Model Testing and Numerical Simulations of Seakeeping Performance for High-Speed Vessels

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ABSTRACT

Given the need to support the long distance deployment of men and material, the US Navy has been exploring the engineering limits and capabilities of open ocean operation for high-speed ships. Of great concern are the risks associated with:

- *Ship Motions - Human Factors*
- *Ship Dynamic Stability and Manoeuvring*
- *Ship Dynamic Loads*

In order to address these risks, an initial assessment of design tools has been be carried out under the auspices of the Office of Naval Research. The initial goal of this effort was to determine the current state of the art in predicting ship motions of high-speed ships.

Under this initiative, the ship motions and loads prediction program, Large Amplitude Motions Program (LAMP), has been evaluated. This program is a time-domain simulation model specifically developed for computing the motions and loads of a ship operating in extreme sea conditions.

In order to perform these simulations, LAMP uses a time stepping approach in which all of the forces and moments acting on the ship are integrated in the time-domain using a 4th-order Runge-Kutta algorithm. Specific account of those forces due to the wave-body interaction, appendages, control systems, and green-water-on-deck, are included in the computation at each time step and the 6-degree-of-freedom (DOF) equations of motions.

Using the LAMP suite of programs, numerical predictions were made and compared with two sets of model test data. Included among the comparisons were predictions for pitch, roll and heave acceleration in both head and oblique sea conditions.

1.0 INTRODUCTION

Whether it is enhanced operational capability or the ability to rapidly deploy men and material, the US Navy is investigating the use of novel hull form concepts to meet the challenges of the twenty-first century.

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However, the use of novel hull forms leads to a pushing of the design envelope, beyond which traditional means of hull form evaluation can be considered acceptable.

For example, traditional methods for assessing seakeeping performance such as strip theory (Salvesen et al 1970), becomes less acceptable as basic assumptions such as wall sidedness and long slender hull forms are violated. Thus, what is required is a new generation of design tools which are capable of supporting a first principles approach to hull form evaluation. Furthermore, these emergent methods must be capable of simulating response in the time domain so that nonlinear responses can be explicitly identified and must inherently account for the proper physics within their models.

To meet these objectives, the US Navy has been supporting the development of a range of computational methods for predicting the dynamic response of a ship in a seaway. Among the codes, which are under development, is the Large Amplitude Motions Program (LAMP). This program applies three-dimensional hydrodynamics along with a time stepping approach to determine all forces and moments acting on the ship (Shin et al 2003).

The program can provide both linear and nonlinear solutions to the seakeeping problem.

- LAMP-1 (Body linear solution): Both perturbation potential and hydrostatic / Froude-Krylov forces solved over the mean wetted hull surface.
- LAMP-2 (Approximate body nonlinear solution): The perturbation potential is solved over mean wetted hull surface while the hydrostatic / Froude-Krylov forces are solved over the instantaneous wetted hull surface.
- LAMP-4 (Body nonlinear solution): Both the perturbation potential and the hydrostatic / Froude-Krylov forces are solved over the instantaneous wetted hull surface.

For most problems, the most practical level is the “approximate body-nonlinear” (LAMP-2) solution, which combines the body-linear solution of the perturbation potential with body-nonlinear hydrostatic-restoring and Froude-Krylov wave forces. This latter approach captures a significant portion of nonlinear effects in most ship-wave problems at a fraction of the computation effort for the general body-nonlinear formulation. However, body-nonlinear hydrodynamics and nonlinear incident wave effects can be important depending on ship geometry and operating conditions. Post-processors for predicting impact loads are also available.

1.1 IRF-Based Formulation

In order to address the issue of lengthy computational times, an impulse response function (IRF) based hydrodynamic formulation (Liapis 1986, King et al., 1988, Bingham et al., 1993) was integrated into the LAMP System to complement the standard Rankine source formulation. In the IRF formulation, velocity potentials are pre-computed for steady forward speed, impulsive motions in up to six modes, and impulsive incident waves for each speed and heading angle. The hydrodynamic problem is reduced to a convolution of the IRF potentials with the actual ship motions and incident wave elevation, thereby allowing numerical simulations to be performed 40-100 times faster than real time using modest computational resources and without compromising the accuracy of the hydrodynamic calculation. The IRF formulation can be used with both the body linear (LAMP-1) and approximate body nonlinear (LAMP-2) versions of the LAMP program (Weems et al., 2000).

To date, this program has been used to evaluate several monohull design concepts. However, a systematic evaluation of LAMP with model tests results for a multi-hull design had not been performed; hence, the genesis of this initiative.

2.0 OVERALL APPROACH

Using available test data for two different catamaran hull form designs, an initial assessment of the LAMP program was performed. For the first catamaran hull form, a set of frequency domain analyses was performed. The second study, using recently completed model test data for the X-Craft hull form, provided a means to perform direct time series comparisons.

2.1 Model Test Data

The model test data, which were used for the initial comparison, is based on a series of tests performed in the Netherlands in the late 1990's (Van't Veer 1997, 1998). The geometry of the model (designated as model 372) is shown in Figure 1. Test conditions, which were used for this comparison, are listed in Table 1.

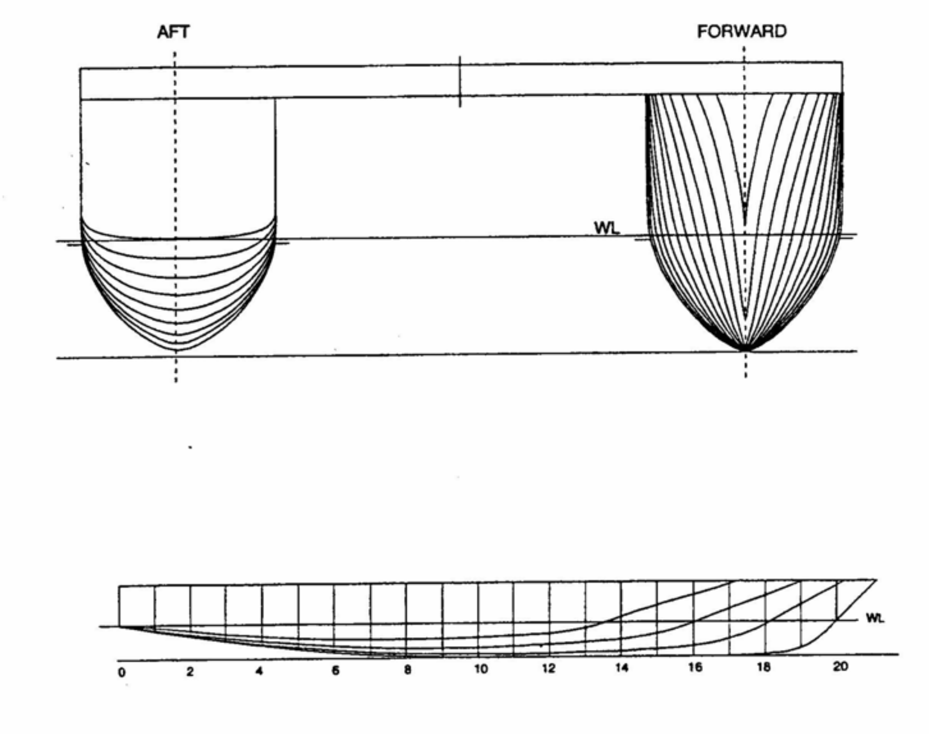

Figure 1: Lines of Catamaran 372

Table 1: Test conditions used for LAMP comparisons wit model 372

Ship Speed (Froude Number)	Heading (degrees)	Wave heights (cm)
0.3	0, 15, 45	1.14 – 2.81
0.45	0	2
0.6	0, 15, 45	1.14 – 2.81
0.75	0, 15, 45	1.14 – 2.81

The second series of simulations used the X-Craft hull form. A picture of the panelized hull form geometry is shown in Figure 2. Test conditions used in this comparison are listed in Table 2.

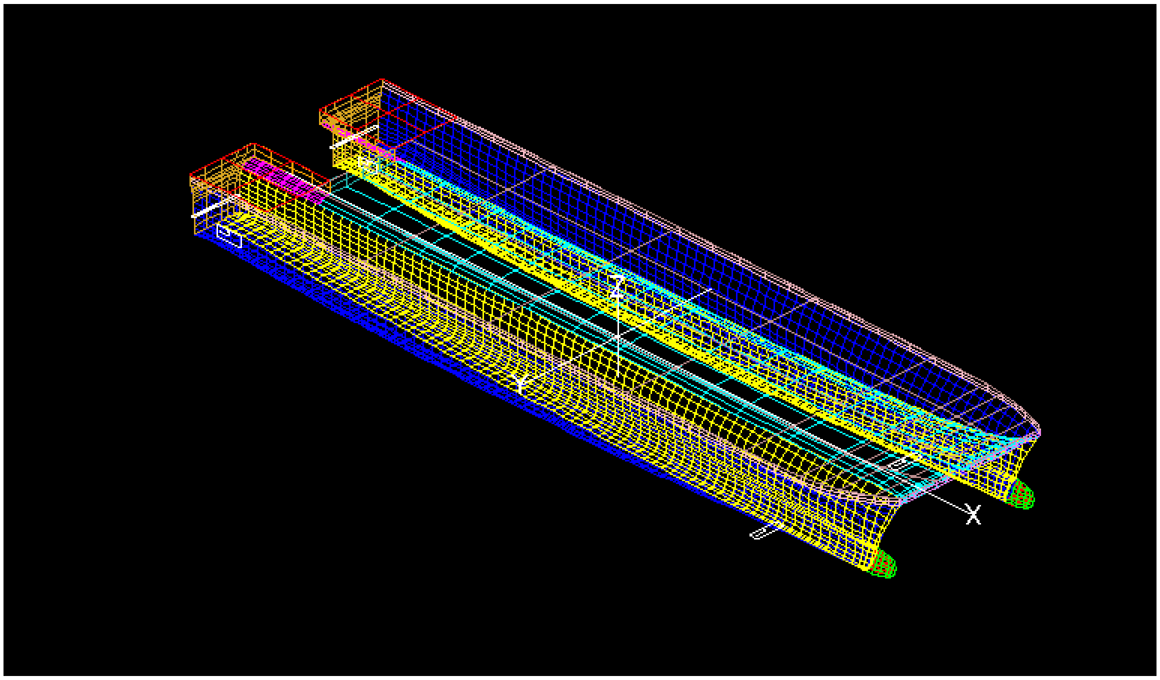

Figure 2: Panelization of X-Craft Catamaran

Table 2: Test Conditions Used for LAMP Comparisons with X-Craft

Ship Speed (Knots)	Heading (degrees)	Wave Heights (meters)
5	0	2.6
12	0	2.6
20	0	3.25
40	0	2.6
20	30	3.25
20	60	3.25

In both cases, the initial effort centered on determining the most reasonable combination of gridding scheme and time steps. Once a practical computational domain was found, numerical simulations were performed for select model test conditions. The selected conditions ranged in speed and sea state such that a rigorous assessment of LAMP could be accomplished.

3.0 CONVERGENCE STUDY RESULTS

In order to perform a rigorous validation study, a series of convergence tests must first be carried out. This allows the user to determine the best combination of time step, hull form and free surface panel densities. Once a range of possible panel densities and time step combinations were developed for the catamaran hull form geometry, the LAMP program was run for each of the schemes. Numerical simulations for heave and pitch response were then compared. Sine the procedures used for both hull forms were basically the same, only results for Catamaran 372 study are presented.

3.1 Convergence and Sensitivity Studies

3.1.1 The Effect of the Time Step Size

Figure 3 shows the heave and pitch motions in calm water at Fn = 0.75 produced with two different time step sizes, Δt = 0.01 and 0.005 seconds. Since the two curves on each plot is not distinguishable, using Δt = 0.01 second corresponding to nondimensional Δt = 0.018 is enough for producing converged results in terms of the time step size.

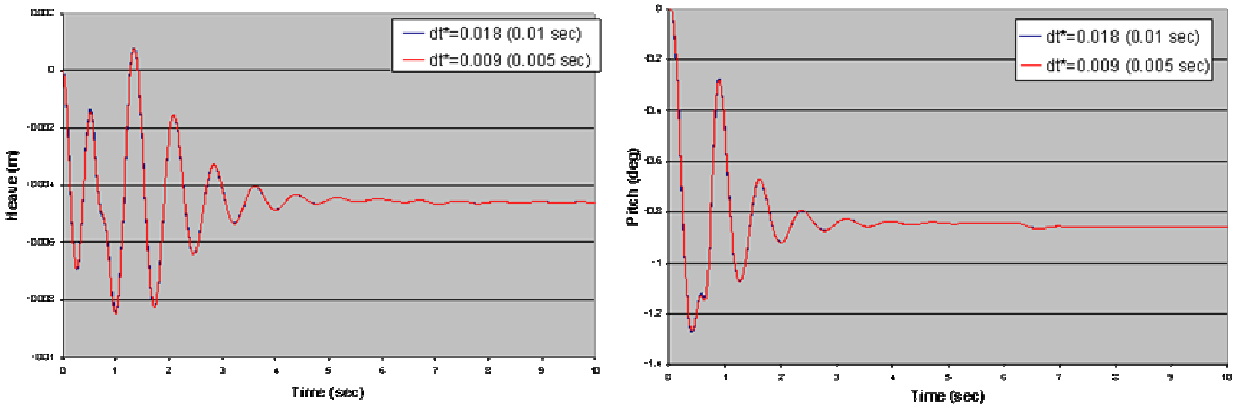

Figure 3: Heave and Pitch Response in Calm Waters at Fn = 0.75 with Two Different Time Steps, Δt = 0.01 vs. 0.005 Seconds

3.1.2 The Effect of the Body Panel Resolutions

Figure 4 shows the same case as in Figure 3, except using two different body panel resolutions: 264 vs. 566. Even though the number of the body panels is more than doubled, the difference in results is very small. This indicates that using more than 264 body panels is not necessary in producing the converged motion results.

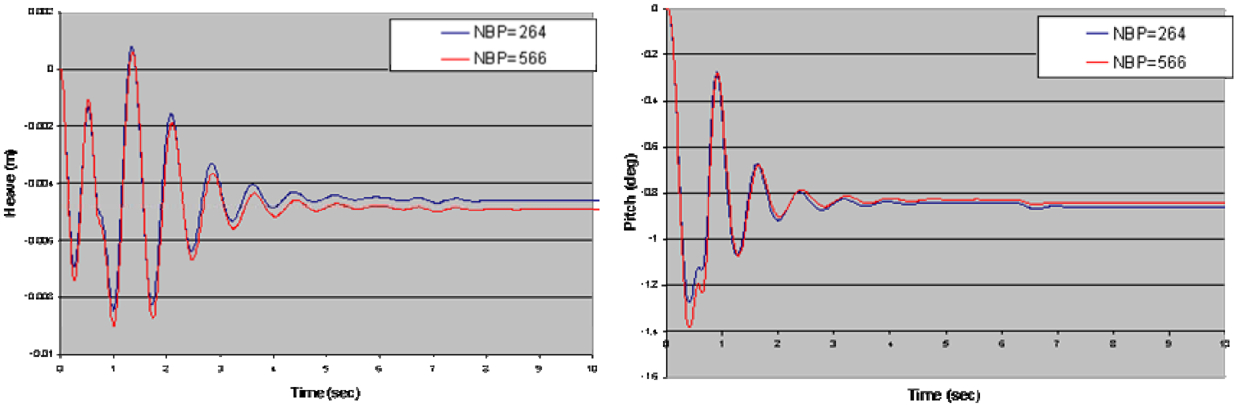

Figure 4: Heave and Pitch in Calm Waters at Fn = 0.75 with Two Different Body Panel Resolutions, NBP = 264 vs. 566

3.1.3 The Effect of the Free Surface Panel Resolutions

The effects of the free surface panel resolutions are demonstrated in Figure 5, where motion response results are presented. At Fn = 0.75, using 4,000 free surface panels seems adequate because the heave responses for 3,600, 4,000, and 4,800 free surface panels are almost same and the difference in the pitch responses at higher λ/L is relatively small.

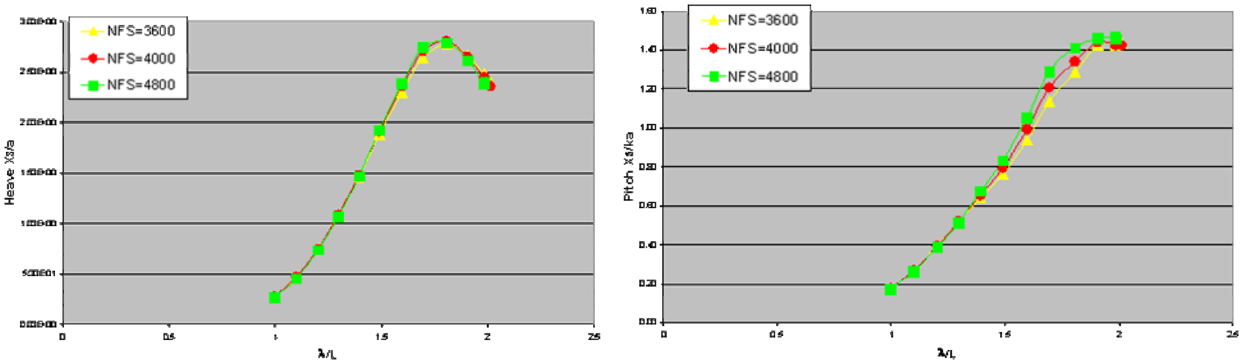

Figure 5: Heave and Pitch Responses at Fn = 0.75 for Three Kinds of Free Surface Resolutions, NFS = 3600, 4000 and 4800

3.1.4 The Effect of the Solution Domain Sizes

The solution domain size is controlled by the free surface domain size when the damping beach algorithm is employed. To determine if the LAMP solution is not sensitive to the free surface domain size, two free surface domains are chosen: 12m × 3m and 9m × 3m. Again, the motion responses at a lower Fn = 0.30 and a higher Fn = 0.75 are calculated and compared. The results are shown in Figure 6. This figure illustrates that the motion responses are less sensitive to the domain change at the lower speed than at the higher speed. It also shows that the heave responses are almost the same for both the lower and the higher speed. However, the pitch responses show some difference as the solution domain changes, especially at the higher speed.

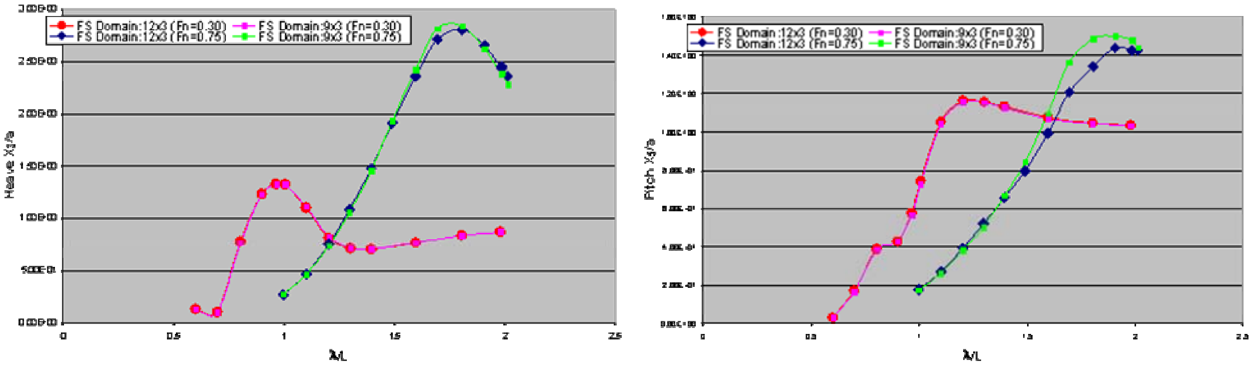

Figure 6: Heave and Pitch Responses for Fn = 0.30 and 0.75 with Two Different Free Surface Domains, 12m x 3m vs. 9m x 3m

3.2 Parameter Selection for the Catamaran Validation Study

Based on the above convergence and sensitivity study, an appropriate set of parameters was chosen to carry out all the LAMP calculations presented in this section. These parameters are:

- The time step size: 0.01 second (LAMP-2) or 0.008 sec. (LAMP-4 at Fn> = 0.6);
- The number of body panels: 264 (one demi-hull);
- The number of free surface panels: 100 × 40 = 4000 (one side of the free surface domain); and
- The solution domain: 12m × 3m = 4L × 1L (one side of the free surface domain).

It should be pointed out that, at lower speed, the time step can be increased from 0.01 seconds to at least 0.02 seconds.

4.0 LAMP VALIDATION RESULTS FOR CATAMARAN 372

4.1 Heave and Pitch for Catamaran_372_Delft (Head Seas)

The heave and pitch motions are calculated for Fn = 0.30, 0.45, 0.60, and 0.75. The results are presented in Figure 7 through Figure 10. The heave is normalized by the wave amplitude a and the pitch is normalized by the wave amplitude a and the wave number κ.

4.1.1 Fn = 0.30

In Figure 7, red dots represent LAMP-2 results, blue squares represent Delft's experiment, and black triangles represent MARIN's experiment.

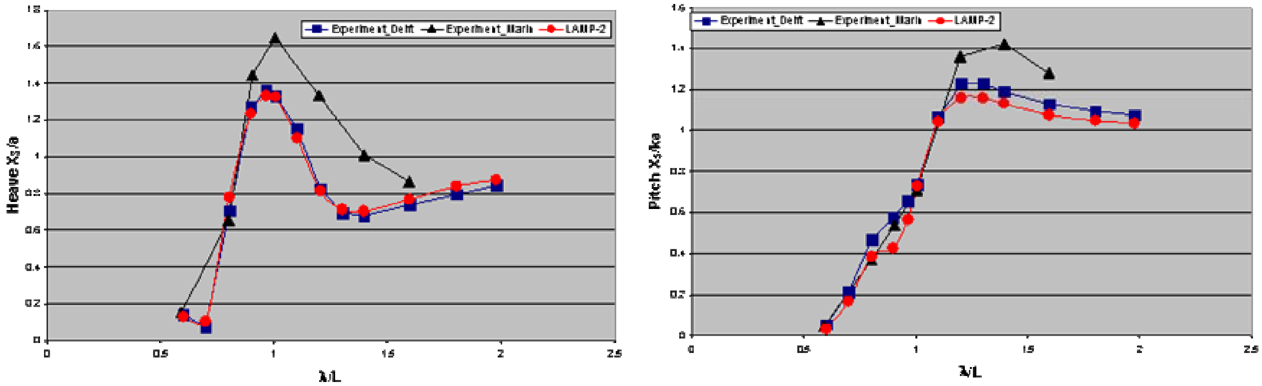

Figure 7: Heave and Pitch Responses for Fn = 0.30

It is worth pointing out in Figure 7 that the experimental results from MARIN are also plotted against the results from Delft University and the LAMP-2 calculation. It indicates that even with the almost identical model, the difference between the model tests from MARIN and Delft is as much as 15%.

4.1.2 Fn = 0.45

In Figure 8, red dots represent LAMP-2 results and blue squares represent Delft's experiment.

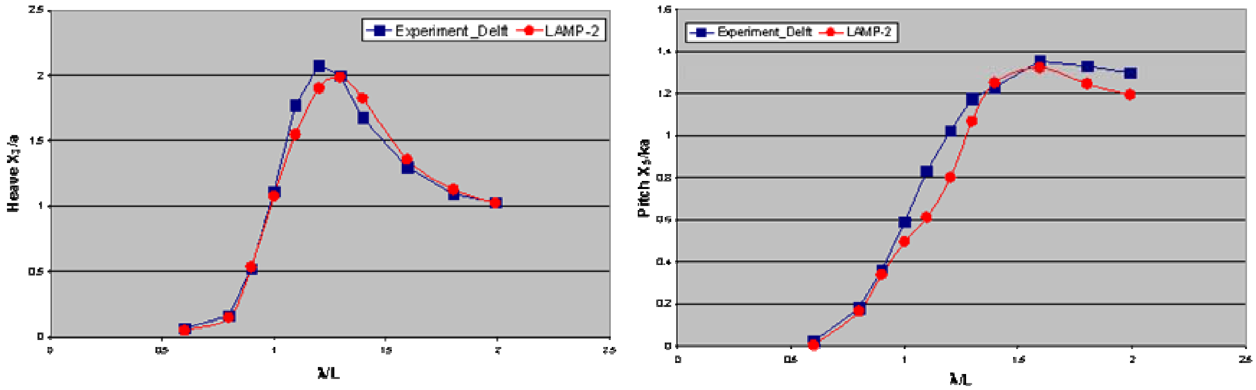

Figure 8: Heave and Pitch Responses for Fn = 0.45

4.1.3 Fn = 0.60

In Figure 9, red dots represent LAMP-2 results, purple diamonds represent LAMP-4 results, blue squares represent Delft's experiment, and black triangles represent MARIN's experiment.

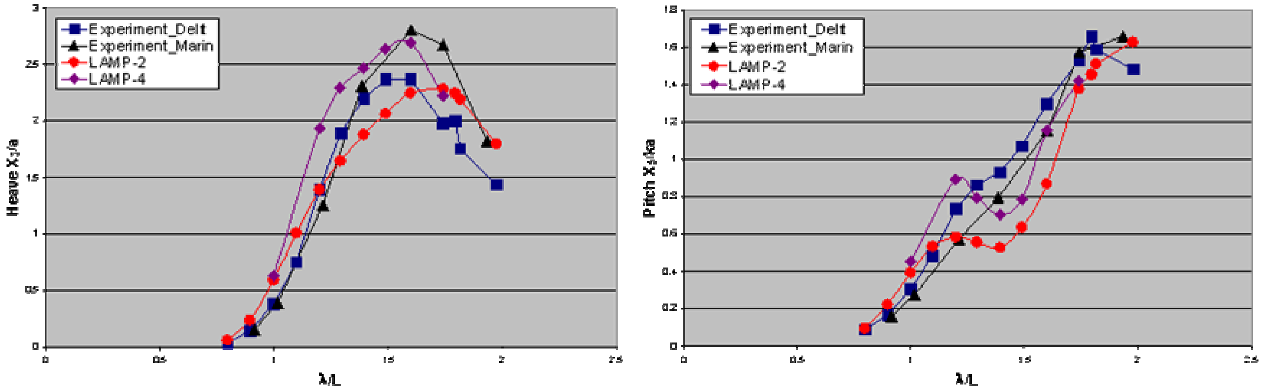

Figure 9: Heave and Pitch Responses for Fn = 0.60

For Fn = 0.60, both LAMP-2 and some LAMP-4 results are plotted against the experiments at Delft and MARIN. Some differences between LAMP-2 and LAMP-4 are shown for heave and pitch at this speed, but they are still in the range of the experiments. The cause of the "hump" in pitch is unknown at this stage. Further investigation is needed.

4.1.4 Fn = 0.75

In Figure 10, red dots represent LAMP-2 results, blue squares represent Delft's experiment, and black triangles represent MARIN's experiment.

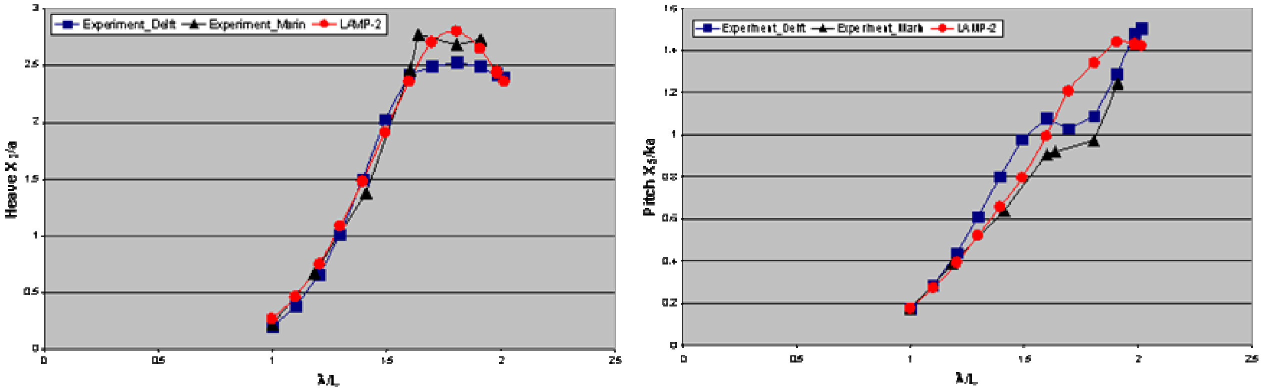

Figure 10: Heave and pitch responses for Fn = 0.75

A good agreement in heave and pitch are found for Fn = 0.75. It is interesting to notice that the pitch response has a "hump" in the experimental data but not in the LAMP calculation.

The overall comparison of the LAMP-2 results with the experiment at Delft University is satisfactory and encouraging, especially for the lower Froude numbers (Fn ≤ 0.45). This is true for both calm-water sinkage and trim calculation and the response calculation for heave and pitch. There is some uncertainty in the pitch response for Fn = 0.60 where LAMP-2 calculation has a “hump” but the experiment does not. Targeting this phenomenon, LAMP-4 runs were carried out, which show the similar characteristics, although the magnitude is closer to the experiment than LAMP-2. It is interesting to notice that for a higher Froude number, Fn = 0.75, the “hump” shows up in the experiment but not in the LAMP-2 calculation. The cause of the “hump” is unknown at this stage. More thorough investigation must be done to determine whether it is a physics-related phenomenon or a numerical-approximation issue.

4.2 Motions and Loads for Catamaran_372_MARIN (Oblique Seas)

In addition to the head seas results presented along with the Delft results above, the test of the Catamaran 372 model at MARIN included tests for long-crested bow oblique seas at two heading angles (15º and 30º off the bow) and three speeds (Fn = 0.30, 0.60, and 0.75). LAMP-2 simulations were made for each of the tested conditions and the computed heave, pitch, and roll motions were compared with the results of the MARIN experiments.

Because the oblique sea runs require double the number of panels in the calculation, the IRF-based scheme is adopted for all the oblique sea cases. This scheme gives almost identical results as the non-IRF based direction simulations as used for the head sea cases, but it runs much faster to obtain the motion and load time histories once the IRFs are pre-computed. The use of the IRF-based scheme also allowed rapid re-generation of results for soft-spring coefficients and sectional load calculation models.

The comparison with the experiment at MARIN for oblique seas shows that the motion responses for heave and pitch from the LAMP calculation agree with the experiment fairly well for all three speeds (Fn = 0.30, 0.60, and 0.75) and two headings (195°, and 225°). At some wavelengths, LAMP-2 results tend to underestimate the response values, but the magnitude of that underestimation is relatively small. Roll motions also qualitatively agree with the experiment. Results are shown in Figure 11through Figure 22. In all figures, red dots represent LAMP-2 results and blue squares represent MARIN’s experiment.

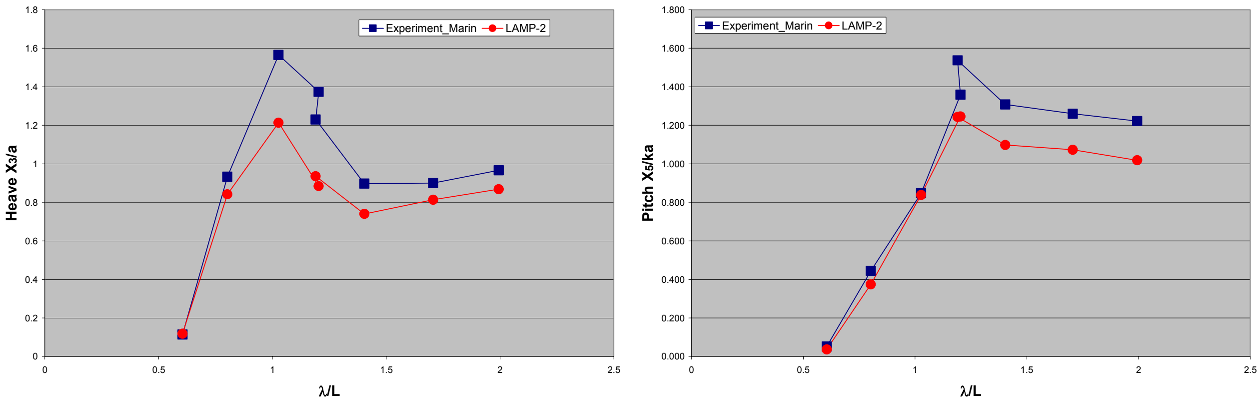

Figure 11: Heave and Pitch Responses for β = 195° & Fn = 0.30

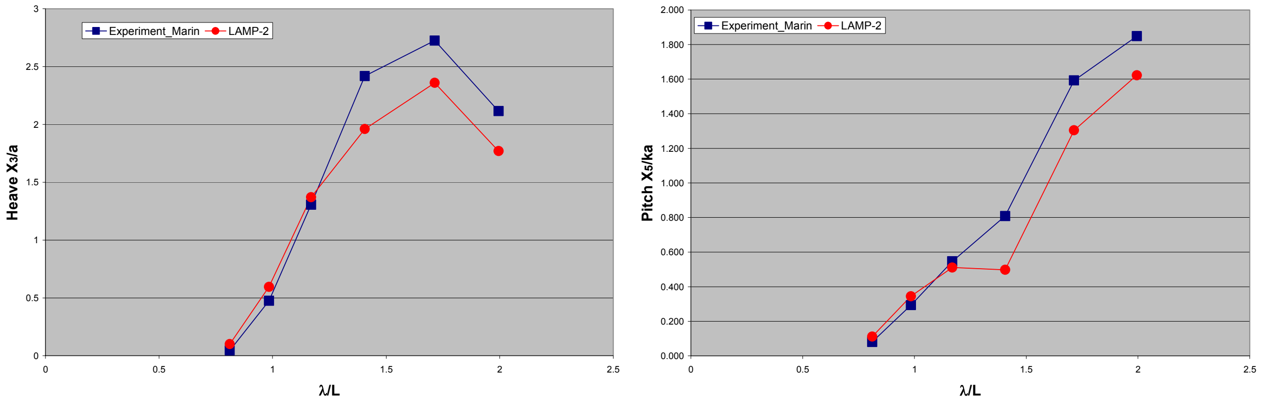

Figure 12: Heave and Pitch Responses for β = 195° & Fn = 0.60

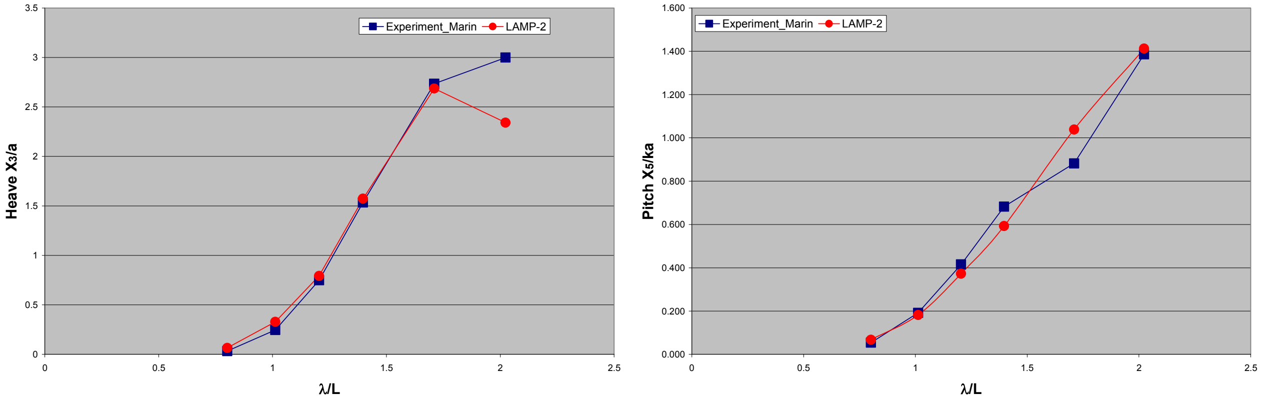

Figure 13: Heave and pitch responses for β = 195° & Fn = 0.75

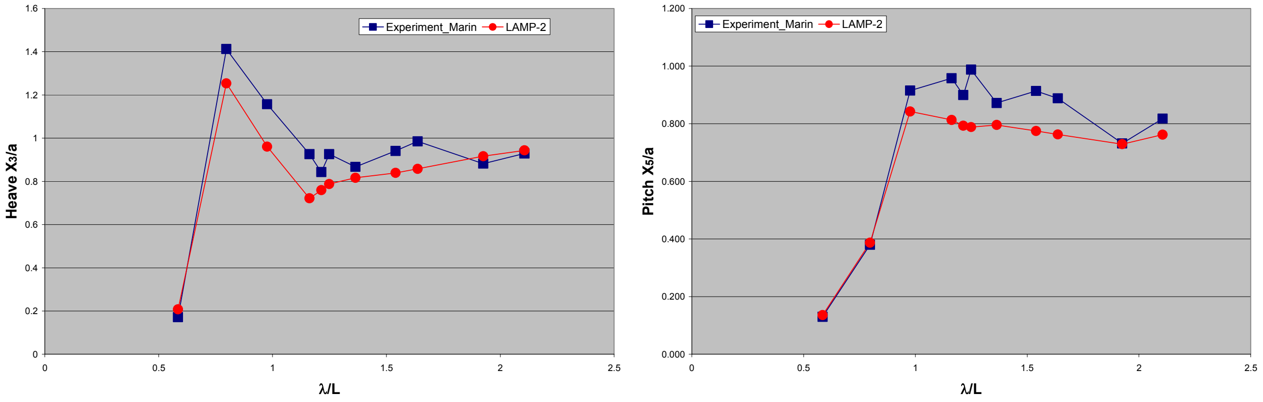

Figure 14: Heave and Pitch Responses for β = 225° & Fn = 0.30

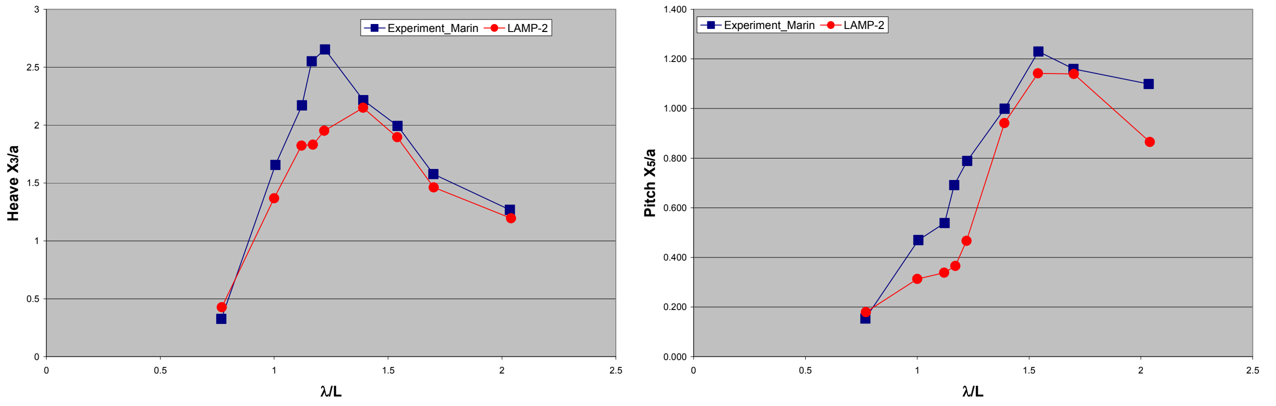

Figure 15: Heave and Pitch Responses for β = 225° & Fn = 0.60

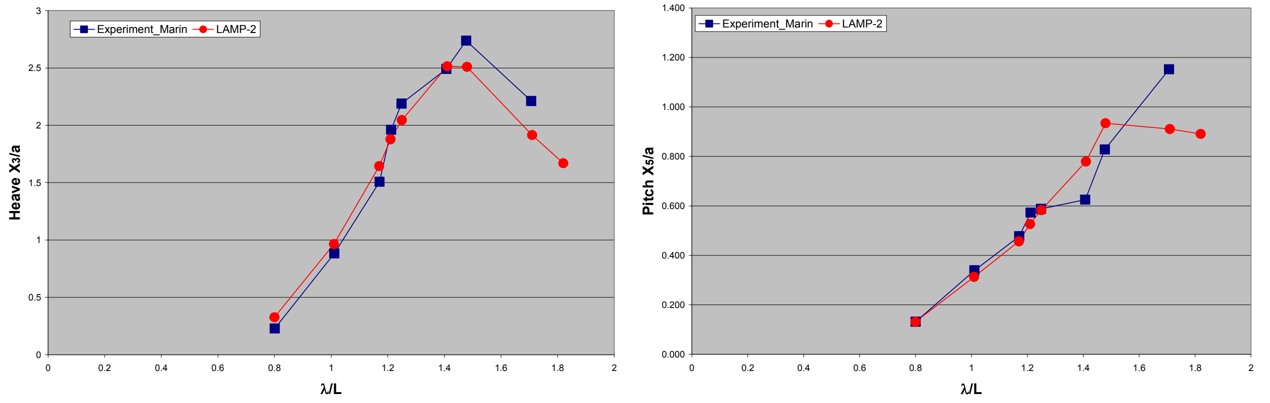

Figure 16: Heave and Pitch Responses for β = 225° & Fn = 0.75

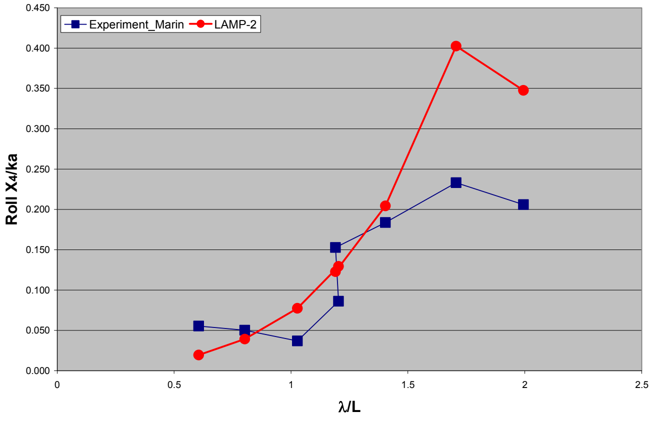

Figure 17: Roll Responses for β = 195° & Fn = 0.30

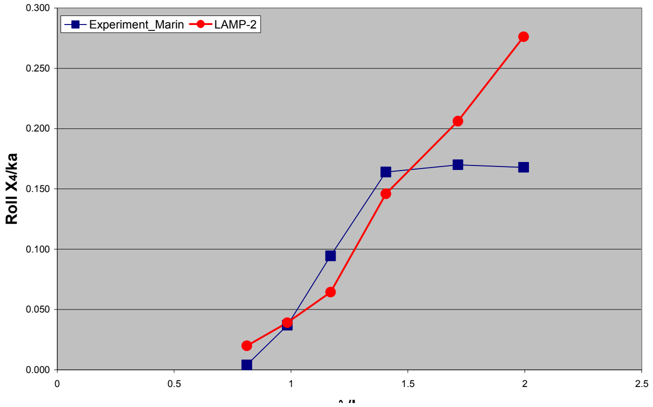

Figure 18: Roll Responses for β = 195° & Fn = 0.60

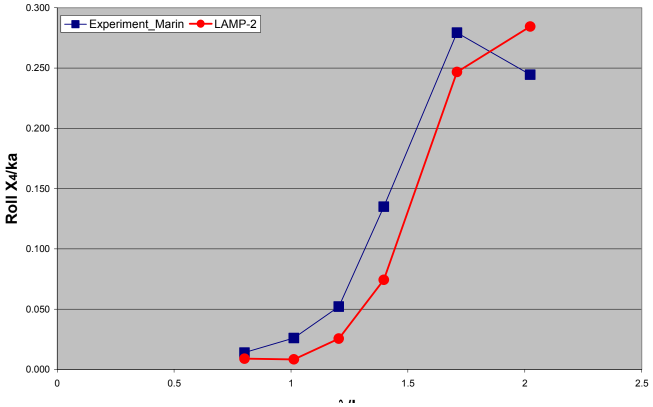

Figure 19: Roll Responses for β = 195° & Fn = 0.75

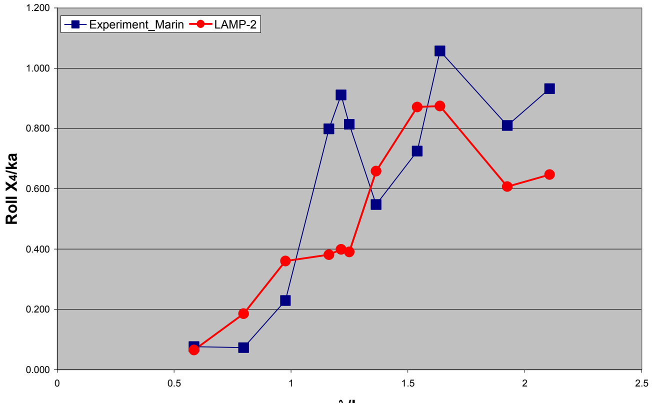

Figure 20: Roll Responses for β = 225° & Fn = 0.30

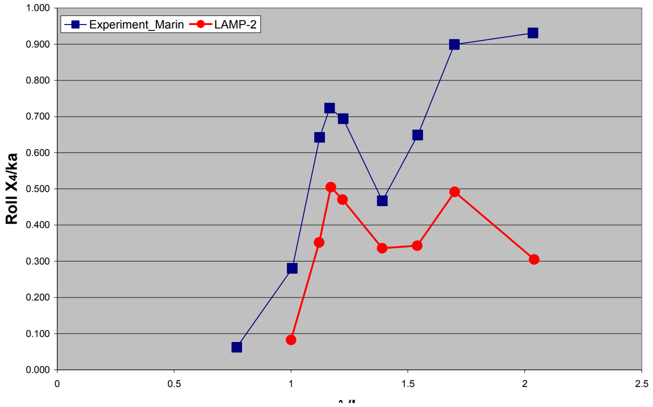

Figure 21: Roll Responses for β = 225° & Fn = 0.60

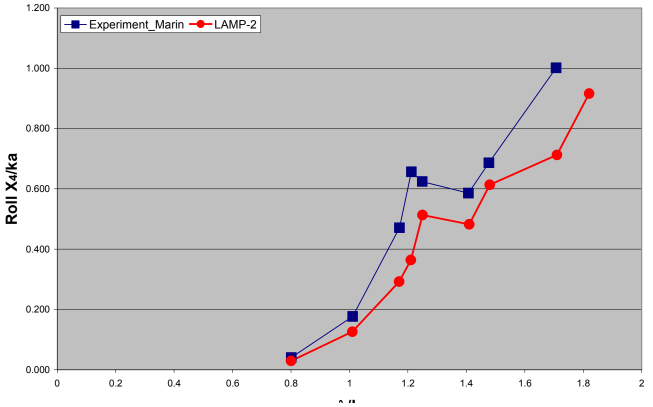

Figure 22: Roll Responses for β = 225° & Fn = 0.75

5.0 LAMP VALIDATION RESULTS FOR X-CRAFT

The second assessment effort compares numerically simulated time series data with measured results. In order to perform the numerical simulations, all wave time series data were translated from the wave probe to the models center of gravity based wave dispersion theory. An example of this transformation is shown in Figure 23.

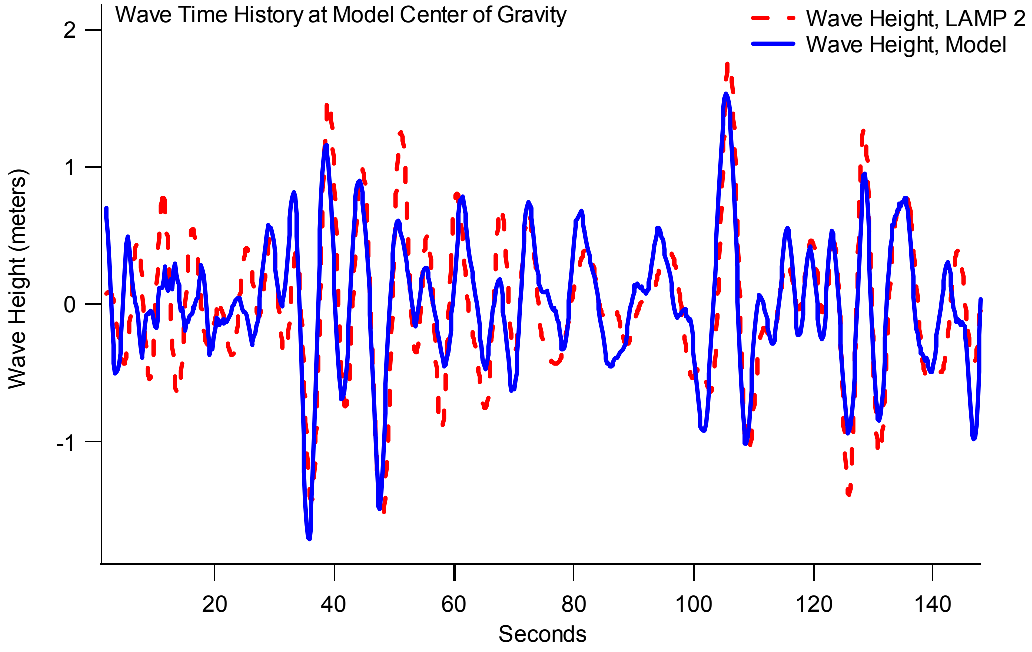

Figure 23: Comparison of Wave Time History for Sea State 4

5.1 Pitch, Roll and Heave Acceleration for X-Craft (Head Seas)

Pitch motion and heave acceleration are calculated for speeds of 5, 12 and 40 knots in Sea State 4 and 20 knots in Sea State 5. The results are presented in Figure 24 through Figure 31.

In general, the comparisons look fairly good. However, what does seem to show up is an over-prediction of pitch response at the lower speeds. There are two possible reasons for this. The first is that the physical model has higher damping than is being accounted for in the simulations. Alternatively, an examination of the model and numerically simulated wave time histories, show that, for some instances in time, the peaks of the numerically simulated waves are higher than that of the physical wave train. Hence, the higher excitations exhibited in the numerical simulation.

At the top speed used for comparison, insufficient information is available to ascertain the ability of LAMP to predict overall behavior. The main problem is related to the limits placed on the physical run length of the model (that is, we physically run out of room to test). As a result, definitive comparisons must be statistical in nature.

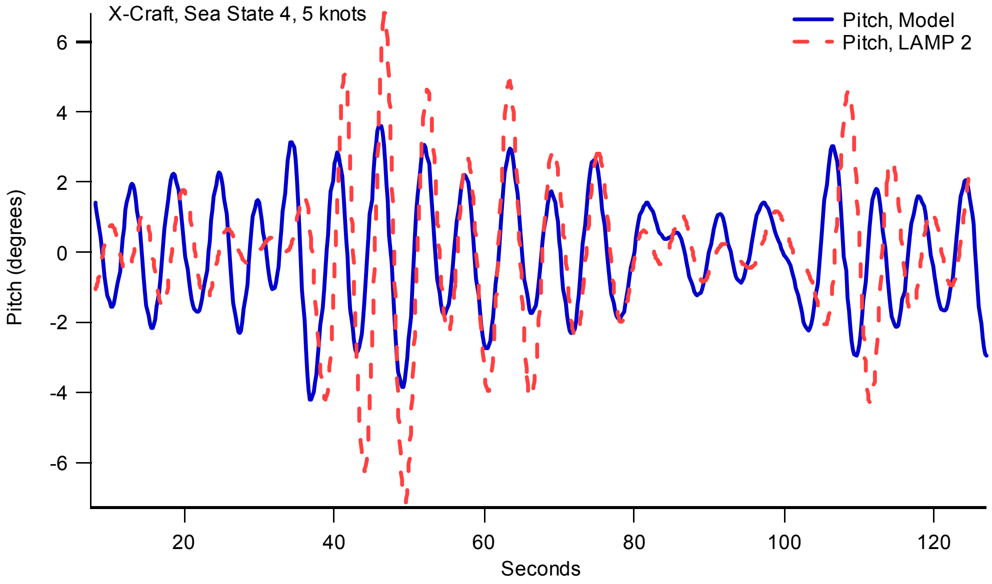

Figure 24: Comparison of Pitch Motion, Sea State 4, 5 knots, Head Seas

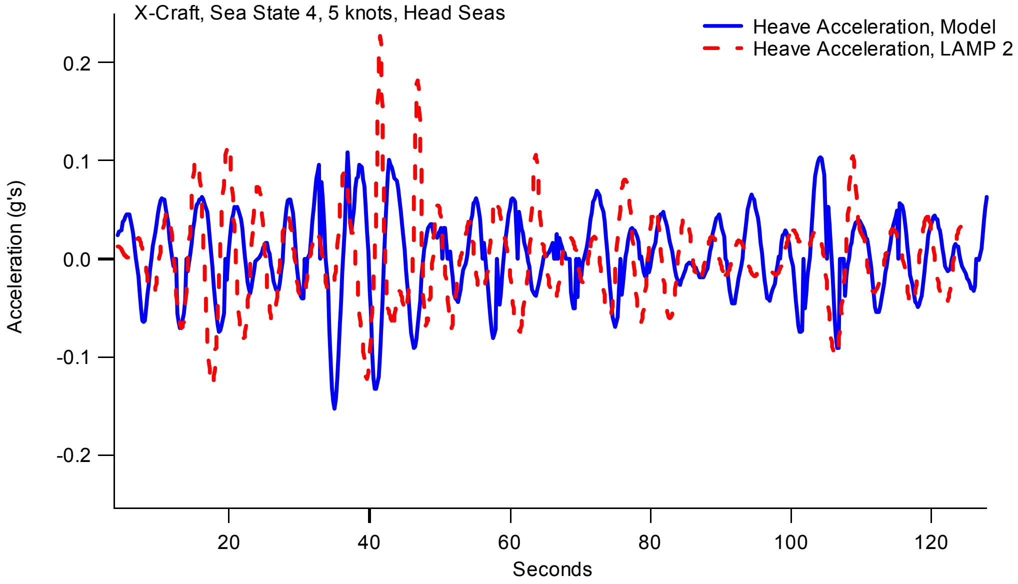

Figure 25: Comparison of Heave Acceleration, Sea State 4, 5 knots, Head Seas

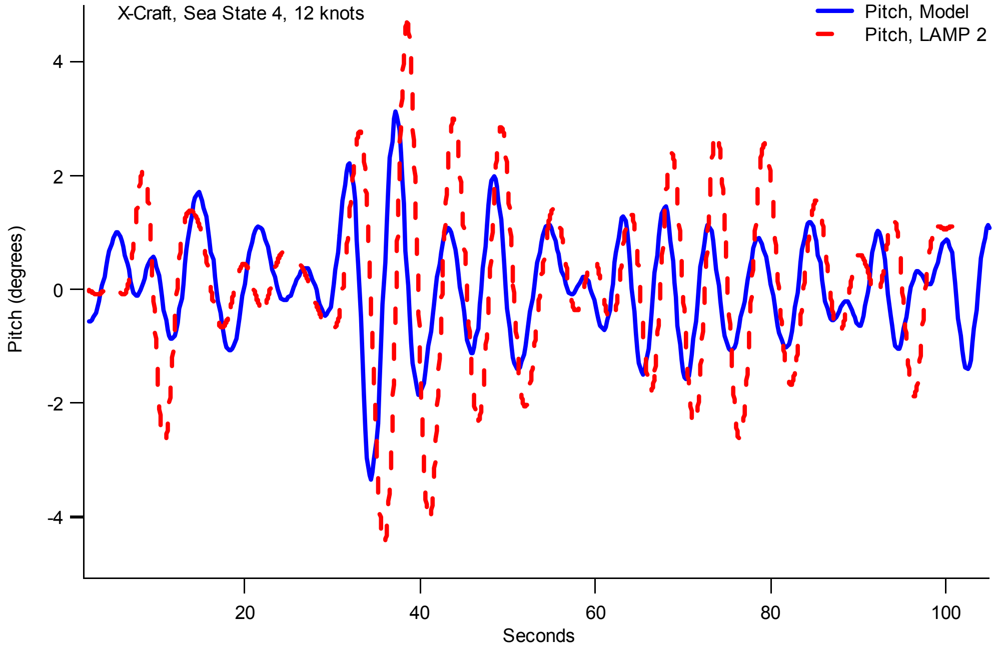

Figure 26: Comparison of Pitch Motion, Sea State 4, 12 knots, Head Seas

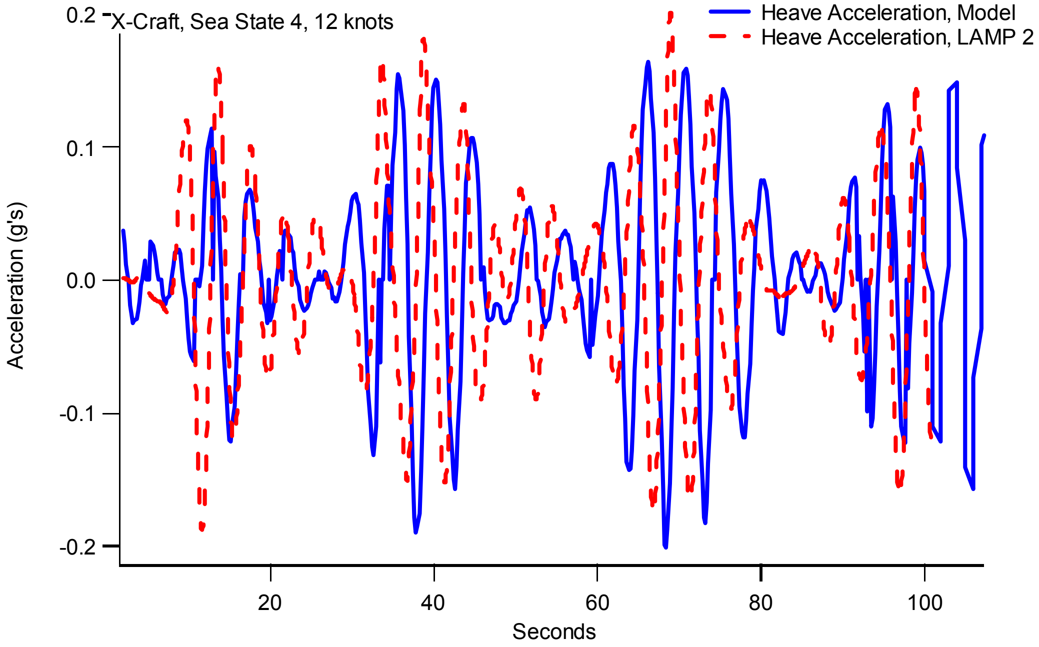

Figure 27: Comparison of Heave Acceleration, Sea State 4, 12 knots, Head Seas

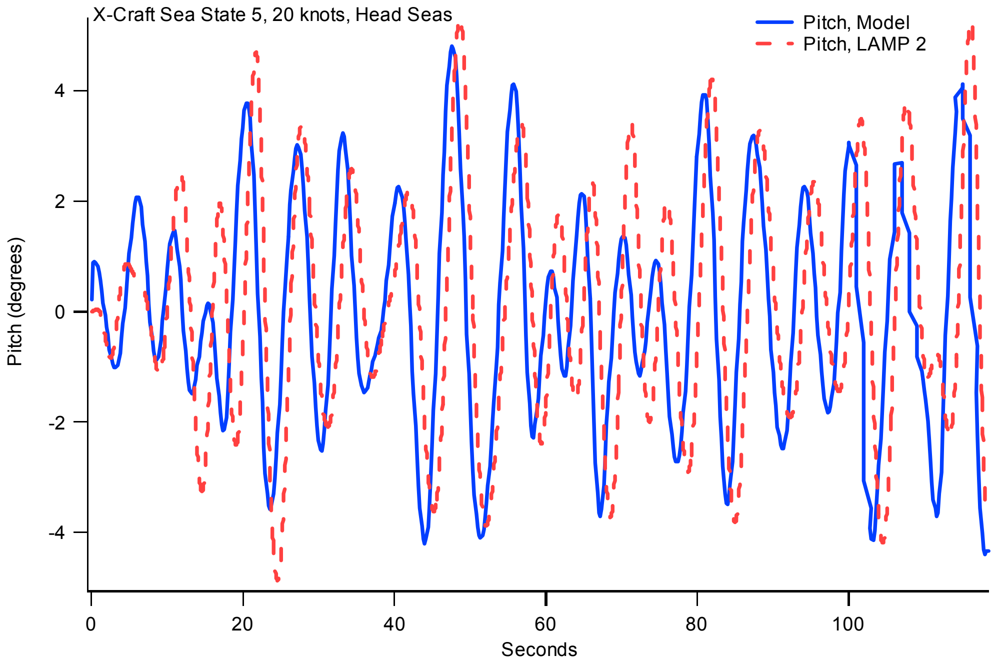

Figure 28. Comparison of Pitch Motion, Sea State 5, 20 knots, Head Seas

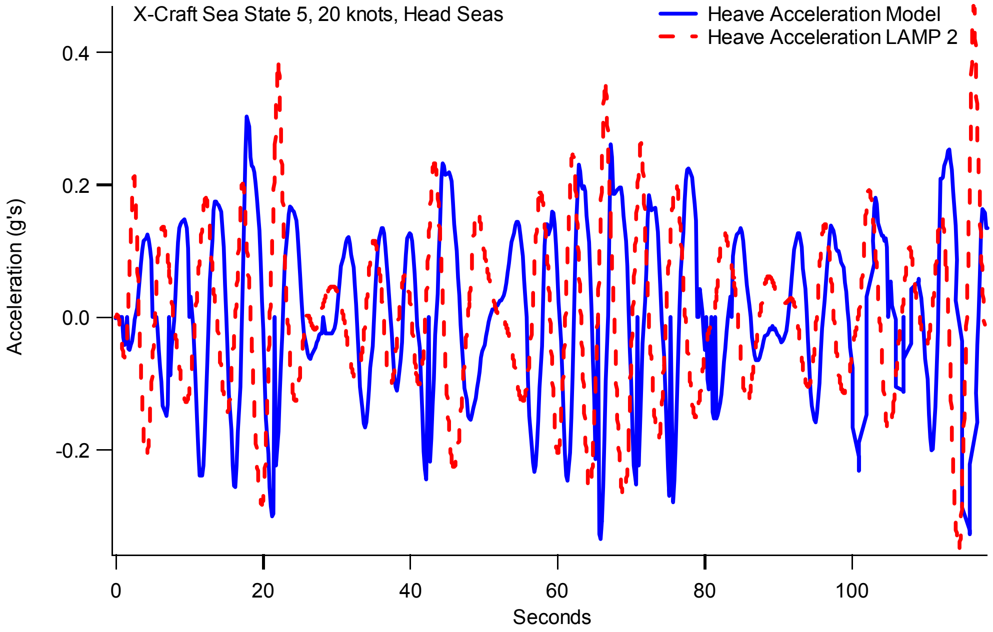

Figure 29: Comparison of Heave Acceleration, Sea State 5, 20 knots, Head Seas

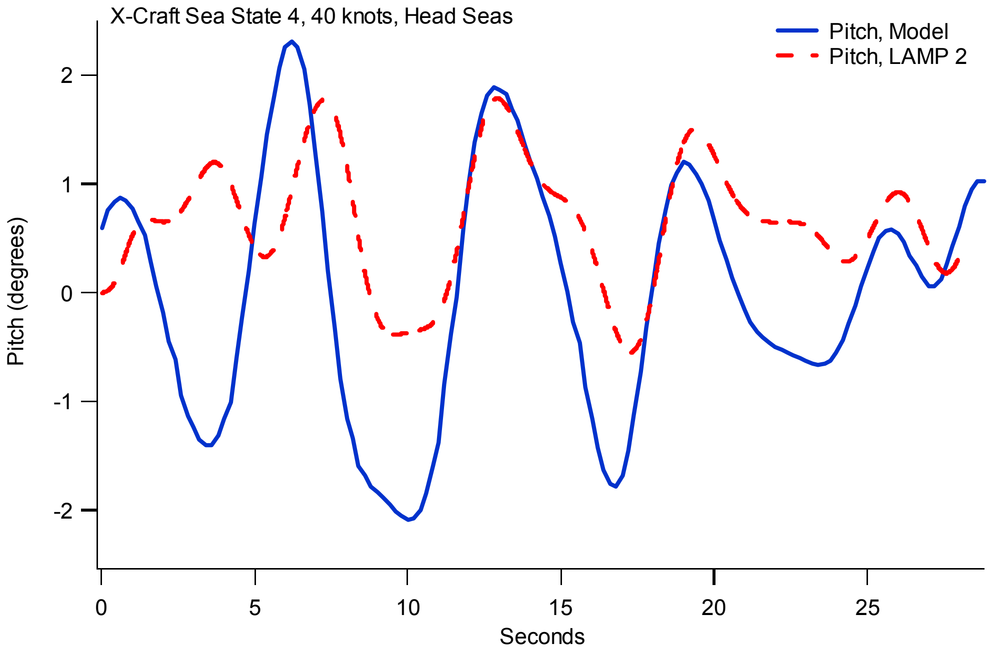

Figure 30: Comparison of Pitch Motion, Sea State 4, 40 knots, Head Seas

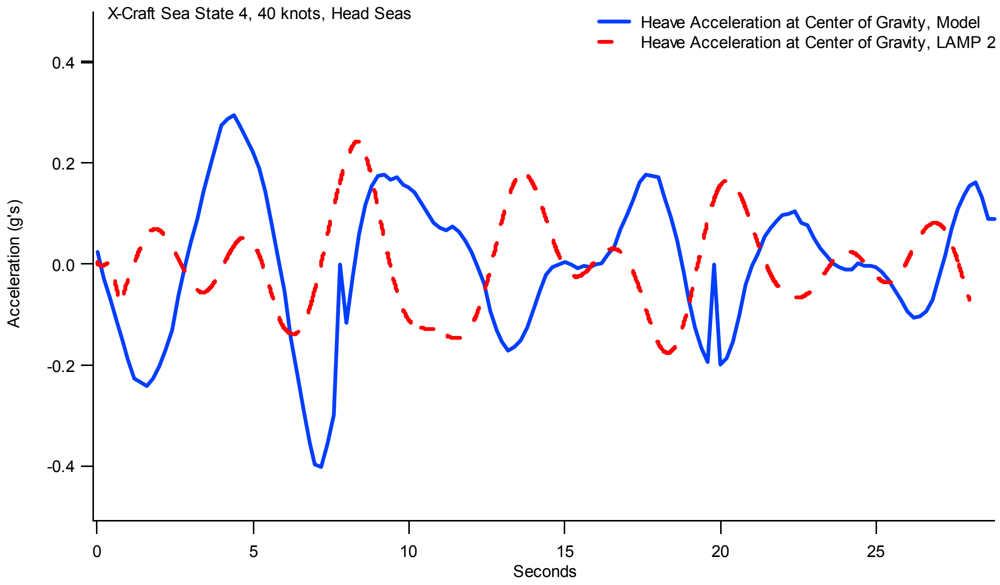

Figure 31. Comparison of Heave Acceleration, Sea State 4, 40 knots, Head Seas

5.2 Pitch, Roll and Heave Acceleration for X-Craft (Oblique Seas)

Pitch, roll and heave accelerations are calculated for two bow sea conditions in Sea State 5 at 20 knots. Results are presented in Figure 32 through Figure 37.

As was the case with the head sea simulations, in general, the comparisons look fairly good. Pitch and heave acceleration response is generally quite good, with the exception of one portion of the time trace. The specific reason for this is not known but could be the result of the physical model drift during the test run. A look at the roll response predictions shows a phase shift, but this could be the result of roll damping and or model drift. Given that the critcal damping applied during the simulations is based on a limited knowledge base for multi-hulls, it is felt that the overall predictions are quite reasonable.

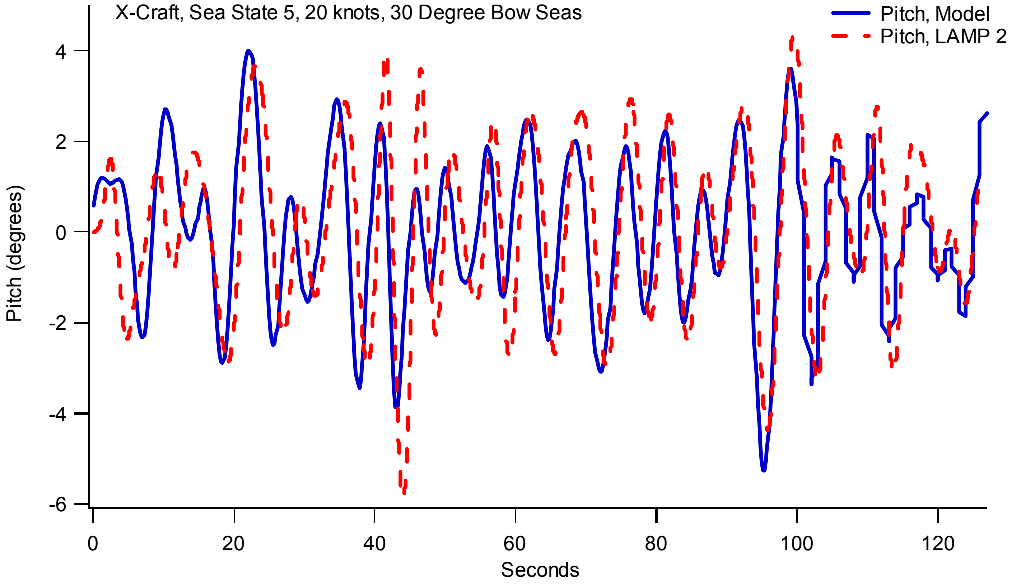

Figure 32: Comparison of Pitch Motion, Sea State 5, 20 knots, 30 Bow Seas

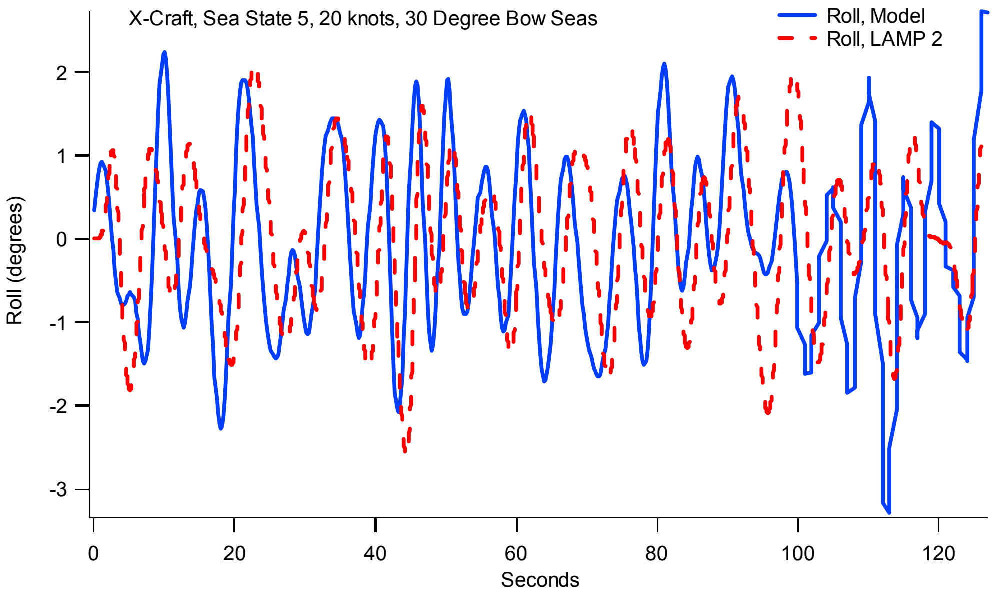

Figure 33. Comparison of Roll Motion, Sea State 5, 20 knots, 30 Bow Seas

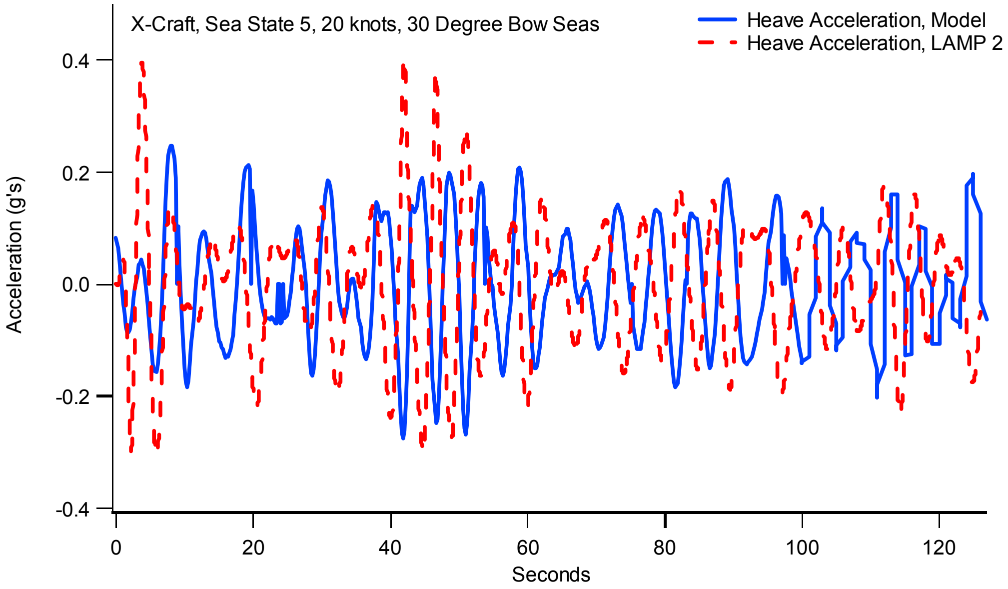

Figure 34: Comparison of Heave Acceleration, Sea State 5, 20 knots, 30 Bow Seas

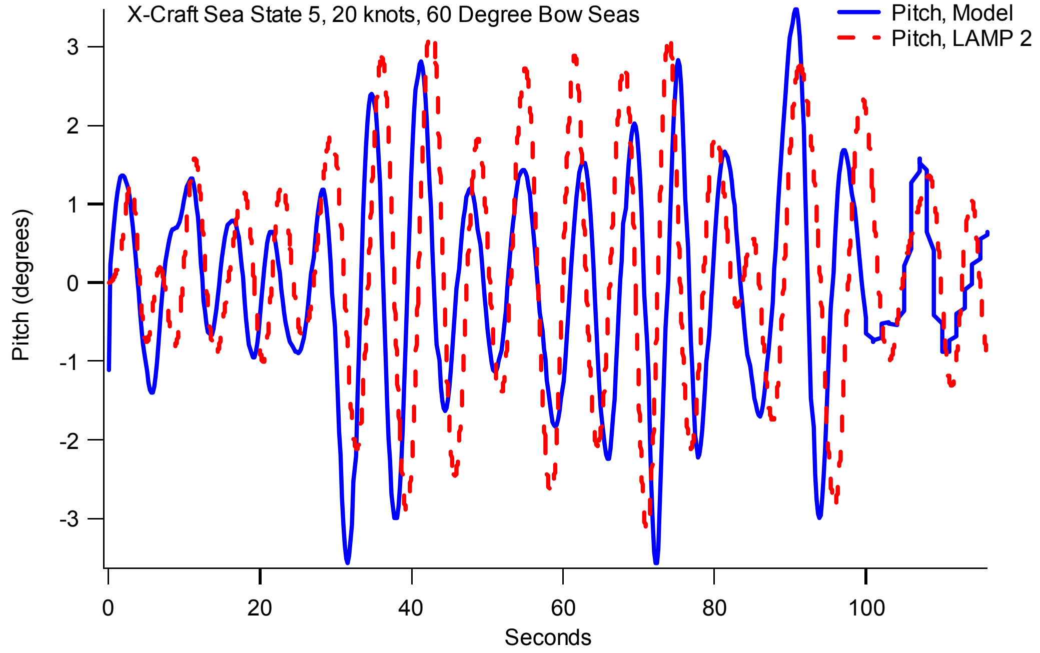

Figure 35. Comparison of Pitch Motion, Sea State 5, 20 knots, 60 Bow Seas

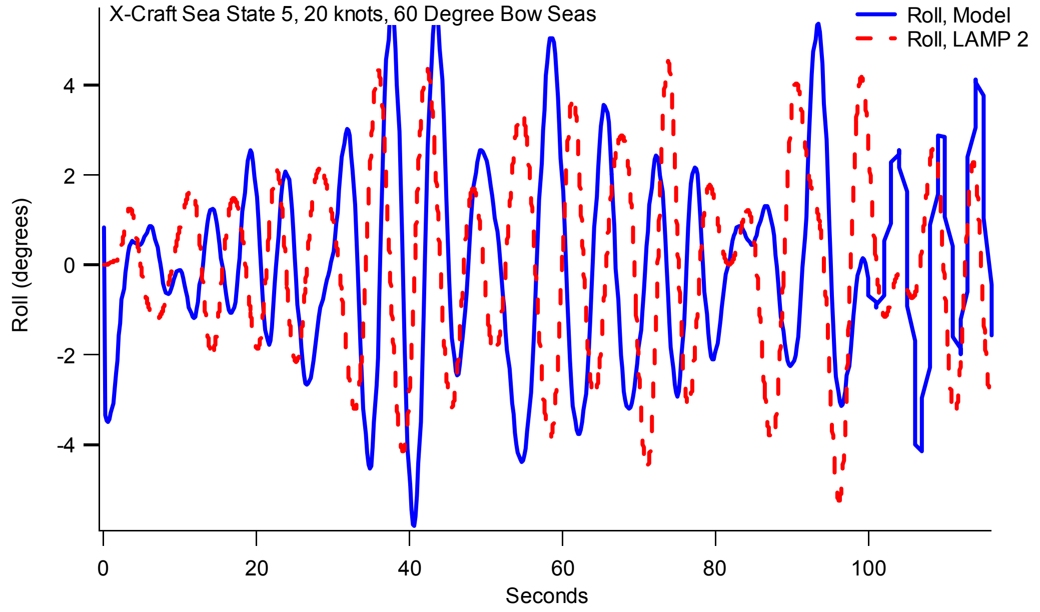

Figure 36: Comparison of Roll Motion, Sea State 5, 20 knots, 60 Bow Seas

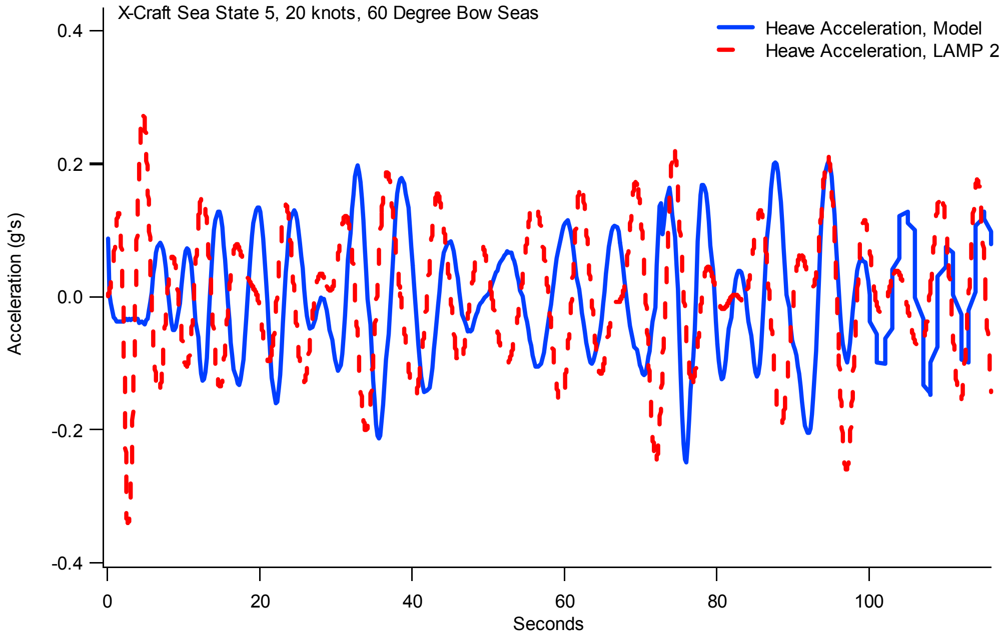

Figure 37: Comparison of Heave Acceleration, Sea State 5, 20 knots, 60 Bow Seas

6.0 APPLICATION OF NUMERICAL METHODS IN SUPPORT OF DESIGN

The use of numerical simulations during the design process provides naval architects with a means to perform design tradeoff studies in a cost effective, efficient manner. Issues such as seakeeping, human factors and operational assessments can all benefit through the use of such tools. This is of particular importance as the marine industry continues to pursue the development of advanced hull form concepts.

Although 2-D strip theory programs include multiple hull interaction in a 2-D plane, important 3-D body/wave interaction effects are not included. Therefore, predictions becomes less accurate as the hulls become closer. The emergence of 3-D methods provides naval architects with the ability to properly account for multi-hull 3-D body/wave interaction effects.

Based on the initial assessment of a state of the art time domain program, such as LAMP, it is clear that 3-D methods can be used to support the overall design process. However, some of the initial findings suggest that additional developments will be required before such tools can be used on a routine basis in support of high-speed, multi-hull design. These are described in the following sections.

6.1 Viscous effects

The current methods available for predicting ship motions and loads rely on potential flow. Since vertical plane motions are governed by potential flow wave damping, predictions for heave and pitch are typically found to be quite accurate. However, unless a ship's geometry is such that it produces significant amounts of radiated waves and has little viscous damping, roll motions will be dominated by nonlinear viscous and rotational effects. This typically is not the case for surface ships.

In order to account for the nonlinearities, it has been the practice to correct potential flow predictions by including real-fluid based empirical approximations. Unfortunately the accuracy of these empirically based corrections is dependent upon how well the hull form in question mirrors the hulls included within the test database.

With the move to develop advanced multi-hull hull form concepts, available methods for predicting damping are suspect. A review of available roll damping for multi-hulls is strongly recommended before productions runs are performed in support of design.

During the simulations of the X-Craft design, the issue of pitch damping has been raised. As discussed previously, it is unclear whether this is truly and issue or not. Further study of the available data sets is warranted before a definitive statement on this issue can be made.

6.2 Lifting effects

It is generally believed that lifting effects will become pronounced at higher speeds (Froude numbers of 0.7 and above). Although some of the effects of lift are accounted for in simulations, the effect of planning needs to be directly accounted for in these types of simulations. Due to the limited run times available for the 40-knot test, it is not possible at this stage to make any conclusion with regard to the limitations of the current formulation of the LAMP program. Further analyses, using statistical methods are required.

6.3 CPU time

In general, use of the linear and partial nonlinear versions of the LAMP program provided reasonable response times for comparisons with test runs. This seems to be true even when one needs to develop sufficient run lengths in support a stochastic analysis. Based on the CPU to real time ratios exhibited during some of the convergence studies

It is doubtful that the nonlinear (LAMP4) version of the code could be used on a regular basis to support design. This is particularly true for higher speed and/or oblique sea simulations. Use of the fully nonlinear code should be used judiciously, based on findings of simulations based on lower versions of the code.

ACKNOWLEDGEMENTS

The author would like to thank Mr. Ken Weems for his help with the intricacies of the LAMP suite of programs and for running the Netherlands data simulation sets. Mr. Dan Hayden and the rest of the NSWCCD test crew are recognized for their efforts in conducting the X-Craft model tests, and Mr. Bill Belknap for developing the original hull form geometry file used in the LAMP simulations.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P29 A.H. Engle 'Model Testing and Numerical Simulation of Seakeeping Performance for High Speed Vessels', (Naval surface Warfare Centre, US)

The US Navy has been supporting the development of a range of computational methods for predicting the dynamic response of a ship in a seaway. The code LAMP (Large Amplitude Motions Program) was used in the presented study. This program applies three-dimensional hydrodynamics along with a time stepping approach to determine all forces and moments acting on the ship. Realistic model test data were used to validate the predictions allowed by the simulation for pitch, roll and heave acceleration in head and oblique sea conditions. A sensivity analysis has been conducted on the modelling tools for choosing the model parameters; detailed results (comparisons) are listed: the use of such numerical simulations obviously ease the design process while issues such as sea-keeping, human factors and operational assessments can all benefit through the use of such tools.

Discussor's name: B. Masure
Q. For a high speed vessel, the study of unsteady motions is of course important for the efficiency of crews and armaments. Your presentation deals with these unsteady motions in heave, roll, pitch…, but you do not present any result concerning the drag of these high speed vessels (either calculated or measured). Drag is a very important parameter, in particular to determine the power necessary to sustain the speed. Can you comment on that?
For a mono hull ship, the value of say 0.6 for the Froude number is a frontier. Below Fr = 0.6, the mono hull ship can be considered as a displacement ship. For Fr in the vicinity of 0.6, the ship begins to plan and the drag presents a hump. For Fr>0.6, the ship must be considered as a planning ship. All these remarks are valuable for a mono hull ship. Are there critical values of Froude number for multi-hulls ships? Values for Catamaran? For Trimaran?
R. In addition to predicting ship motion and loads, the LAMP program can also predict resistance in waves. However, for this present study, only ship motions were examined.
It is expected that lifting effects will come into play at Froude numbers of around 0.6/0.7.

Discussor's name: M-C Tse
Q. Did you include the weight in the simulation? Why are the responses high for the range of $1<M<2$?
R. Yes, the numerical models used in the simulations were set at the same hydrostatics as the physical models. It is not clear at this point, why roll response was over predicted for wavelength / ship length ratios greater than 1.0. Perhaps roll damping was set at to low value in the simulations.

Discussor's name: L.P. Purtell
Q. What can be done about limited length of run time for tank tests of high speed module?
R. Short at building a new facility, the only solution is to "bite the bullet" and just perform multiple runs until sufficient statistics can be developed. High speed runs in following seas is most problematic. Smaller models than what has been tested (approx 3 meters in length) are not the solution as sealing at lifting surfaces can become an issue. There is also the issue of physical space required to place instrumentation within the model and trying to ballast down to the required test displacement.