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Theoretical Prediction of the Seakeeping Characteristics of Fast Displacement Catamarans

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Abstract

The increase in the number of high speed craft of all types operating throughout the world that has been seen over the last decade is continuing. With this likely to remain so for the foreseeable future, there is considerable interest in being able to predict the motions of such vessels in a seaway with accuracy.

This report employs both two-dimensional and three-dimensional potential flow analyses to evaluate the hydrodynamic coefficients and responses of high speed displacement catamaran forms. The hullform is based on the NPL round-bilge series, and is considered in three configurations; as a monohull and two catamaran demihull spacings. These hull configurations were investigated in regular head waves at three different forward speeds, corresponding to Froude numbers of 0.2, 0.53 and 0.8.

Hydrodynamic coefficients and heave and pitch responses are presented for all of the configurations examined. Comparisons with experimental data are included and discussed. For one of the catamaran configurations comparisons of pressure measurements at points around the hull are also presented.

The limitations of the theoretical models used are discussed with reference to:

a) Their treatment of forward speed effects,

b) Viscous damping effects around the resonant responses,

c) The effects of changes in hull attitude with forward speed,

d) The modelling of a transom stern, particularly at higher speeds.

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1 Introduction

As the use of high speed catamarans throughout the world has increased over the last few years, there has been a corresponding increase in the need to understand all aspects of the behaviour of such vessels, both in calm water and in waves. The subsequent research has focussed both on experimental and theoretical approaches to these problems.

Initially work was directed towards investigation of the calm water characteristics of catamarans and this has been investigated in detail at the University of Southampton over a number of years (Insel, 1990; Insel and Molland, 1992; Molland et al., 1994). More recently experimental work has been undertaken in order to assess the seakeeping performance of such vessels in regular head seas (Wellicome et al., 1995a,b). This report contains the results of the theoretical prediction of the seakeeping characteristics of two different catamaran configurations, as well as those of a monohull. Theoretical approaches of differing complexity were used and the advantages and disadvantages associated with each method are discussed.

2 Model Details

The theoretical investigation has concentrated on one of the hullforms used in the experimental work (Wellicome et al., 1995a). This, using the notation of previous work (Molland et al., 1994), is model 4b. Details are given in Table 1.

The model is of symmetrical round bilge form with a transom stern (see Figure 2) and has been derived from the NPL round bilge series (Bailey, 1976). This hullform is broadly representative of a number of catamarans in service. For details of the construction of the models used in the experimental work, reference should be made to Wellicome et al., (1995a).

The catamaran has been investigated in two configurations, with centreline to centreline separation to length (S/L) ratios of 0.2 and 0.4. Calculations for the monohull and the two catamaran configurations were undertaken for three speeds, corresponding to Froude numbers (Fn) of 0.2, 0.53 and 0.8 (Wellicome et al 1995a,b).

The centre of gravity was positioned coincident with the LCB in the longitudinal direction and at $1.5T$ in the vertical direction. The longitudinal moment of inertia in pitch was set such that the pitch radius of gyration was $25\%L$.

3 Mathematical Model

3.1 Equations of Motion

The motions of a rigid vessel undergoing small perturbations, in regular sinusoidal waves, about an equilibrium position can be represented by the coupled linear equations of motion:

$$\sum_{k=1}^{6} \left[-\omega_e^2 (M_{jk} + A_{jk}) + i\omega_e B_{jk} + C_{jk}\right] \eta_k = F_j^I + F_j^D \quad j = 1, 2, \ldots, 6 \tag{1}$$

where,

M_{jk} =element of mass or inertia matrix
ω_e =frequency of encounter
A_{jk} =added mass in the j^{th} mode due to unit motion in the k^{th} direction
B_{jk} =damping coefficient in the j^{th} mode due to unit motion in the k^{th} direction
C_{jk} =hydrostatic restoring coefficient
η_k =complex motion amplitude
F_j^I =complex amplitude of the incident wave exciting force (Froude-Krylov)

F_j^D =complex amplitude of the diffraction wave exciting force

The terms in this equation can be evaluated by a number of methods, such as two-dimensional strip theory and three-dimensional potential flow analysis, each assuming the fluid homogeneous, inviscid and the fluid motion irrotational (Salvesen et al., 1970; Inglis and Price, 1982a,b). The fluid motion can now be represented by a velocity potential satisfying the Laplace equation throughout the fluid domain. Unfortunately, calculating the total velocity potential in its most general form is difficult and, for practical use, some simplification is necessary. Thus, the total potential can be expressed as a linear summation of components:

$$\phi(x, y, z, y) = (-Ux + \phi_s(x, y, z)) + \phi_T e^{i\omega_e t} \qquad (2)$$

where

- U is the forward speed,
- ϕ_s is the perturbation potential due to steady translation and
- ϕ_T is the unsteady perturbation potential which can be decomposed to give:

$$\phi_T = \phi_I + \phi_D + \sum_{j=1}^{6} \phi_j \eta_j \qquad (3)$$

with

- ϕ_I as the incident wave potential,
- ϕ_D as the diffraction potential and
- ϕ_j denoting the radiation potential due to unit motion in the j^{th} direction

In equation (2) the first two terms represent the problem of the ship advancing at steady forward speed in calm water. These can be determined separately from the unsteady potentials. Using equation (3) and appropriate boundary conditions solutions to equations (1) are obtained.

3.2 Methods of Evaluation

Evaluation of the radiation and diffraction potentials, which are used to calculate the added mass and damping coefficients and the diffraction component of the wave excitation force respectively, can be carried out in several different ways (Newman, 1978). For this investigation, a two-dimensional (strip theory) and three-dimensional method were used.

The 2-D analysis involves dividing the wetted surface of the hulls into a number of longitudinal sections, each of which is then represented by a number of segments each containing a singularity at its centre. In this manner a source-dipole distribution on each contour is obtained (Wu, X.J. and Price, 1986, 1987). Using this method each hull was represented by 20 strips in the longitudinal direction, with each strip contour being divided into 14 segments.

The 3-D analysis is a boundary-element method, whereby the problem of modelling the whole fluid domain can be reduced to that of modelling the boundaries of the fluid, in this case by application of Green's 2nd theorem. By suitable choice of the singularity to be used, the problem can be further reduced to modelling the body surface only. Thus, in the 3-D approach used the wetted surface of the hull is discretised by four cornered panels each of which contains a singularity at its centre. In this case two types of singularity were tried, a pulsating source and a translating pulsating source (Bishop et al, 1986; Inglis and Price, 1982a,b). Both of these singularities satisfy the Laplace equation throughout the fluid domain, a radiation condition at infinity and the linearised free surface condition. The difference between the two singularity distributions is in the application of the linear free surface boundary condition. The pulsating source potential satisfies a further simplification assuming low forward speed and high frequencies of oscillation. The translating pulsating source retains the full linearised form. Neither distribution includes interaction effects between the steady and unsteady components of the velocity potential. This arises from the assumption, when formulating the boundary condition on the body surface, that the perturbation of the steady flow due to the presence of the hull is negligible.

The software for the 3-D methods was modified in order to calculate and output local pressures around the hull.

4 Results

4.1 Hydrodynamic Coefficients

The hydrodynamic coefficients related to the heave added mass and damping are presented for all of the configurations examined in figures 4 to 6. Although there are no experimental results for added mass and damping, discussion of those generated by the various theories can give considerable insight to the subsequent prediction of motions by these theories.

As has been discussed previously (Hudson, Price and Temarel, 1995), the heave added mass for a multihull differs from that of a monohull in that in certain regions it exhibits troughs which may result in negative values, particularly at low Froude numbers. These negative troughs are caused by the fluid interaction between the hulls. This fluid interaction can be of two forms, symmetric or antisymmetric. For a vessel having port/starboard symmetry, symmetric interaction affects motions in the vertical plane (i. e. heave and pitch), whereas antisymmetric interaction affects motions in the horizontal plane (i. e. sway, roll and yaw). Symmetric interaction can be of two forms (see Fig. 1 a,b). The first is simply a vertical motion of the fluid trapped between the hulls and the second is that of a standing wave formed between the hulls. Antisymmetric interaction always takes the form of a standing wave (Fig. 1 c). Clearly higher harmonics than those illustrated can occur, although these are usually at frequencies which are too high to be of interest when considering rigid body behaviour.

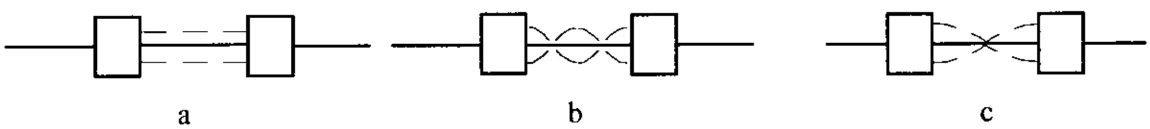

Figure 1: Interaction between twin-hulls

The first troughs seen in the added mass curves, at ω_e=8.0 rad/sec for S/L=0.2 (Fig. 5) and at ω_e=5.5 rad/sec for S/L=0.4 (Fig. 6), are associated with the first type of symmetric interaction. If the separation and frequency range are sufficiently large, further troughs in the added mass can be observed. Thus, for the vessel with S/L=0.4, the apparent discontinuity occurring at ω_e=12.0 rad/sec is associated with the second form of symmetric interaction, that of a symmetric standing wave. The frequency of such a standing wave can be accurately predicted by the usual deep water gravity wave equation. With either type of interaction the heave damping curve has a peak in the region where the heave added mass has its maximum slope and vice versa. This is because the two quantities are out of phase components of the same hydrodynamic force.

Comparing the different theoretical formulations, we can see that for the catamaran configurations investigated the 2-D and 3-D pulsating source methods are in close agreement. The irregular frequency, which can be seen around ω_e=16.0 rad/sec in Fig 5 can be removed from the predictions if required (Wu, X.J. and Price, 1987). For the calculations made using the translating pulsating source for the catamaran with S/L=0.4, it can be seen that the troughs in the added mass curve have been removed at a Froude number of 0.53. The damping curves are also changed accordingly. The predictions at zero forward speed using this method would be the same as those calculated using the pulsating source method. This indicates that the interaction between the hulls is a speed-dependent phenomenon as one might expect.

4.2 Responses

The heave and pitch responses in regular head waves for all of the vessel configurations and Froude numbers tested are presented in figures 7 to 14 in the form of heave RAO=heave amplitude/wave amplitude and pitch RAO=pitch amplitude/maximum wave slope. From these figures it can be seen that the heave and pitch RAOs have one peak for the monohull and the catamaran with the smaller separation (S/L=0.2). For the catamaran with S/L=0.4, the heave and pitch RAOs obtained with the 2-D and 3-D pulsating source methods exhibit two peaks, whereas the experimental results and those obtained with the 3-D translating pulsating source method exhibit only one peak. The second of the two peaks observed in the results for S/L=0.4 can be associated with the troughs seen in the added mass curves (at ω_e=12.0 rad/sec) for this vessel, as calculated by the 2-D and 3-D pulsating source methods. These second resonant peaks can thus be attributed to the formation of a symmetric standing wave between the hulls. The use of a translating pulsating source model eliminates these troughs in the added mass curve and hence the corresponding resonant peak.

Comparing the theoretically derived responses with those from experiments, for the monohull agreement is close for a Froude number (Fn) of 0.2, both in heave and pitch. When the speed is increased to Fn=0.53 the magnitude of the response is correctly predicted by the 3-D pulsating source program, however the frequency of resonance is 2 rad/sec too high. Predictions by the translating pulsating source method are too large, although the frequency of resonance is now correctly predicted. For a Froude number of 0.8, both the pulsating source and the translating pulsating source methods over-predict the resonant response magnitude and frequency. Results for heave and pitch are very similar.

For the catamaran with S/L=0.2, the results for Fn=0.2 indicate a close agreement between experiment and theory both for heave and pitch. Results for the strip theory and 3-D pulsating source method are almost identical. As the speed is increased to Fn=0.53, the strip and 3-D pulsating source theories again provide almost identical results for the most part but the resonant magnitude is now over-predicted, as is the resonant frequency. Agreement for pitch is not quite as good as for heave due to the absence of a significant resonance in the experimental results. At low frequencies in pitch the 3-D pulsating source method and the strip theory differ slightly, the 3-D method providing the better results.

When the separation is increased to S/L=0.4, the agreement at the lowest Froude number (0.2) is still good for all of the methods considered. However, at Fn=0.53 the predictions using the strip and 3-D pulsating source theories exhibit two peaks, whereas the experiments only indicate one. This second resonance, as we have mentioned previously, is a consequence of the standing wave formed between the hulls, the effect of which must therefore be over-estimated by these two theories. The first of the two theoretically produced peaks can thus be identified with the resonance seen in the experiments, although its magnitude is too large. The results obtained by use of the translating pulsating source distribution have only one resonant peak, that associated with the standing wave being eliminated. The first peak is, however, no closer to the experimental one. Results at a Froude number of 0.8 are similar in nature to those seen at Fn=0.53, with the resonance effect due to the standing wave being accentuated in the strip, and 3-D pulsating source, theory results.

4.3 Pressures

Ideally one would like to compare not just the motion amplitudes with experimental results, but also the quantities that affect the prediction of the motions, that is, added mass and damping coefficients. Any discrepancies observed in the motion predictions could then be explained in terms of discrepancies in these quantities. Unfortunately measuring the added mass and damping of a model with forward speed is difficult. Therefore, in order to obtain a more "basic" quantity to compare theory and experiment, the pressure at a number of points around the hull was both measured (Wellicome et al, 1995b) and calculated using the 3-D pulsating source method. The points at which the pressure was investigated are situated at sections 1.5, 3.5, 5.5 and 7.5 and at positions around the girth illustrated in figure 3.

The results of this comparison can be seen in Tables 2 and 3. Looking at these tables, the results for a Froude number of 0.2 indicate that both theory and experiment show the same trends along the hull at the lower frequency but not the higher frequency. The trends around the girth of a section also differ, the experiments predicting greater pressures further from the free surface (Pressure mounts 1 and 4), and the analytical method indicating the opposite trend.

For a Froude number of 0.53, at the highest and lowest frequencies, the predicted variations compare well with the experimental data both in respect of the trends along the hull and for the pressure levels. The predictions for ω_e=12 rad/sec are too high in comparison with the experiments, this is due to the over-prediction of the heave and pitch responses at this frequency, as can be seen from Fig. 11. The predictions girthwise differ from the experiments, as per Fn=0.2, and this needs further investigation.

From a breakdown of the theoretical predictions into components due to diffraction, radiation and incident pressures, the incident pressures seem to dominate all of the results. It should be noted that inclusion of the steady-state wave system in the body-boundary conditions may substantially alter the pressures as calculated, both along and around the hull.

4.4 Discussion

From the results for the monohull and the catamarans we can see that there are two main discrepancies between the theoretical and experimental results. The first of these, particular to catamarans, is the existence of secondary resonant peaks in the heave and pitch results for wider separations. These secondary peaks are due to the formation of standing waves between the hulls and are not seen in the experimental results. The reason for the appearance of these peaks in the results obtained in the strip and 3-D pulsating source methods is the inadequate treatment of forward speed in these formulations. These methods essentially assume that interaction between the two hulls takes place at the same longitudinal section, whereas in reality the effect of the vessel's forward motion will be to change the region of interaction. Increases in separation will have a similar effect. Also note that increases in separation reduce the resonance frequencies associated with standing waves in the 2-D and 3-D pulsating source methods. The use of a more sophisticated method, involving the inclusion of forward speed in the free surface boundary condition (the translating pulsating source), has been shown to eliminate the peak in vessel response due to the standing wave.

The second main discrepancy between theory and experiment is the over-estimation of the magnitude of the primary resonant response at Froude numbers of 0.53 and 0.8 for the catamarans and at Fn=0.8 for the monohull. One possible reason for this is that all theories are based on potential flow. It follows from classical dynamics that any magnification of damping is accompanied by a corresponding decrease in motion amplitude. This argument remains valid in fluid-structure interaction problems despite the hydrodynamic properties not being constant. Thus, it is possible to empirically adjust the response magnitude making allowance for viscous damping effects. With a monohull, energy is radiated to infinity on both sides, whereas with a catamaran energy is reflected between the hulls. This means that the hydrodynamic (potential) damping associated with a catamaran is less than for two monohulls infinitely separated (Lee and Curphey, 1977), hence the importance of allowing for viscous effects could be greater for catamarans than monohulls.

It is however important to look at all possible reasons for this remaining discrepancy between experimental and theoretical results. When the physical problem is considered it is apparent that the theoretical treatment of the fluid-structure interaction is deficient in a number of ways. The first of these is that, as mentioned in section 3, the interaction between the steady-state potential and the unsteady potentials is neglected in all of the methods considered thus far, including the translating pulsating source model. Since the steady waves generated by each of the catamaran hulls will interact with each other it is likely that accounting for the interaction between the unsteady and steady waves is more important for the catamaran configuration. In order to include this interaction, the body boundary conditions must be modified to allow for the steady-state wave effect, this is solved for prior to finding the unsteady solution. It is possible to modify either of the three dimensional methods to achieve this (Inglis and Price, 1982a,b).

Another deficiency in the theoretical method is that the fluid forces are evaluated on the mean wetted surface of the hull at rest, rather than the instantaneous running wetted surface. There are several consequences of this; the above water shape of the hull can have no influence on its motions, the effects of sinkage and trim as the vessel travels, particularly with increasing forward speed, are neglected and the transom stern running "dry" at higher Froude numbers is not modelled. Accounting for the above water shape of the hull requires a time-domain analysis of the problem, with calculation of the fluid forces at each time step on the instantaneous wetted surface of the hull (Lin and Yue, 1990). It should be noted that even such an approach is not necessarily fully non-linear, since the free-surface condition used is often, although not always, linearised. The steady-state sinkage and trim of the vessel may be accounted for, even in the present methods, by adjusting the wetted surface of the hull to be the mean *running* wetted surface, rather than the mean *static* wetted surface. Unfortunately the presence of a transom stern, running dry at the higher speeds, complicates the adoption of such a procedure in the present work. A proper treatment of the transom stern requires the inclusion of a Kutta-type condition at the stern to ensure that the pressure at this section is atmospheric. Methods of approximating such a condition were studied in the calm water wave resistance case (Couser, 1996) and found to be reasonably successful.

5 Conclusions

- Analytical predictions of the responses of a high speed displacement hull shape, in catamaran and monohull configurations, travelling in regular head waves with three different forward speeds, have been carried out using both two and three dimensional methods and the results compared with experimental data. For one of the catamaran configurations a more advanced three dimensional method (a translating pulsating source distribution) was applied.

- The results obtained indicate that two and three dimensional methods are capable of predicting the motions of both the monohull and catamaran configurations at low speeds. As speed is increased these methods overpredict the vessel response. For the monohull, the three-dimensional method is accurate at relatively higher speeds.

- In addition to this inadequacy in the treatment of forward speed, which is seen for both mono and multihulls, the two and three dimensional methods also overestimate the effect of standing waves formed between the hulls of a catamaran. Using the more complex translating pulsating source method this deficiency is overcome, although the problems with forward speed still remain. Unfortunately the adoption of such a method results in a considerable time penalty in the computations.

- To further enhance the predictions, particularly with respect to the treatment of forward speed, a three dimensional method incorporating the interaction between steady and unsteady wave systems is expected to prove beneficial. Additional improvements are also expected with a proper treatment of the transom stern running dry at speeds in excess of Fn=0.53. These improvements will be at the expense of further computing time.

- Comparison of analytical (three-dimensional pulsating source distribution) and experimental pressure measurements indicate a reasonably good agreement for longitudinal distribution, except at resonance. More measurements, particularly on the inside of the catamaran hulls, is required to generalise this conclusion.

Acknowledgements

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Table 1: Principal particulars of model 4b.

Length (LBP)	L	1.6m
Length/(Displacement)$^{\frac{1}{3}}$	$L/\nabla^{\frac{1}{3}}$	7.4
Length/Beam	L/B	9.0
Beam/Draught	B/T	2.0
Block Coefficient	C_B	0.40
Prismatic Coefficient	C_P	0.69
Max. Section Area Coeff.	C_M	0.57
Wetted Surface Area	WSA	0.338m^2
Long. Centre of Buoyancy	LCB	6.4% aft of midships

Table 2: RMS Wave and pressure measurements, Model 4b, S/L=0.2, Fn=0.2, outside pressure mounts 1-6.

T_0 s	ω_e rad/s	RMS Wave mm	RMS Heave mm	RMS Pitch deg	RMS P1 mmH_2O	RMS P2 mmH_2O	RMS P3 mmH_2O	RMS P4 mmH_2O	RMS P5 mmH_2O	RMS P6 mmH_2O
Measured:										
0.962	10.00	10.56	1.45	1.19	6.52	6.26	6.11	3.66	2.57	2.11
0.841	12.00	13.43	3.46	0.88	13.54	11.47	10.14	2.62	2.80	3.52
Predicted:										
0.962	10.00	10.56	2.54		5.45	7.59	9.60	4.75	6.46	8.08
0.841	12.00	13.43	3.46		5.22	4.98	5.64	11.32	10.77	10.50

Table 3: RMS Wave and pressure measurements, Model 4b, S/L=0.2, Fn=0.53, outside pressure mounts 1-6.

T_0 s	ω_e rad/s	RMS Wave mm	RMS Heave mm	RMS Pitch deg	RMS P1 mmH_2O	RMS P2 mmH_2O	RMS P3 mmH_2O	RMS P4 mmH_2O	RMS P5 mmH_2O	RMS P6 mmH_2O
Measured:										
1.285	10.02	6.20	6.19	0.83	7.94	5.38	7.25	3.41	3.57	3.43
1.141	12.00	7.85	8.19	0.83	11.82	8.84	11.01	6.51	5.78	5.23
1.033	14.01	9.38	5.54	0.88	12.56	9.23	10.64	8.79	8.04	7.10
Predicted:										
1.285	10.02	6.20	6.61	1.03	6.94	8.31	9.02	3.36	3.11	4.46
1.141	12.00	7.85	21.75	2.97	15.07	22.97	26.14	21.46	15.02	22.51
1.033	14.01	9.38	4.99	1.13	5.39	7.40	8.28	8.43	6.00	5.18

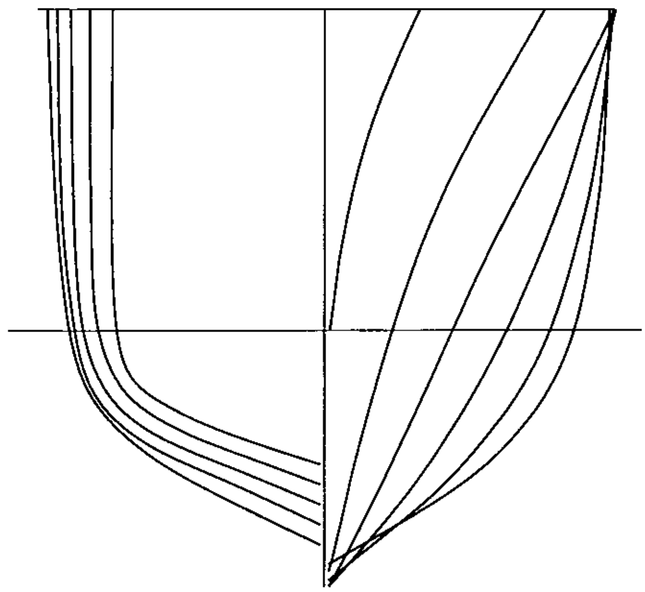

Figure 2: Body plan for model 4b.

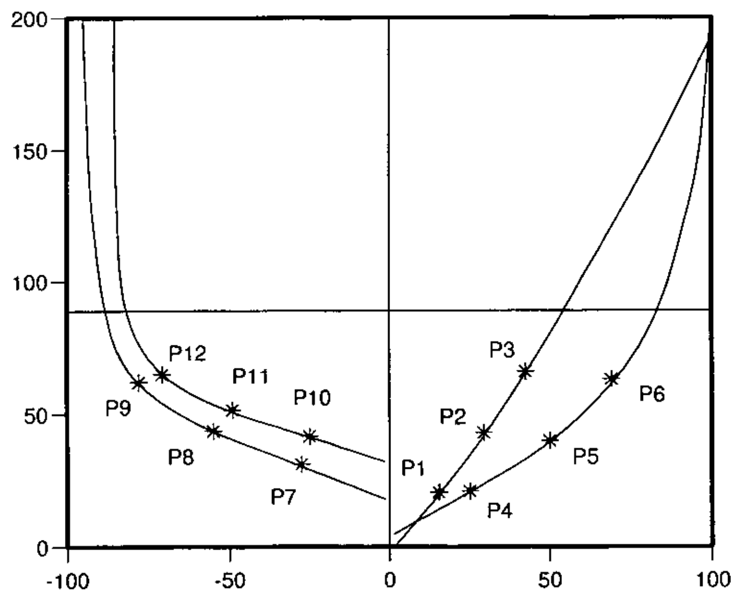

Figure 3: Pressure Transducer mounting points.

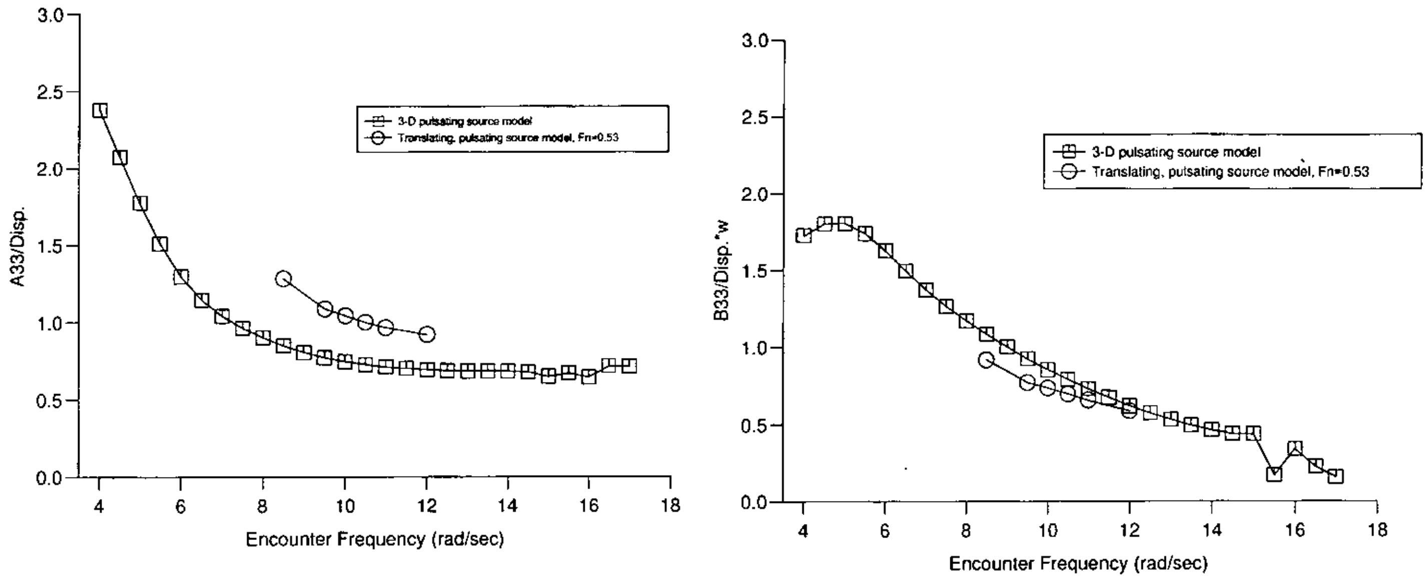

Figure 4: Added Mass and Damping Coefficients for Monohull.

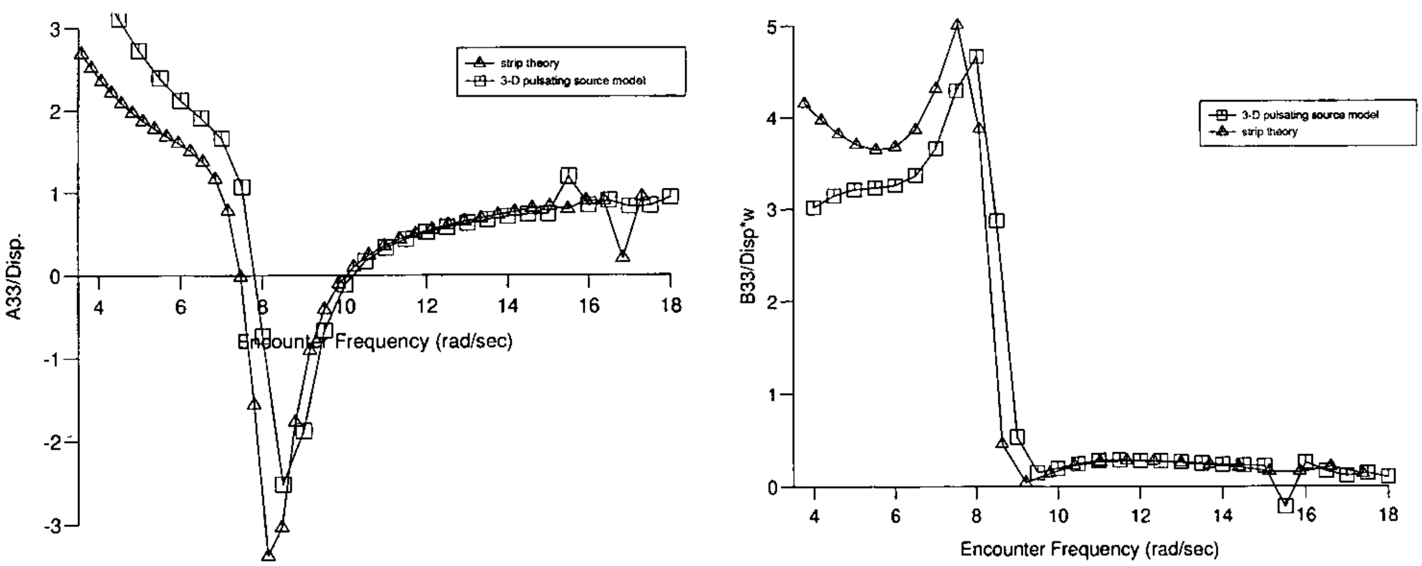

Figure 5: Added Mass and Damping Coefficients for Catamaran S/L=0.2.

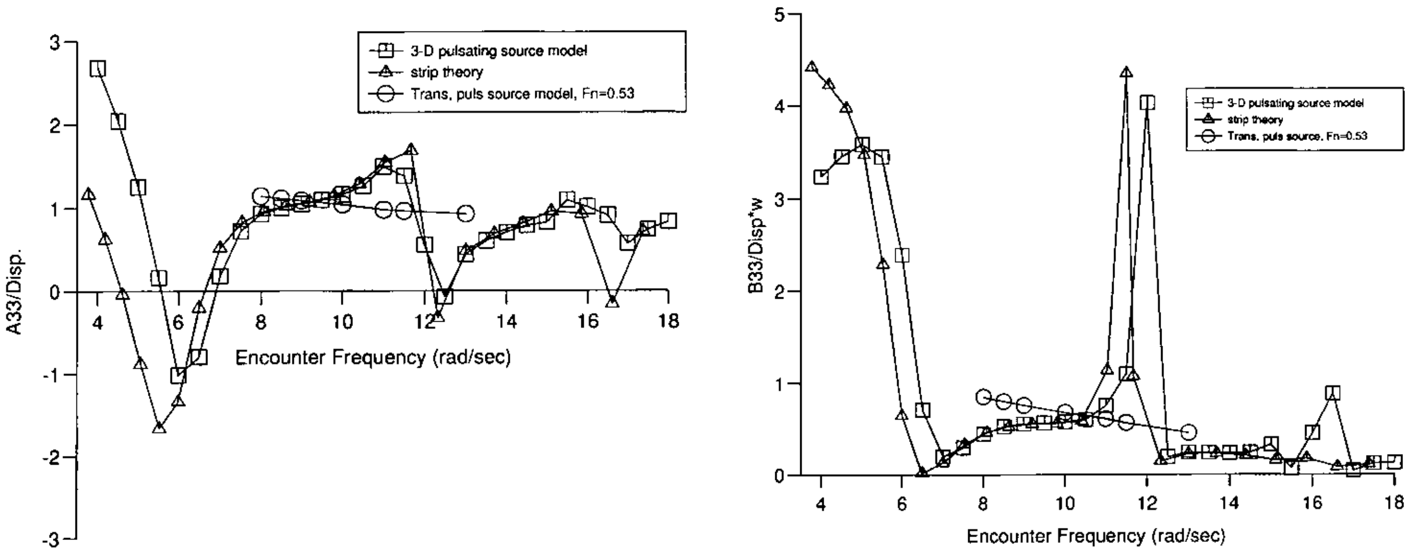

Figure 6: Added Mass and Damping Coefficients for Catamaran S/L=0.4.

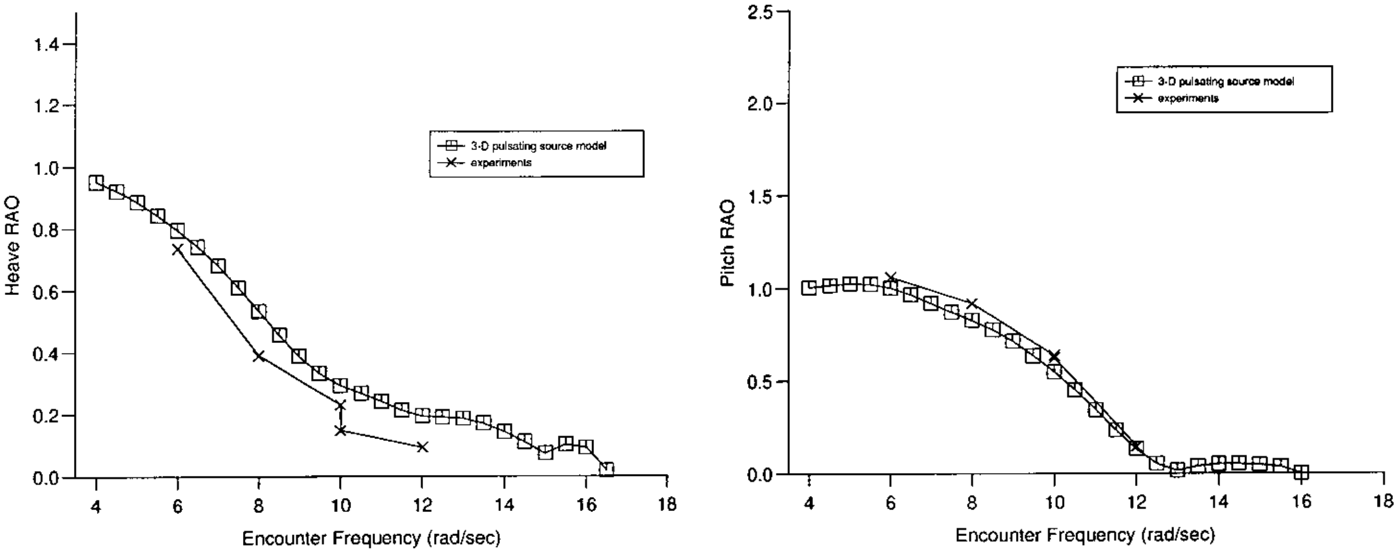

Figure 7: Heave and Pitch RAOs for Monohull at Fn=0.2.

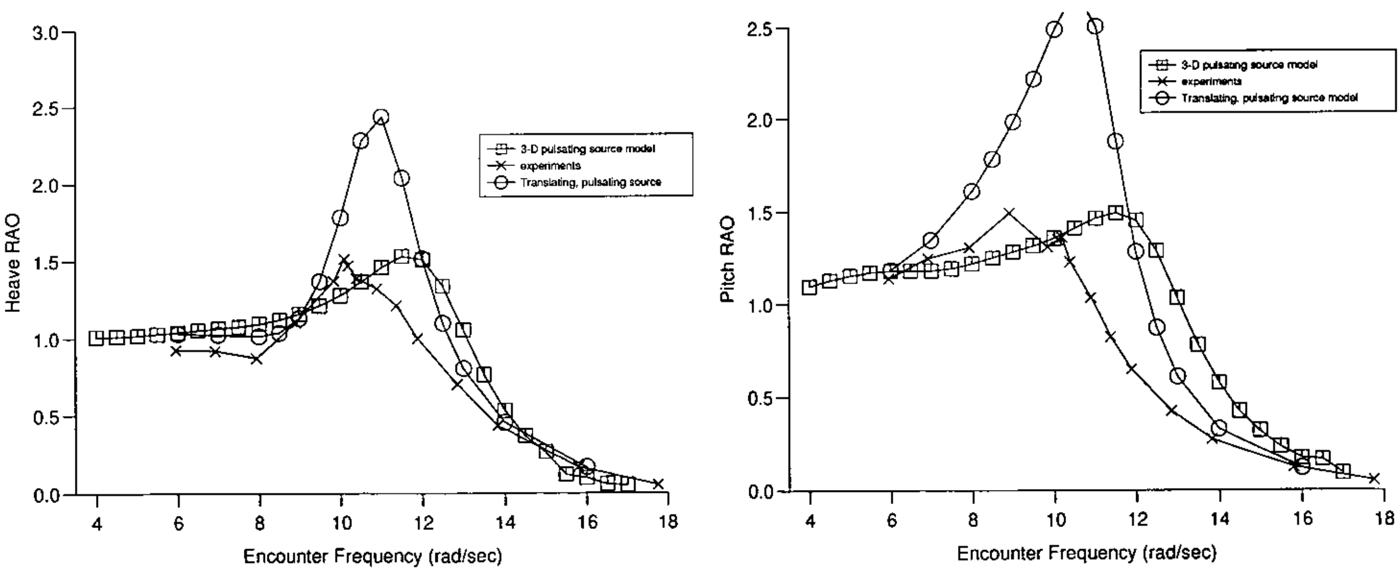

Figure 8: Heave and Pitch RAOs for Monohull at Fn=0.53.

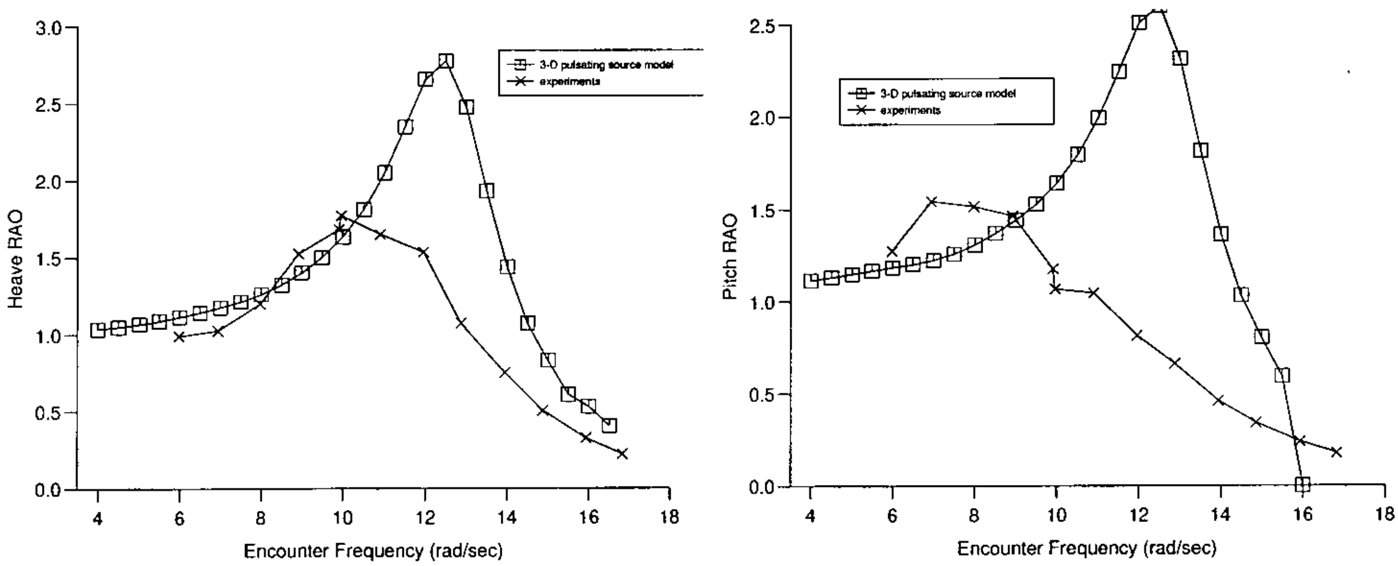

Figure 9: Heave and Pitch RAOs for Monohull at Fn=0.80.

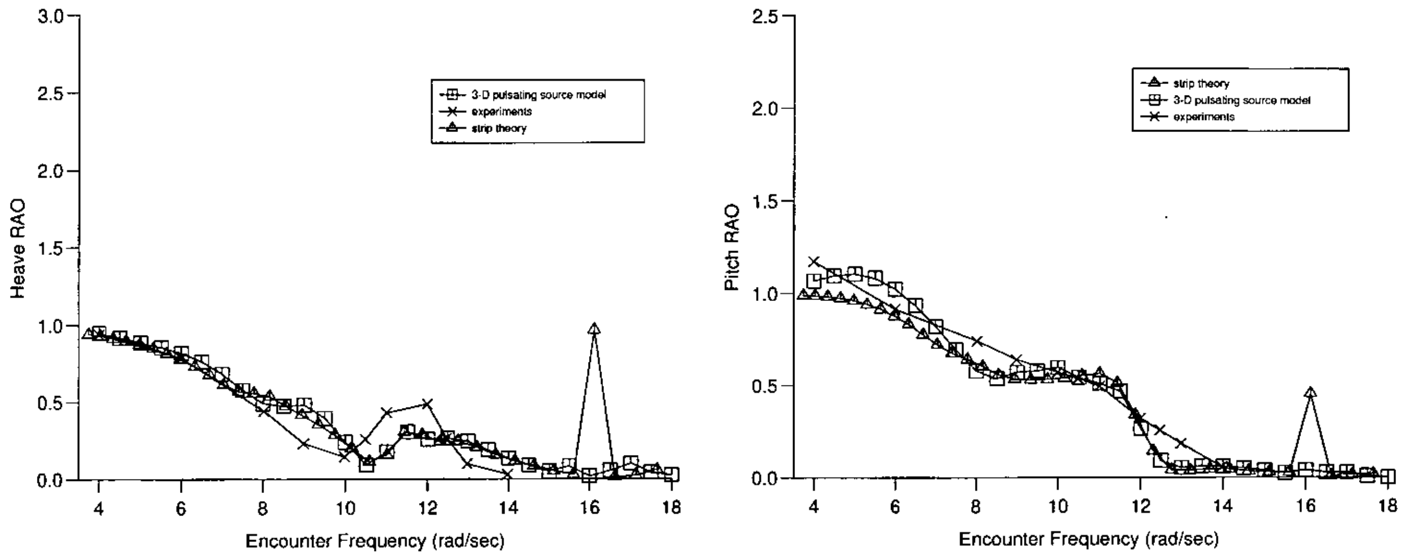

Figure 10: Heave and Pitch RAOs for Catamaran S/L=0.2 at Fn=0.2.

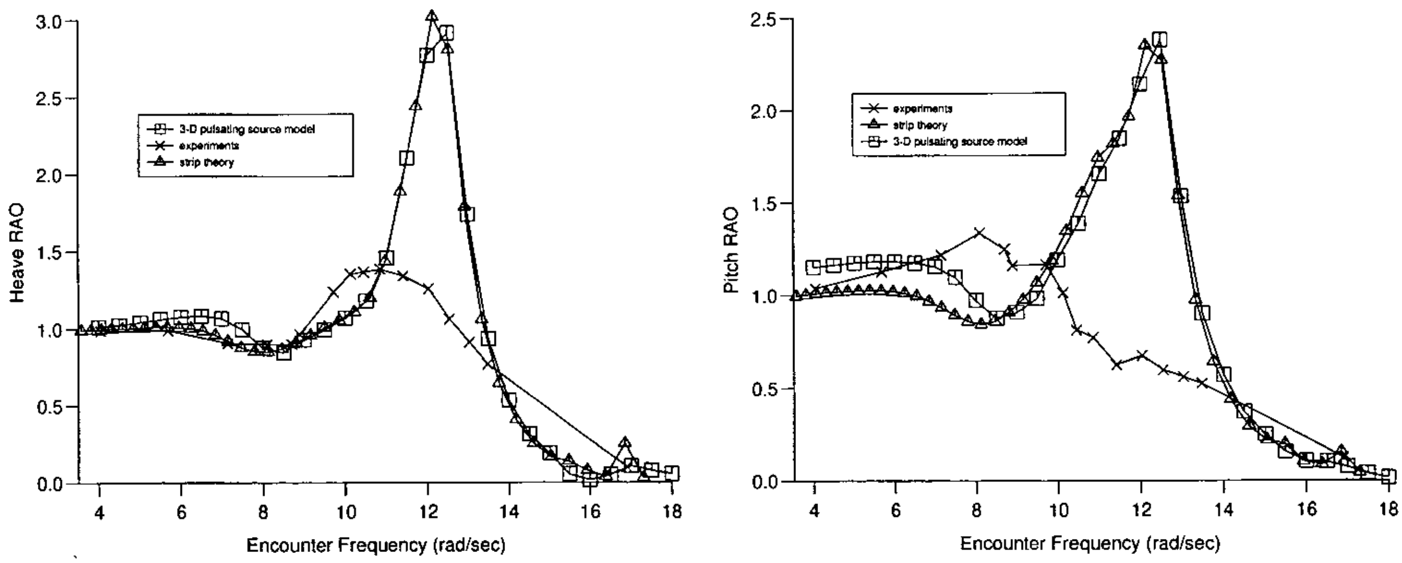

Figure 11: Heave and Pitch RAOs for Catamaran S/L=0.2 at Fn=0.53.

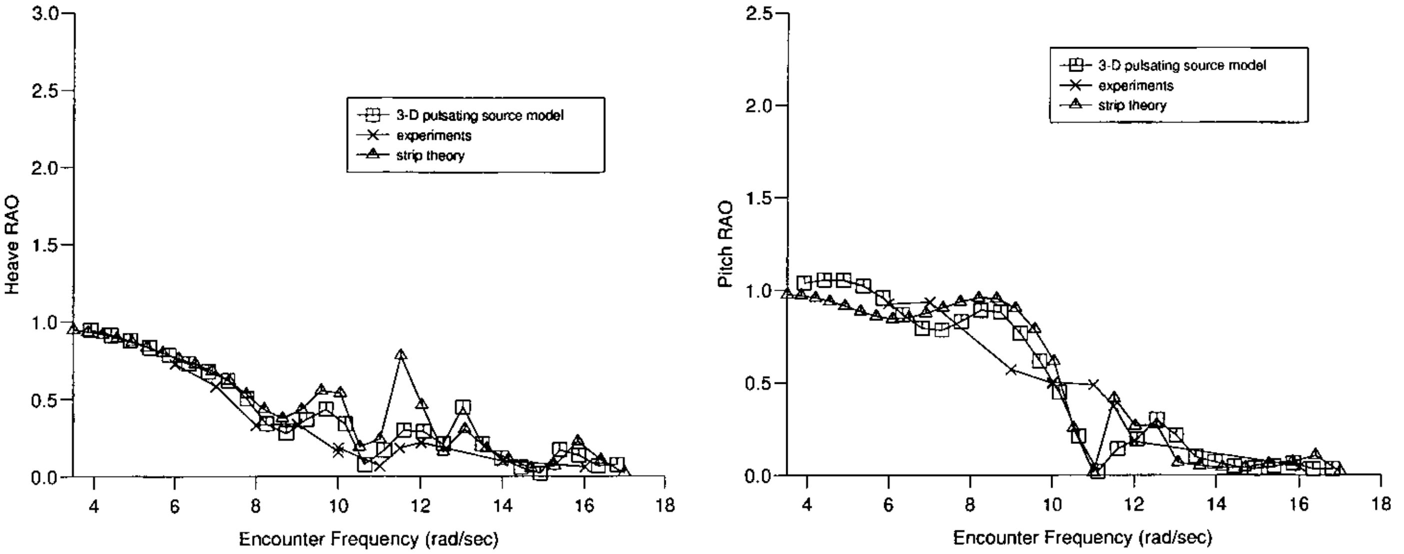

Figure 12: Heave and Pitch RAOs for Catamaran S/L=0.4 at Fn=0.2.

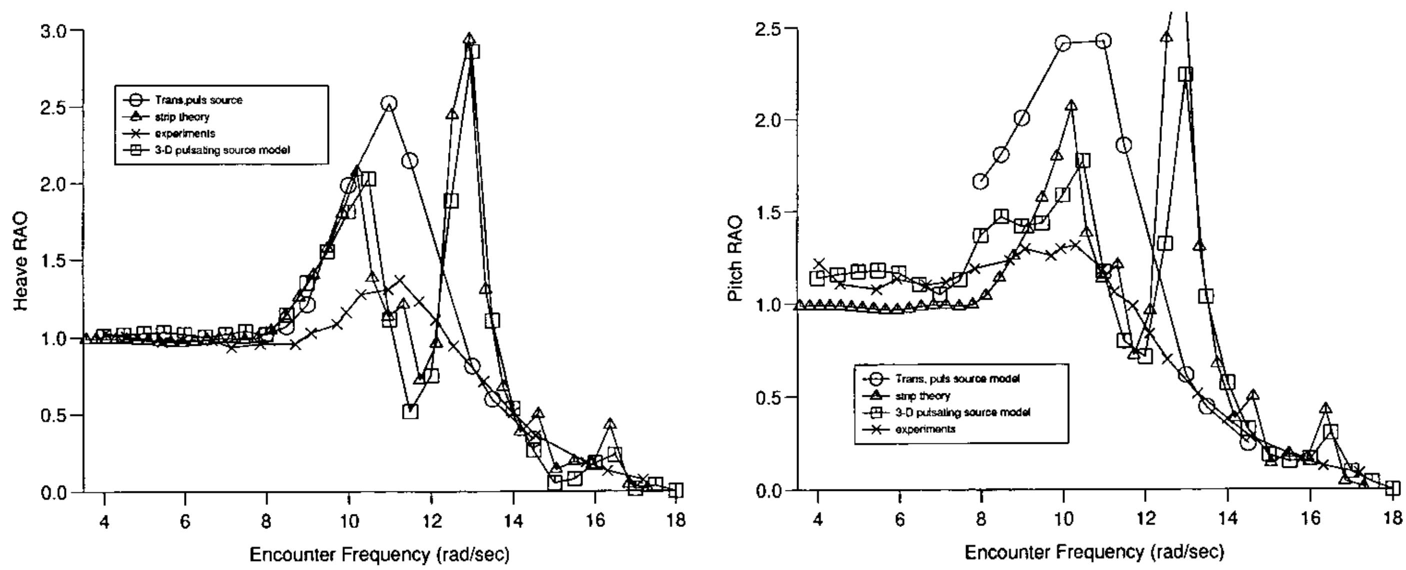

Figure 13: Heave and Pitch RAOs for Catamaran S/L=0.4 at Fn=0.53.

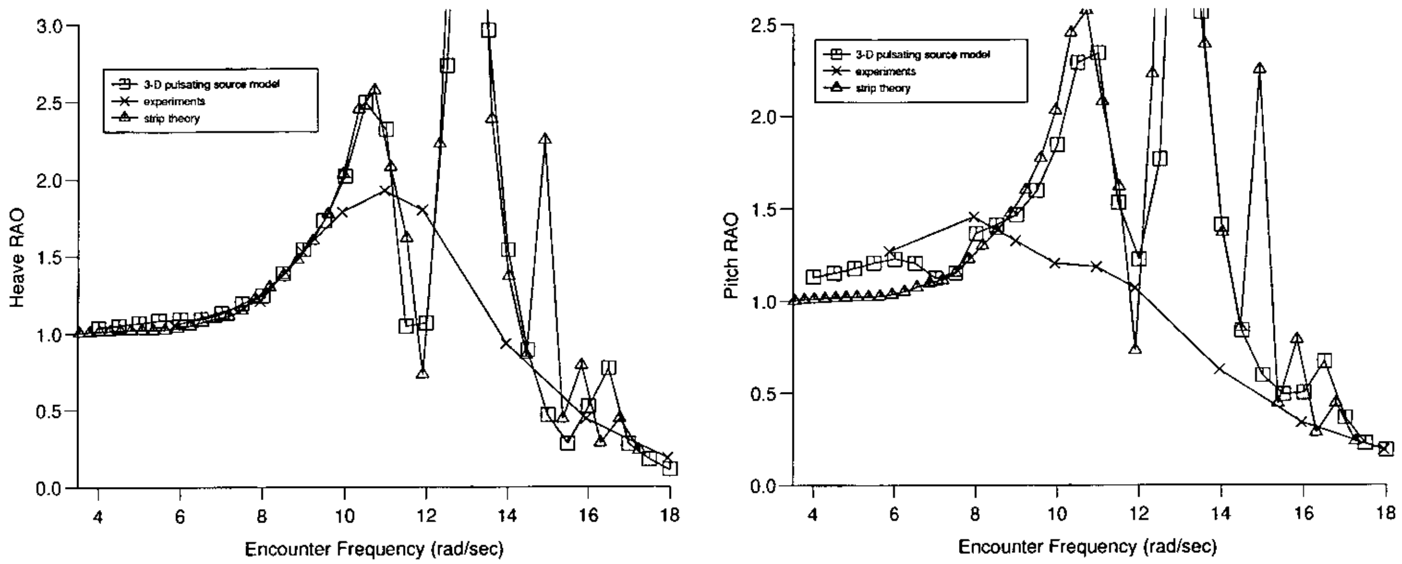

Figure 14: Heave and Pitch RAOs for Catamaran S/L=0.4 at Fn=0.80.

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