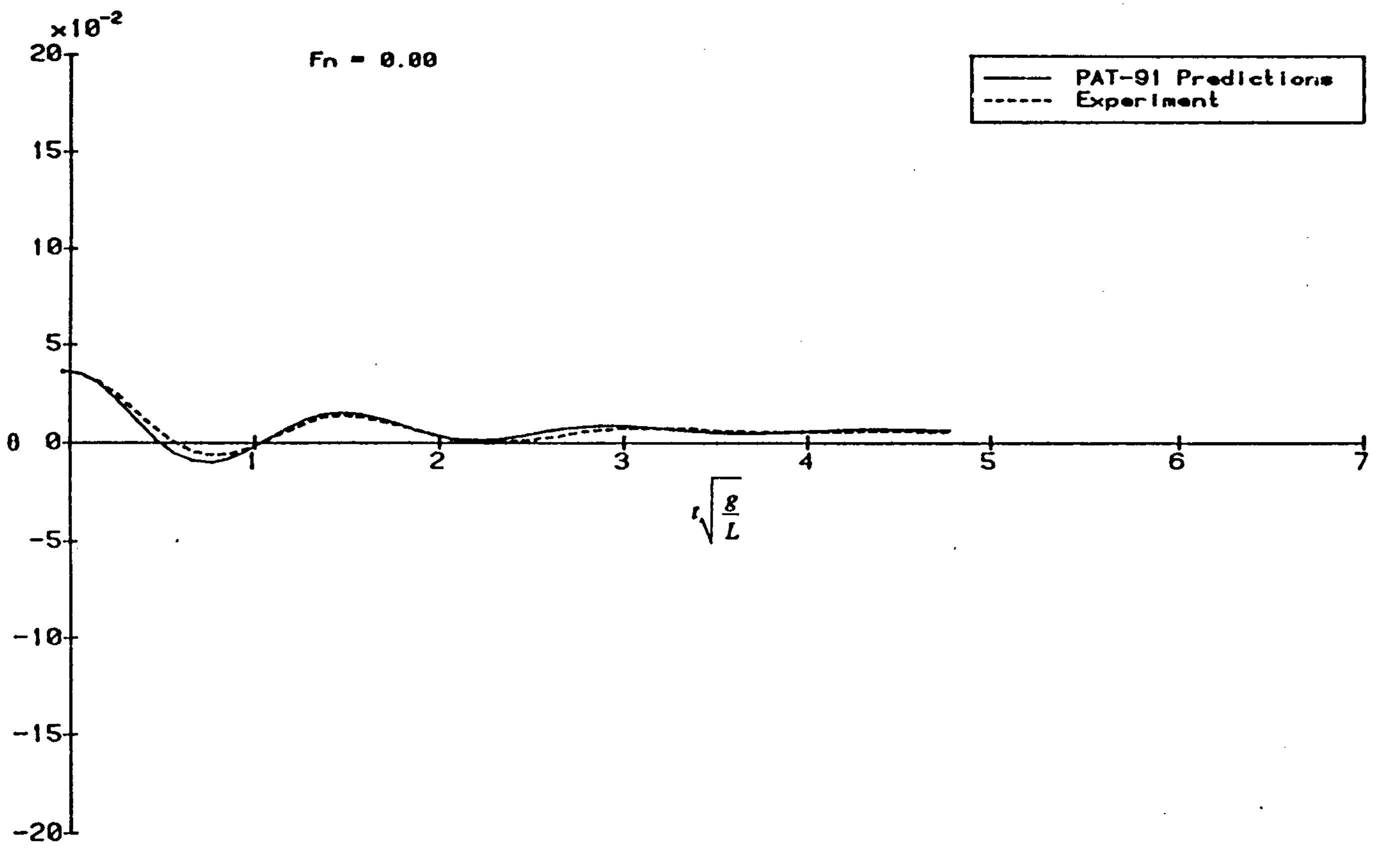

Figure 5

PITCH DECAY TIME HISTORY

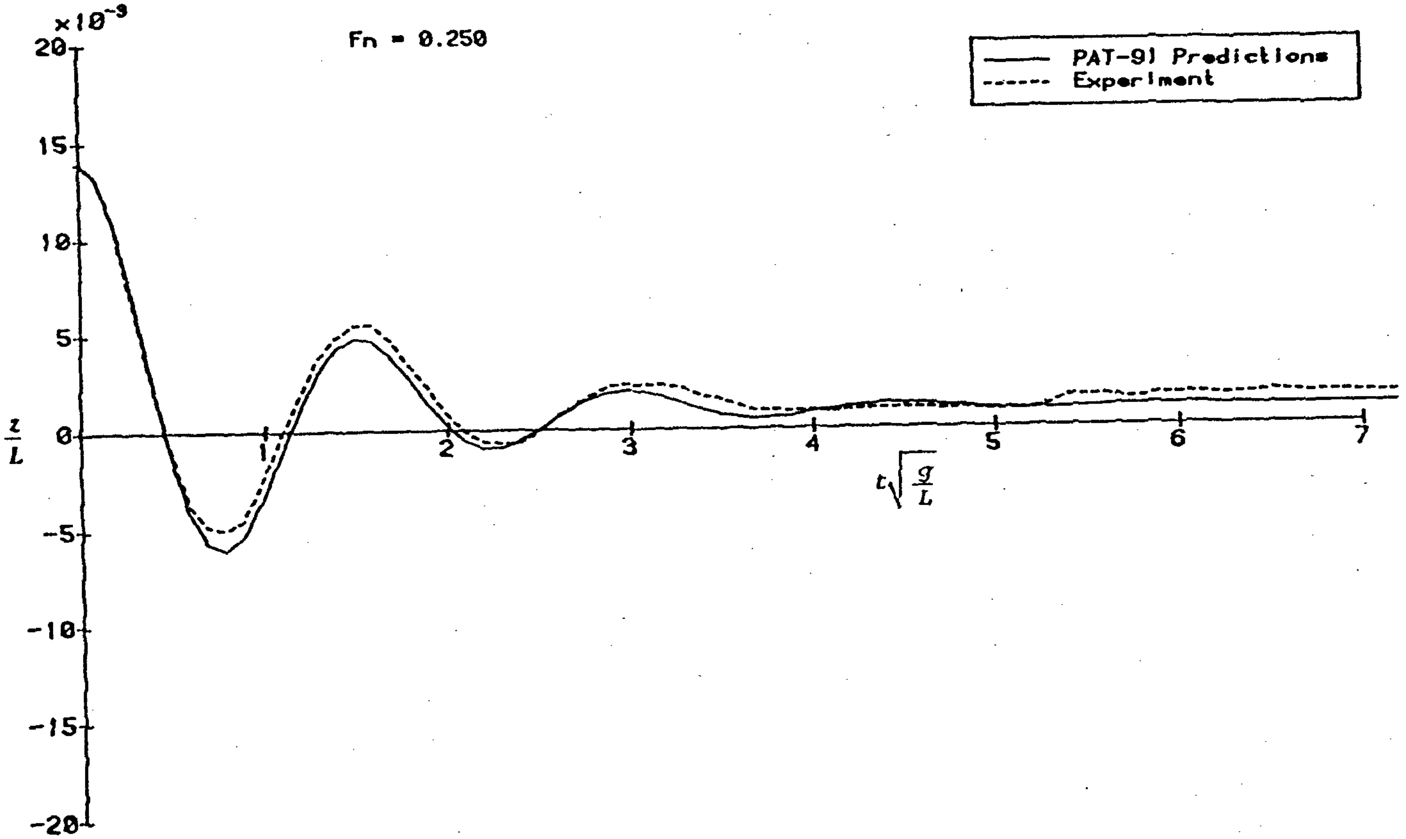

Figure 6

HEAVE DECAY TIME HISTORY

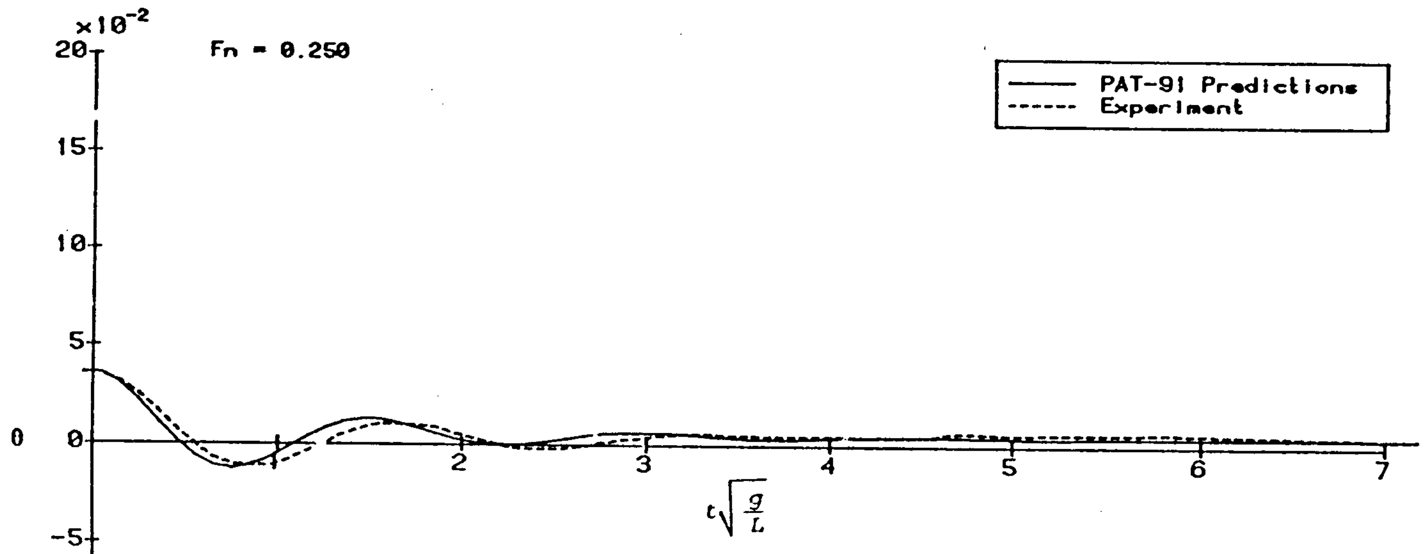

Figure 7

PITCH DECAY TIME HISTORY

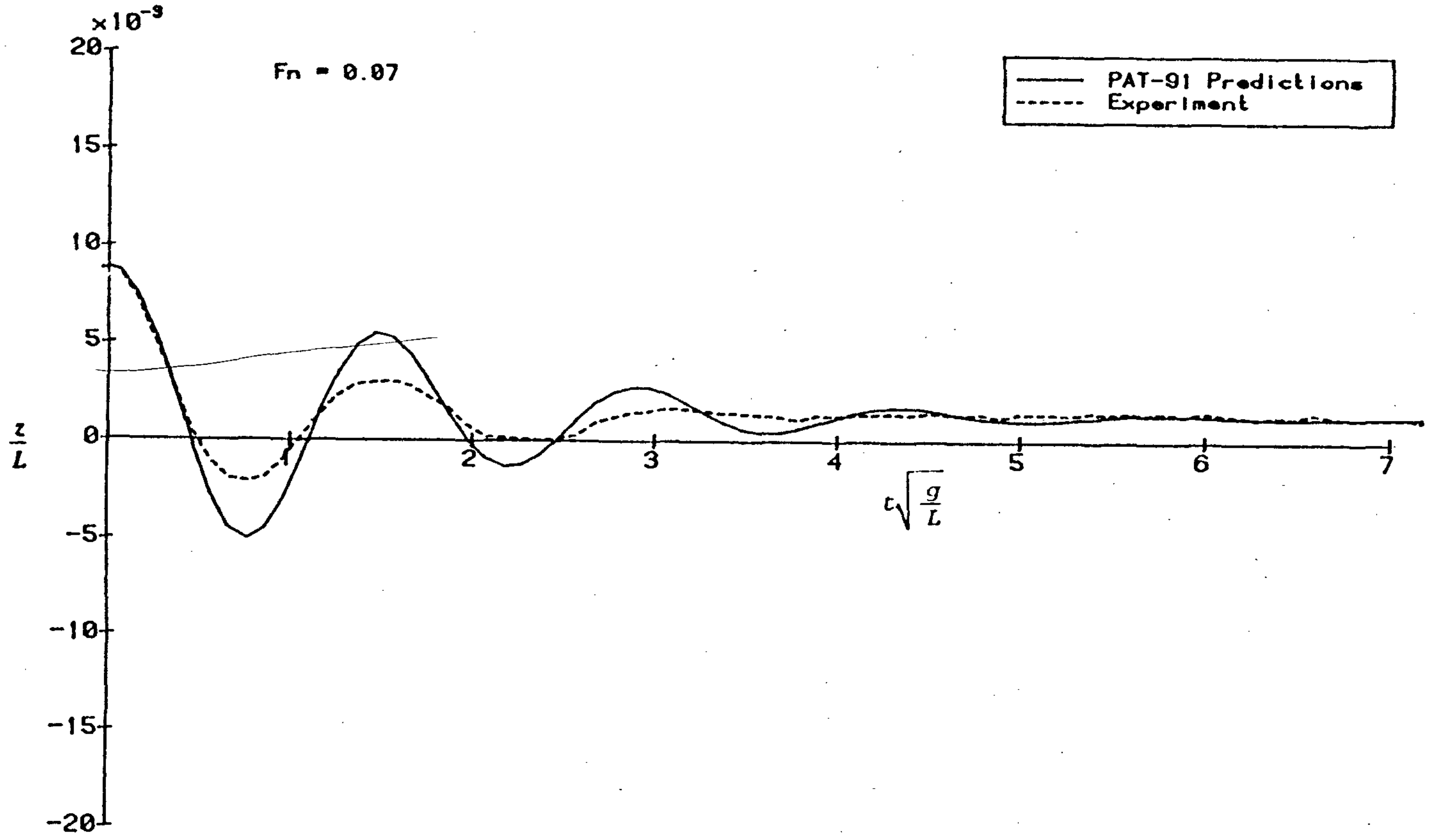

Figure 8

HEAVE DECAY TIME HISTORY

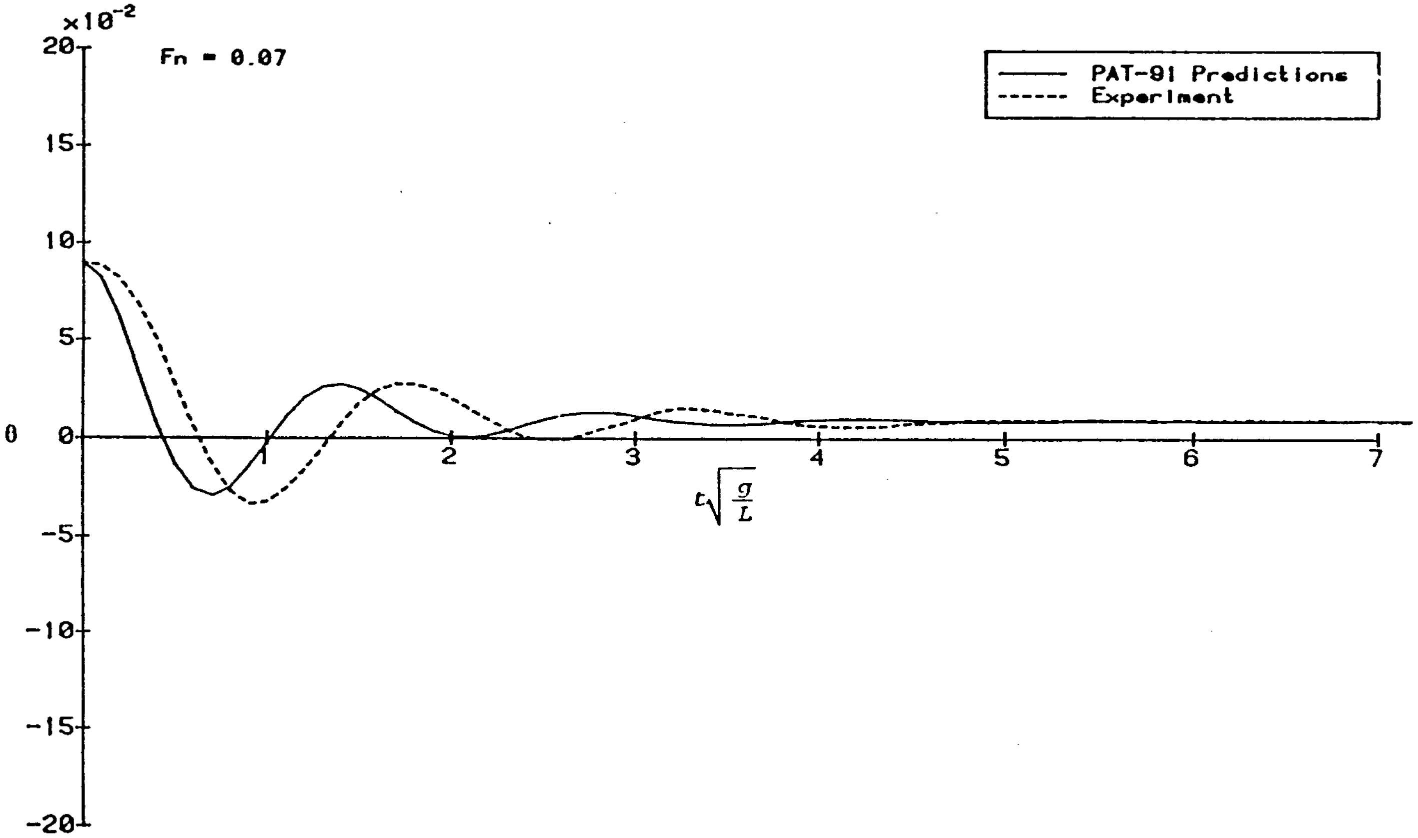

Figure 9

PITCH DECAY TIME HISTORY

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Originator's Reference/Report No
DRA TM(AWMH)92340

Month OCTOBER
Year 1992

Originator's Name and Location
DEFENCE RESEARCH AGENCY
HASLAR GOSPORT HANTS PO12 2AG

Monitoring Agency Name and Location

Title
THE FREE DECAY OF COUPLED HEAVE AND PITCH MOTIONS OF A MODEL FRIGATE

Report Security Classification
UNLIMITED

Title Classification (U,R,C or S)

Foreign Language Title (In the case of translations)

Conference Details

Agency Reference

Contract Number and Period

Project Number

Other References

Authors
P CROSSLAND, P A WILSON AND J C BRADBURN

Pagination and Ref

Abstract

The PAT-91 ship program has been found to over predict damping especially at resonant frequencies, resulting in there being no significant peak in the transfer function of pitch at resonance. This memorandum presents the results of a series of experiments that measured the decay time histories of a model frigate free to move in the vertical plane, in an attempt to identify where the problems might be occurring.

Judgements are made concerning the components in the heave and pitch motions using the terms in the full two dimensional strip theory heave and pitch motion equations to explain the trends shown.

The investigation has shown that the sectional damping coefficient appears to be over predicted. This results in a relatively poor prediction of heave decay curves at low speed and over estimates the damping in the pitch decay curves. It appears that the discrepancies seen in the heave and pitch transfer functions could be due to the wave excitation being predicted incorrectly.

Abstract Classification (U,R,C or S)

Descriptors
SHIP MOTION, EXPERIMENTAL DATA, STRIP THEORY, PAT-91 COMPUTER PROGRAM

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