



NSWC-CARDEROCK AND ABS COLLABORATION SUMMARY REPORT

Submitted to:

**Office of Naval Research
875 North Randolph Street, Room 273
Arlington, VA 22203-1995**

**Dr. Paul Rispin, Program Manager
ONR Code 331
703.696.0339
rispin@onr.navy.mil**

**In fulfillment of the requirements for:
Cooperative Agreement No. N00014-04-2-0003
*Agile Port and High Speed Ship Technologies***

**FY 05 Project 05-8, Program Element 2.35
*Development of a Route/Mission Dependent Prediction Program for Rational
Structural Dynamic Loads for High-speed Sealift Applications***

Classification: Unclassified

Prepared and submitted by:

**Center for the Commercial Deployment of Transportation Technologies
California State University, Long Beach Foundation
6300 State University Drive, Suite 220 • Long Beach, CA 90815 • 562.985.7394**

January 23, 2007

NSWC-CD AND ABS COLLABORATION SUMMARY

**FY 05 PROJECT 05-8, PE 2.35
TASK NO. 8.4**

NSWC-CD and ABS Collaboration Summary

System:

ROUTE/MISSION DEPENDENT PREDICTION PROGRAM FOR RATIONAL
STRUCTURAL DYNAMIC LOADS FOR HIGH-SPEED SEALIFT APPLICATIONS

By:

CDI Marine Systems Development Division
900 Ritchie Highway, Suite 102
Severna Park, MD 21146

For:

Center for the Commercial Deployment of Transportation Technologies
6300 State University Drive, Suite 220
Long Beach, CA 90815

CCDoTT Fiscal 2005 Sub-agreement: S07-306205CDI
Prime Agreement No.: N00014-04-2-0003
Task 8.4 - Initial Collaboration with NSWC-CD and ABS

CCDoTT Project Director:
Stanley Wheatley
CCDoTT
6300 State University Drive, Suite 220
Long Beach, CA 90815

CDIM-SDD Technical Manager:
Manish Gupta
CDIM-SDD
900 Ritchie Highway, Suite 102
Severna Park, MD 21146

This material is based upon work supported by the Office of Naval Research, under Cooperative Agreement No N00014-04-2-0003 with the California State University, Long Beach Foundation, Center for the Commercial Deployment of Transportation Technologies, (CCDoTT).

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Center for the Commercial Deployment of Transportation Technologies (CCDoTT) at California State University, Long Beach.

FOREWORD

The work described in this report was prepared by CDI Marine Systems Development Division (CDIM-SDD) for the Center for Commercial Deployment of Transportation Technologies (CCDoTT) at California State University, Long Beach. The principal point of contact at CCDoTT was Mr. Stanley Wheatley. The Project Manager and Technical Lead for CDIM-SDD was Mr. Manish Gupta.

TABLE OF CONTENTS

| | <u>PAGE</u> |
|---|--------------------|
| 1.0 Introduction | 1 |
| 2.0 Hullform Comparison – Deep-V Monohull | 1 |
| 3.0 Hullform Comparison – Catamaran | 5 |
| 4.0 Hullform Comparison – Trimaran | 8 |
| 5.0 ABS Comments | 11 |
| 6.0 Summary | 14 |
| 7.0 References | 14 |

LIST OF FIGURES

| | <u>PAGE</u> |
|--|--------------------|
| 1 Vertical Acceleration Trends for Deep-V Monohull | 2 |
| 2 Vertical Acceleration Trends for Catamaran | 5 |
| 3 Roll Connecting Moment RAO's for Catamaran in Beam Seas | 6 |
| 4 Pitch Connecting Moment RAO's for Catamaran in Quartering Seas | 7 |
| 5 Vertical Acceleration Trends for Trimaran | 9 |
| 6 Vertical Bending Moment RAO's for Trimaran | 10 |
| 7 ABS Proposed Direct Analysis Method | 12 |
| 8 ABS Proposed DLA Procedure | 13 |

LIST OF TABLES

| | <u>PAGE</u> |
|---|--------------------|
| 1 Comparison of Deep-V and Unimak Principal Characteristics | 3 |
| 2 Comparison of Deep-V and Unimak Seakeeping Data | 4 |
| 3 Comparison of Deep-V and FF-1043 Slam Frequency | 5 |

1.0 INTRODUCTION

The current project is Phase II of an on-going three-phase program to develop a prediction tool to predict rational structural dynamic loads for high-speed multihull vessels. Phase I was successfully completed in the 2001-2002 fiscal year with the development and demonstration of the first part of the prediction tool. The first part was to predict the global hull loads that are wave height and frequency dependent and therefore could be predicted using a frequency-domain tool. The detail report describing the Phase I effort was provided in CDIM-SDD Working Paper 727-1, August 2002, submitted to CCDoTT.

The current Phase II effort is spread over two fiscal years. The first part of the current phase, Phase II-A, is being performed using FY 2005 funding. The follow-on effort to complete Phase II, which is Phase II-B, will be performed in FY 07 using FY 06 funding. The final phase, Phase III, which is extensive validation of the tool along with incorporation into rule-making procedure, is scheduled for 2008. The objective of the Phase II effort is to determine the probabilities of slamming and the loads associated with slamming, which can be predicted using a time-domain program to be developed in the current phase. Under this current effort, Phase II-A, slamming load prediction algorithms are to be developed along with some limited verification on a few high-speed hullforms.

During the course of this effort, periodic collaborative discussions and feedback were solicited from both Naval Surface Warfare Center – Carderock Division (NSWC-CD) and American Bureau of Shipping (ABS). NSWC-CD's involvement was in the area of hullform selection, hullform comparison and verification. ABS's support was in the area of reviewing the overall approach and providing guidance and feedback in terms of incorporating the methodology into their rule-making procedure.

The current report provides a brief summary of the tasks performed in collaboration with NSWC-CD and Mr. Jerry Sikora (Ret.-NSWC-CD), who was a consultant on this project. In addition, preliminary comments from ABS and their future involvement are also discussed.

2.0 HULLFORM COMPARISON – DEEP-V MONOHULL

Since the seakeeping data were generated using a frequency-domain numerical modeling tool, SHIPMO, it was essential to compare the simulated data with actual recorded full-scale or prototype data to gain some confidence and ensure the validity of the simulated seakeeping data.

Accelerations

As expected, based on the vertical and longitudinal accelerations at the forward perpendicular of the Deep-V Monohull from SHIPMO, the vertical accelerations were larger than the longitudinal accelerations and are the most significant for structural design. The largest of the average of the one-tenth highest vertical accelerations exceeded 8.0 m/s^2 , occurring in sea-state 5 at 30 knots. This is in close agreement with sea trial data of the U.S. Coast Guard Cutter Unimak which measured heave accelerations at the CG of a comparable sized ship to have exceeded 1.0 g (9.8 m/s^2) only three times in 61 days at sea.

Figure 1 shows the effects of speed on the average of the one-tenth highest vertical accelerations for sea-states 5, 6 and 7. As expected, accelerations increase with both ship speed and sea-state.

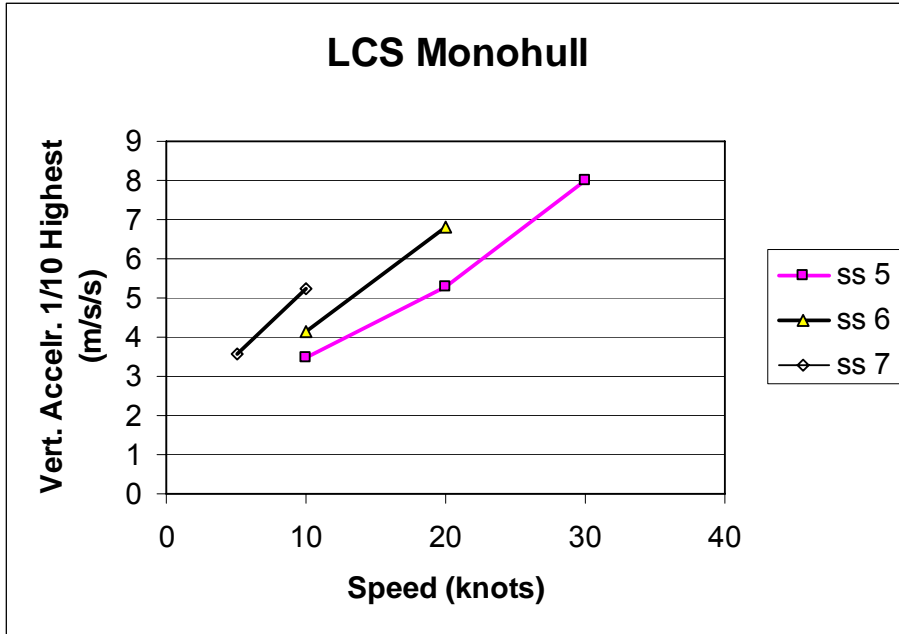


Figure 1. Vertical Acceleration Trends for Deep-V Monohull

An algorithm was developed to predict the average of the one-tenth highest vertical accelerations at the forward perpendicular of the Deep-V Monohull.

$$\text{Vert Acl (1/10)} = 0.568 + 0.17 \cdot \text{WH} + (0.1444 + 0.026 \cdot \text{WH}) \cdot V$$

Where: Vert Acl (1/10) is in units of m/s^2
 WH is the significant wave height in units of meters

And: V is the ship speed in units of knots

The algorithm matches the SHIPMO predictions to $\pm 0.24 \text{ m/s}^2$.

Slam Initiation

Algorithms for predicting slam rates as functions of encounter frequency (f_e) and wave height were initially developed for fine bow ships in Ref. 4. The slam rate (slams/hour) can be approximated by:

$$\text{Slam Rate (slam/hour)} = 30 f_e / \text{Lbp}$$

Where f_e is in units of wave encounters per hour and the ship length is in units of feet. The following is an approximation for the wave encounter frequency:

$$f_e = 720/\sqrt{H} + 46.8 (V/H) \cos \Theta$$

Where H is the significant wave height in meters, V is the ship speed in knots, and Θ is the heading off the bow.

Thus, one would expect a slam rate of 42 slams per hour (86 seconds between slams) at the onset of slamming at 10 knots in 4.2 meter seas and a slam rate of 31 slams per hour (116 seconds between slams) at 5 knots in 6 meter seas. The slam rate will increase with higher ship speeds.

Vertical Bending Moment

Algorithms for midship vertical bending moments from Ref. 4 contain factors for ship speed:

$$F = 1.0 + C \cdot V$$

Where V is the ship speed in knots and C is a coefficient for ship type. A C value of 0.011 was suggested for frigates, which most closely correspond to the Deep-V Monohull. Thus, the algorithm would predict the vertical bending moments to increase by 30% by increasing the ship speed from 10 to 40 knots. However, larger ships in that study had smaller coefficients, so a somewhat larger value may be appropriate for the Deep-V Monohull.

The seakeeping data was first compared against the sea trial data of USCG Cutter Unimak. The size and hullforms of the Deep-V and the Unimak are quite similar, so one would expect the motions and loads to be of the same magnitude. Although the bow of the Unimak does not have the forward strake of the Deep-V, both are considered Vee bows with minimal bow flare. Table 1 provides a comparison of the principal characteristics of the two hulls.

Table 1
Comparison of Deep-V and Unimak Principal Characteristics

| | | Deep-V | Unimak | |
|-------------------|----------|--------|--------|----|
| Length BP | LBP | 100.2 | 91.4 | m |
| Beam at Waterline | BWL | 13.7 | 12.5 | m |
| Draft - Design | DWL | 3.34 | 3.53 | m |
| Displacement | Δ | 2,315 | 2,800 | MT |
| Block Coefficient | C_b | 0.547 | 0.571 | |
| Waterplane Coef. | C_w | 0.791 | 0.703 | |

During the mid 1950's, sea trials were conducted on the USCG Cutter Unimak for over two months off the coasts of Newfoundland and New England. Data were recorded during fall and winter months on oscillograph charts and peak values were manually measured.

During the trials, pitch angles (double amplitude) exceeded 20 degrees seventeen times. Roll angles (double amplitude) exceeded 50 degrees four times during the trials. Heave accelerations measured at the Center of Gravity (CG) of the ship exceeded 1.0 G (9.81 m/s^2) three times during the trials. Pitch accelerations measured near the forward quarter point exceeded 0.68 rad/s^2 thirty-five times.

Strain gages mounted on the main deck amidships recorded stresses in excess of 6.7 Ksi (46.2 MPa) four times. Converting stresses to vertical bending moments using the section modulus amidships gives a bending moment of 32,900 ft-LT (99.9 MN-m). Since these values were recorded on oscillographs, they represent the combination of ordinary wave bending with any slam-induced whipping components.

One-inch diameter pressure gauges were mounted near the keel in the bow region and recorded pressures of 100 psi (0.69 MPa) frequently during the trials. Using pressure area reductions, based on Allen & Jones, 1978 (Ref. 1), this corresponds to equivalent uniform pressures of 39 psi (0.27 MPa) over a one square meter patch.

Based on the similarity of hullforms, both would be primarily affected by bow slamming on the keel rather than flare slamming as occurs on cruisers and aircraft carriers. Since the Unimak very likely experienced seas in excess of the sea-state 6 of the SHIPMO runs for the Deep-V Monohull, one would expect the sea trial values to be larger than the SHIPMO predictions. Table 2 provides some comparative seakeeping data between the two hulls, where the roll, pitch and vertical acceleration are the maxima

experienced by the Unimak and the corresponding average of 1/100th highest as predicted by SHIPMO for the Deep-V Monohull.

Table 2
Comparison of Deep-V and Unimak Seakeeping Data

| Motions & Loads | Deep-V | Unimak |
|---|---------------|---------------|
| Roll (deg) | 18 | 24 |
| Pitch (deg) | 7 | 10 |
| Acceleration (m/sec²) | 11.5 | 10 |
| Slam Pressure (psi) | 35 | 39 |

For the Deep-V Monohull, the SHIPMO predictions for vertical accelerations were 14.4 m/s² at point 3 and 11.5 m/s² at point 4 during 20-knot operations in head seas. These accelerations are 17% - 47% larger than the extreme heave accelerations measured at the center of gravity (CG) of the Unimak. Since the local bow accelerations would be larger than those at the CG, they seem to be of the right magnitude.

Vertical accelerations at the bow can be used to approximate slam pressures on the keel near the bow. The 14.4 m/s² (1.47 g's) vertical bow acceleration times the displacement of the vessel (2,315 MT) gives a total vertical force of 3,403 MT. This force uniformly spread over a total impact area of 36% of the total waterplane area, which is 388 m², gives an average pressure of 8.77 MT/m² or 12.6 psi (0.09 MPa). Based on the guidance of Ref. 1, using a pressure area reduction factor of 2, an equivalent uniform slam pressure of 35 psi (0.24 MPa) would be experienced over a patch of one square meter. This is virtually the same as the 39 psi (0.27 MPa) pressure measured on the Unimak.

Additional comparison was conducted with a U.S. Navy Frigate FF-1043. As a background, when either a bottom slam or bow flare slam occurs, the hull girder is excited and vibrates at its lowest natural frequency (as a free-free beam in vertical bending) in a phenomenon referred to as whipping. This bending moment is superimposed on any ordinary wave bending that may be present. Ref. 2 found that such slams invariably occur in either head or bow seas. For frigates, destroyers and cruisers (Ref. 3), slam-induced whipping occurred when: (a) ship speeds were greater than 10 knots and significant wave heights were above 5 meters; or (b) ship speeds were greater than a nominal 5 knots and significant wave heights exceeded 7 meters. (Other ship types and sizes have other ranges.) Any incidental slamming at lower speeds and sea states did not excite significant whipping moments.

The Deep-V Monohull has a similar bow and hullform to the frigates, etc. of the database developed in Ref. 4. The FF-1043 was one of the smaller frigates in the slamming database with a length between perpendiculars (LBP) of 118.9 meters. The ratio of the length of the Deep-V Monohull (100.2 meters LBP) to the FF-1043 is 0.843. By maintaining this same ratio for wave height, pitching motion is held constant. Hence, it is estimated that the Deep-V Monohull would initiate pitching that may lead to significant slamming in: (a) 4.2 meter seas when traveling at 10 knots or more; and (b) 6 meter seas when traveling at a nominal 5 knots. Significant slamming can also occur at lower sea-states at higher speeds. Based on the measured slam occurrence frequency and magnitude, Ref. 5 developed slam prediction algorithms for large monohull vessels. Table 3 compares the Deep-V Monohull slam predictions with the measured slams of FF-1043.

The hullform comparisons provided sufficient information to conclude that the seakeeping simulation data from SHIPMO was valid and could be used to obtain preliminary slam prediction estimates and for follow-on time-domain simulations.

Table 3

Comparison of Deep-V and FF-1043 Slam Frequency

| Slam Prediction | Deep-V | FF-1043 |
|-----------------------|--------|---------|
| Speed (Knots) | 10 | 10 |
| Sig. Wave Height (m) | 4.2 | 4 |
| Slam Frequency (#/hr) | 42 | 42 |

3.0 HULLFORM COMPARISON – CATAMARAN

Similar to the Deep-V Monohull, the seakeeping data generated using SHIPMO for the Catamaran was also compared with actual recorded data or rule-based estimates to gain some confidence and ensure the validity of the simulated seakeeping data.

Along with the seakeeping data, such as accelerations, global loads on the entire hull were also reviewed, as multihulls tend to have different governing load cases than typical monohulls.

Accelerations

Both vertical and longitudinal accelerations at the forward perpendicular of the Catamaran hullform were obtained from SHIPMO. As expected, the vertical accelerations were larger than the longitudinal accelerations and are the most significant for structural design. The largest of the average of the one-tenth highest vertical accelerations exceeded 33 m/s^2 , occurring in sea-state 7 at 15 knots.

Figure 2 shows the effects of speed on the average of the one-tenth highest vertical accelerations for sea-states 5, 6 and 7. As expected, accelerations generally increase with both ship speed and sea-state.

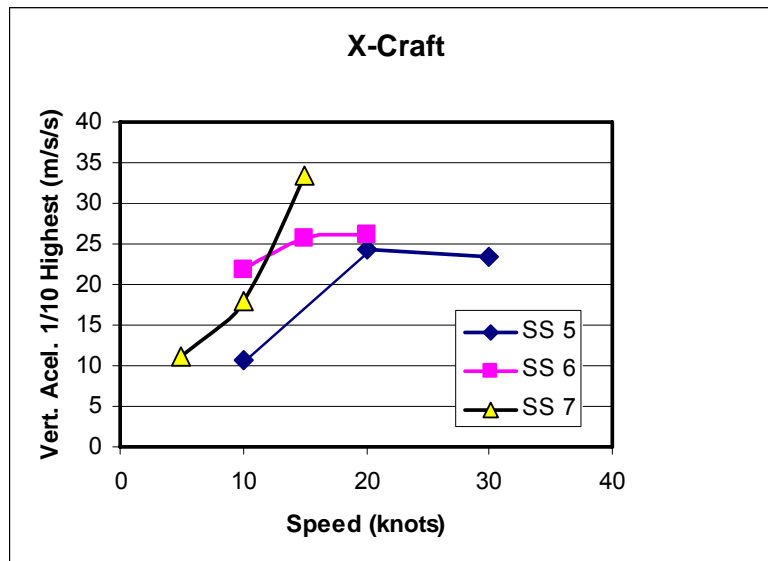


Figure 2. Vertical Acceleration Trends for Catamaran

An algorithm was developed to predict the average of the one-tenth highest vertical accelerations at the forward perpendicular of the Catamaran hullform for sea-states 5 and 6. The accelerations appear to increase with moderate ship speed (15 to 25 knots) and then level off or even decrease.

$$\text{Vert Acl (1/10)} = 22 + \text{WH} - 0.13 * \text{WH} * (\text{V} - 30 + 2 * \text{WH})^2$$

Where: Vert Acl (1/10) is in units of m/s^2
 WH is the significant wave height in units of meters

And: V is the ship speed in units of knots

Vertical accelerations for sea-state 7 increased approximately linearly with ship speed.

$$\text{Vert Acl (1/10)} = 2.09 * \text{V}$$

As always, extrapolation of algorithms beyond the range of the data from which they were developed would only be performed with adequate due diligence and engineering judgment.

Roll Connecting Moments

The roll connection moment, or the prying and spreading of the two hulls, can be one of the most significant primary loadings on a catamaran. These moments result from transverse forces acting on the mid-draft of the demi-hulls and are most severe in beam seas. Response amplitude operators of the roll connecting moment (RCM) were developed for the Catamaran for zero speed in beam seas at the wet-deck level by Froude scaling the experimental data of four dissimilar catamarans. It was found that the magnitude of the roll connecting moment decreases with increases in ship speed. Figure 3 shows the square root of the roll connecting moment RAO's for beam seas at 0 knots. The units of the root RAO's are in foot-ltons/foot of wave height, which is virtually the same as meter-mtons/meter of wave height.

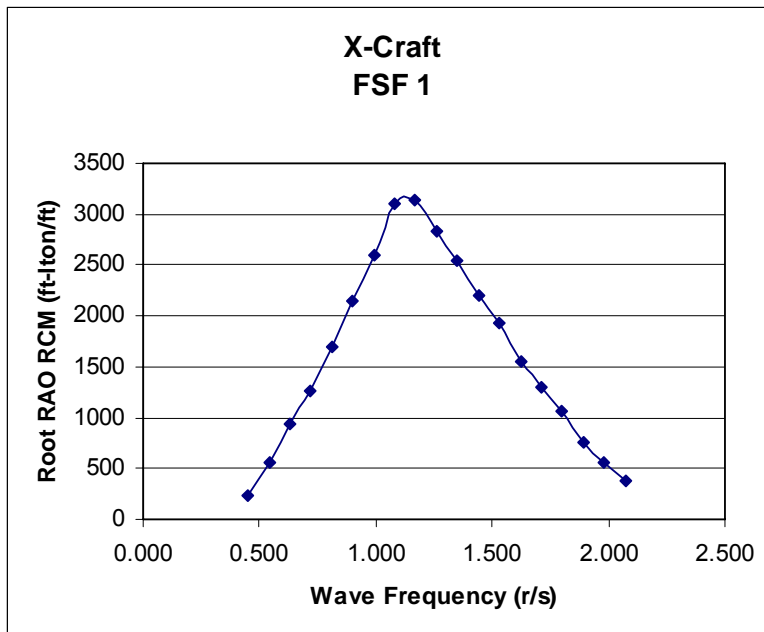


Figure 3. Roll Connecting Moment RAO's for Catamaran in Beam Seas

Ref. 5 provides algorithms for predicting the maximum lifetime transverse side forces (TSF) acting on the demi-hulls as a function of hull length (L) and demi-hull draft (T). The length and draft are in units of feet and the side force is in units of long tons (virtually equal to metric tons).

$$\begin{aligned}
 \text{TSF} &= 0.021 * L * T^2 \\
 &= 693 \text{ lton} \\
 &= 6.9 \text{ MN}
 \end{aligned}$$

The roll connecting moment is the product of the transverse side force acting at the mid-draft level of the hulls and a vertical moment arm (VA). For a nominal moment arm (to the wet-deck level) of 6 meters, the maximum lifetime roll connecting moment is:

$$\begin{aligned}
 \text{RCM} &= \text{TSF} * \text{VA} \\
 &= 13,650 \text{ ft-lton} \\
 &= 41.4 \text{ MN-m}
 \end{aligned}$$

Pitch Connecting Moment

The relative pitching motion of the two hulls of a catamaran induces a torsional moment in the cross-structure known as the pitch connecting moment. The pitch connecting moment (PCM) is most severe in bow and stern quartering seas and has been found to be fairly insensitive to ship's forward speed. Figure 4 provides the square root of the pitch connecting moment RAO's of the Catamaran in quartering seas. The plot was developed from an upper bound of experimental data from four dissimilar catamaran hullforms, Froude scaled to the X-Craft's size. The units of the root RAO's are in foot-ltons/foot of wave height, which is virtually the same as meter-mtons/meter of wave height.

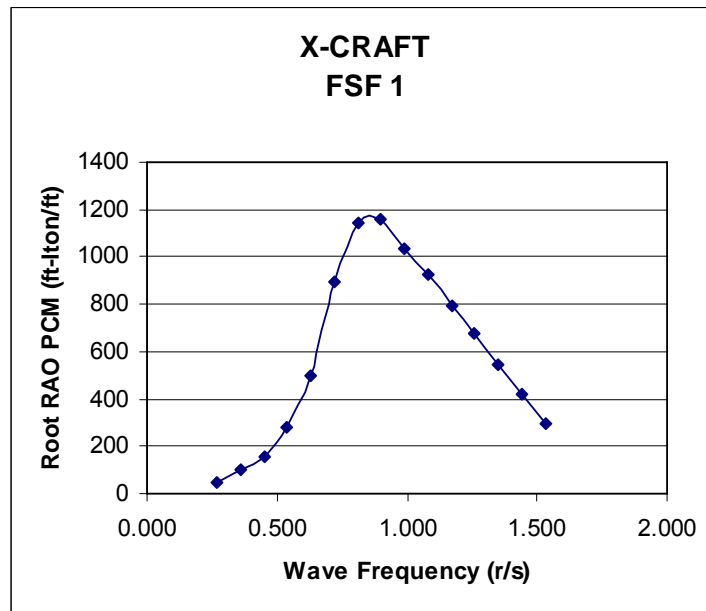


Figure 4. Pitch Connecting Moment RAO's for Catamaran in Quartering Seas

Algorithms for predicting the maximum lifetime pitch connecting moments of a catamaran were presented in Ref. 5 as a function of hull length and the beam at the waterline of one of the demi-hulls. The maximum lifetime pitch connection of the X-craft is:

$$\begin{aligned}
 \text{PCM} &= 0.0217 * L^2 * B \\
 &= 21,600 \text{ ft-lton} \\
 &= 65.5 \text{ MN-m}
 \end{aligned}$$

Vertical Bending Moment

Det Norske Veritas (DnV) provides an algorithm for a design vertical bending moment for twin hull ships in Ref. 6. It is a function of the hull length, the waterline beam of both hulls (B_{WL2}), and the block and waterplane coefficients. Length terms are input in meters.

$$\begin{aligned} VBM_{Hog} &= 0.19 * C_W * L^2 * (B_{WL2} + K) * C_B \\ &= 5.5 \text{ MN-m} \\ &= 1,813 \text{ ft-lton} \end{aligned}$$

$$\begin{aligned} VBM_{Sag} &= 0.14 * C_W * L^2 * (B_{WL2} + K) * (C_B + 0.7) \\ &= 7.96 \text{ MN-m} \\ &= 2,424 \text{ ft-lton} \end{aligned}$$

Where the K terms go to zero for the Catamaran's geometry and the waterplane coefficient was assumed to be 0.70.

The stillwater bending moments must be added to these values to get the total moments. Unlike the previous maximum lifetime loads, these vertical bending moments are the design loads. The greater depth of a twin hull ship compared to a conventional monohull gives it more sectional modulus to resist vertical bending. In addition, the relatively shorter hull length of twin hull ships implies smaller vertical bending moments. Thus, the vertical bending moment is not as critical a load case as the roll and pitch connecting moments.

X-Craft was recently deployed for a full-scale sea trial where seakeeping, seaway loads and slam pressures were recorded for different operational and environmental conditions. During the follow-on effort under Phase II-B, full-scale trial data of the X-Craft will be made available through NSWCD. At that time, verification and validation of the algorithms developed under this effort will be performed, and appropriate adjustments and/or corrections will be proposed to better suit the methodology for high-speed multihull applications.

4.0 HULLFORM COMPARISON – TRIMARAN

Similarly, the seakeeping data for the Trimaran was also compared with actual recorded data or rule-based estimates to gain some confidence and ensure the validity of the seakeeping simulations. In addition to the accelerations and slam initiation conditions, global loads such as vertical bending and transverse loads on side hulls were also reviewed.

Accelerations

Both vertical and longitudinal accelerations at the forward perpendicular of the center hull of the Trimaran hullform were obtained from SHIPMO. As expected, the vertical accelerations were much larger than the longitudinal accelerations and are the most significant for structural design. The largest of the average of the one-tenth highest vertical accelerations approached 1.0 g (9.8 m/s^2), occurring in sea-state 6 at 20 knots and sea-state 7 at 15 knots (the highest speed analyzed for sea-state 7).

Figure 5 shows the effects of speed on the average of the one-tenth highest vertical accelerations for sea-states 5, 6 and 7. As expected, accelerations increase with both ship speed and sea-state.

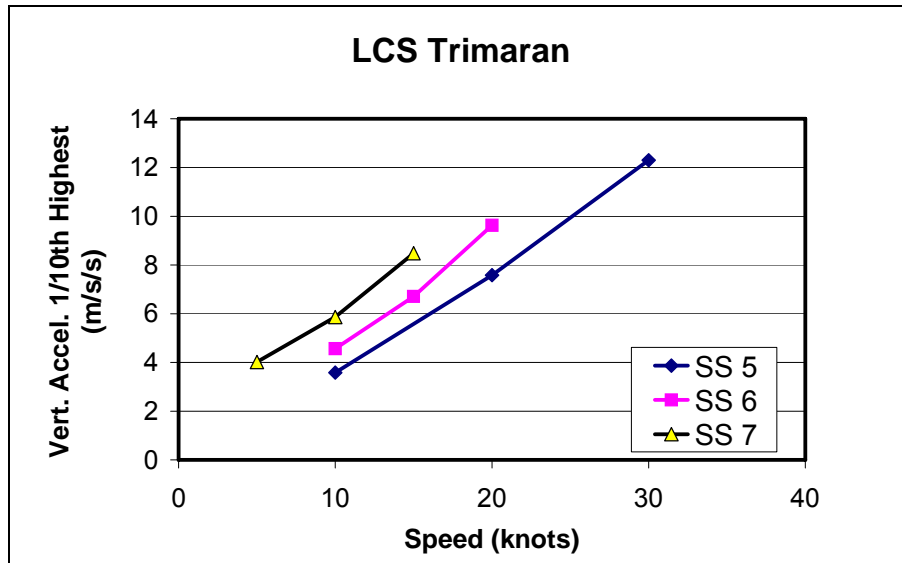


Figure 5. Vertical Acceleration Trends for Trimaran

An algorithm has been developed to predict the average of the one-tenth highest vertical accelerations at the forward perpendicular of the LCS Trimaran in sea-states 6 and 7.

$$\text{Vert Acl (1/10)} = 4.665 - 0.146 \cdot \text{WH} + (-0.478 + 0.1188 \cdot \text{WH}) \cdot V$$

Where: Vert Acl (1/10) is in units of m/s^2

WH is the significant wave height in units of meters (sea-states 6 and 7)

And: V is the ship speed in units of knots

The algorithm matches the SHIPMO predictions to $\pm 0.14 \text{ m/s}^2$.

The speed effects were less significant for the average of the one-tenth highest vertical accelerations in sea-states 4 and 5. The following algorithm was developed as a function of wave height for sea-states 4 and 5.

$$\text{Vert Acl (1/10)} = -3.38 + 1.946 \cdot \text{WH}$$

Where accelerations are in units of m/s^2 and the significant wave height is in meters.

The algorithm matches the SHIPMO predictions to $\pm 0.1 \text{ m/s}^2$ in sea-state 4 and $\pm 0.9 \text{ m/s}^2$ in sea-state 5.

Slam Initiation

Algorithms for predicting slam rates as functions of encounter frequency (f_e) and wave height were initially presented for fine bow monohull ships in Ref. 4. The slam rate for the trimaran (slams/hour) can be approximated by using the center hull length:

$$\text{Slam Rate (slam/hour)} = 30 f_e / L_{bp}$$

Where f_e is in units of wave encounters per hour and the ship length is in units of feet.

The following is an approximation for the wave encounter frequency:

$$f_e = 720/\sqrt{H} + 46.8 (V/H) \cos \Theta$$

Where H is the significant wave height in meters, V is the ship speed in knots, and Θ is the heading off the bow.

Thus, one would expect a slam rate of 31 slams per hour (115 seconds between slams) at the onset of slamming at 10 knots in 5.0 meter seas in head seas and a slam rate of 23 slams per hour (156 seconds between slams) at 5 knots in 7.0 meter seas. The slam rate will increase with higher ship speeds.

The size and relative location of the outriggers on a trimaran would slow the relative bow motion and decrease the rate of bow slamming. The LCS Trimaran has relatively long outriggers located to the aft. The net effect is likely to reduce the slam rate, but, lacking model test or sea trial data, by an unknown amount. The above figures would be upper limits.

Vertical Bending Moments

The vertical bending moment (causing hogging and sagging of the center hull of the Trimaran) is a key loading condition. Response amplitude operators were Froude scaled to the LCS Trimaran from sea trial data of the RV TRITON by the ratio of $L^2 B$. (Where L and B are the length between perpendiculars and the beam at the waterline of the center hull.) Figure 6 shows the square root of the vertical bending moment RAO's for head and beam seas at 10 knots. The units of the root RAO's are in foot-ltons/foot of wave height, which is virtually the same as meter-mtons/meter of wave height.

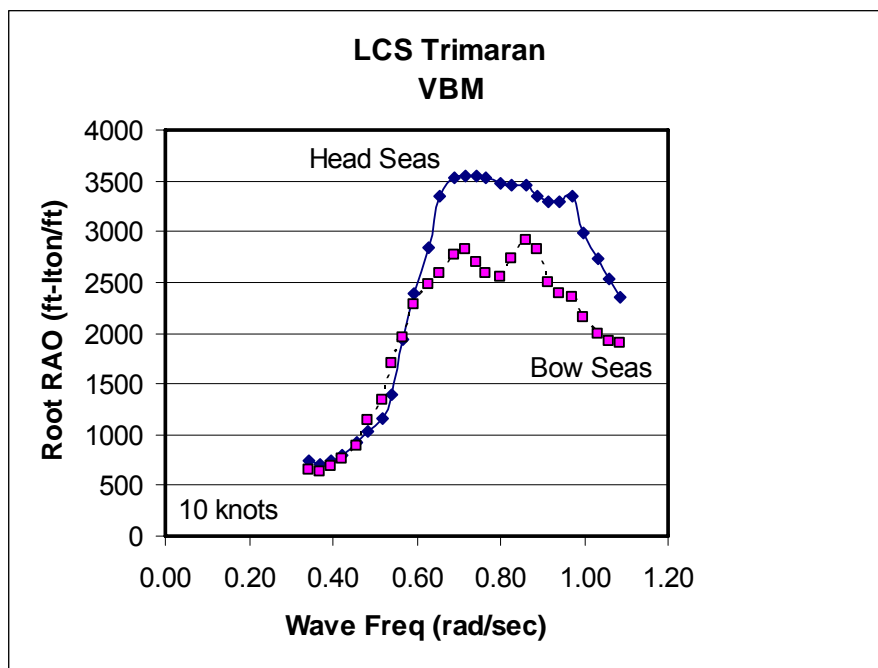


Figure 6. Vertical Bending Moment RAO's for Trimaran

Algorithms for predicting the maximum lifetime vertical bending moments for the center hull of a trimaran with a wave-piercing bow were developed in Ref. 5. The algorithm is a function of the length and beam of the center hull in units of feet.

$$\begin{aligned}
 \text{VBM} &= 0.0000356 L^3 B \\
 &= 80,800 \text{ ft-lton} \\
 &= 25,000 \text{ m-mton}
 \end{aligned}$$

The stillwater bending moment must be included to determine the total hog and sag moments.

Transverse Force on Side Hulls

The roll connection moment, or the prying and spreading of the two side hulls relative to the center hull, can be one of the most significant primary loadings on a Trimaran. These moments result from transverse forces acting on the mid-draft of the side hulls and are most severe in beam seas. Ref. 5 provided initial algorithms for predicting the maximum lifetime transverse side forces acting on the side hulls as functions of side hull length (L), side hull draft (T), and total displacement of the two side hulls (Δ). (The length and draft are in units of feet, displacement is in long tons which is virtually equal to metric tons.)

$$\begin{aligned} \text{TSF} &= 0.0187 L * T^2 / \Delta^{0.156} \\ &= 100 \text{ ltons or metric tons} \\ &= 1 \text{ MN} \end{aligned}$$

As part of the follow-on effort in the next phase, NSWC-CD will be collaborating in verifying and validating the algorithms developed through limited use of model test and/or sea trial data of the LCS Trimaran. NSWC-CD is bound by Non-Disclosure Agreements (NDA) with both the LCS acquisition programs. In the interest of maintaining their NDA's and other proprietary agreements, they are currently discussing with the appropriate program representatives possible ways of supporting this effort during the next phase.

5.0 ABS COMMENTS

As one of the leading classification societies, ABS is continuously faced with evaluating structural design adequacy and classing novel hullforms and high-performance vessels, which utilizes and capitalizes on unique and innovative structural designs. They face these challenges not only in support of their commercial client-base, but also in support of U.S. Navy and U.S. Marine Corps programs. Therefore, any research and technology development to support advancement in the prediction of rational structural dynamic loads for high-performance vessels is of value to them, which they can incorporate into their rule-making process.

ABS's initial comment about the current approach was that it is very much in-line with their own approach which they recommend and apply on the hullforms that do not have adequate performance history. Their recommended approach is called the Direct Analysis Method. One of the specific methods that ABS proposes under the Direct Analysis Method is the Dynamic Load Approach (DLA), which, to a large extent, emulates the current methodology as developed under this project. DLA is not a typical rule-based empirical method, but a combination of a probabilistic and physics-based approach based on direct analysis and first-principles calculations. In that respect, the DLA is very similar to the route/mission dependent method of estimating dynamic structural loads from first principles, unlike the rule-based approach or extrapolation from experimental and/or full-scale data of similar hullforms.

As part of the DLA approach, first a hydrodynamic analysis is performed to estimate the motions and global loads on the vessels. Then those loads are applied to evaluate the structural design in terms of structural response and structural safety. However, DLA is not an all encompassing method of estimating dynamic structural loads, especially for high-performance and high-speed vessels where long-term periodic global loads are not the only major drivers; the aperiodic local slam and impact loads are also important. Therefore, in the absence of conducting experimental assessment of motions and loads, the only other recourse for the DLA method is to perform time-domain analysis using either potential-flow or computational fluid dynamics (CFD) codes. Since both potential-flow and CFD codes are time and resource intensive, even the DLA method can also benefit from the route/mission dependent prediction of dynamic structural loads, especially in the early design stages.

Over the years, ABS has sponsored and invested in a variety of research and development programs pertaining to high-speed and high-performance vessels, particularly in the structural design area. In order to make the most of their R&D dollars, they actively seek to partner and support other initiatives that help advance their objectives. Even in their current thrust areas of High-Speed Craft Guides and Naval Vessel

Rules, they have addressed the Direct Analysis Method as one of the acceptable methods of designing and classing vessels. The route/mission dependent prediction of structural dynamic loads can be easily incorporated into a Direct Analysis Method. Figures 7 and 8 provide the schematic representations of the Direct Analysis Method and the DLA procedure, as provided in Ref. 9.

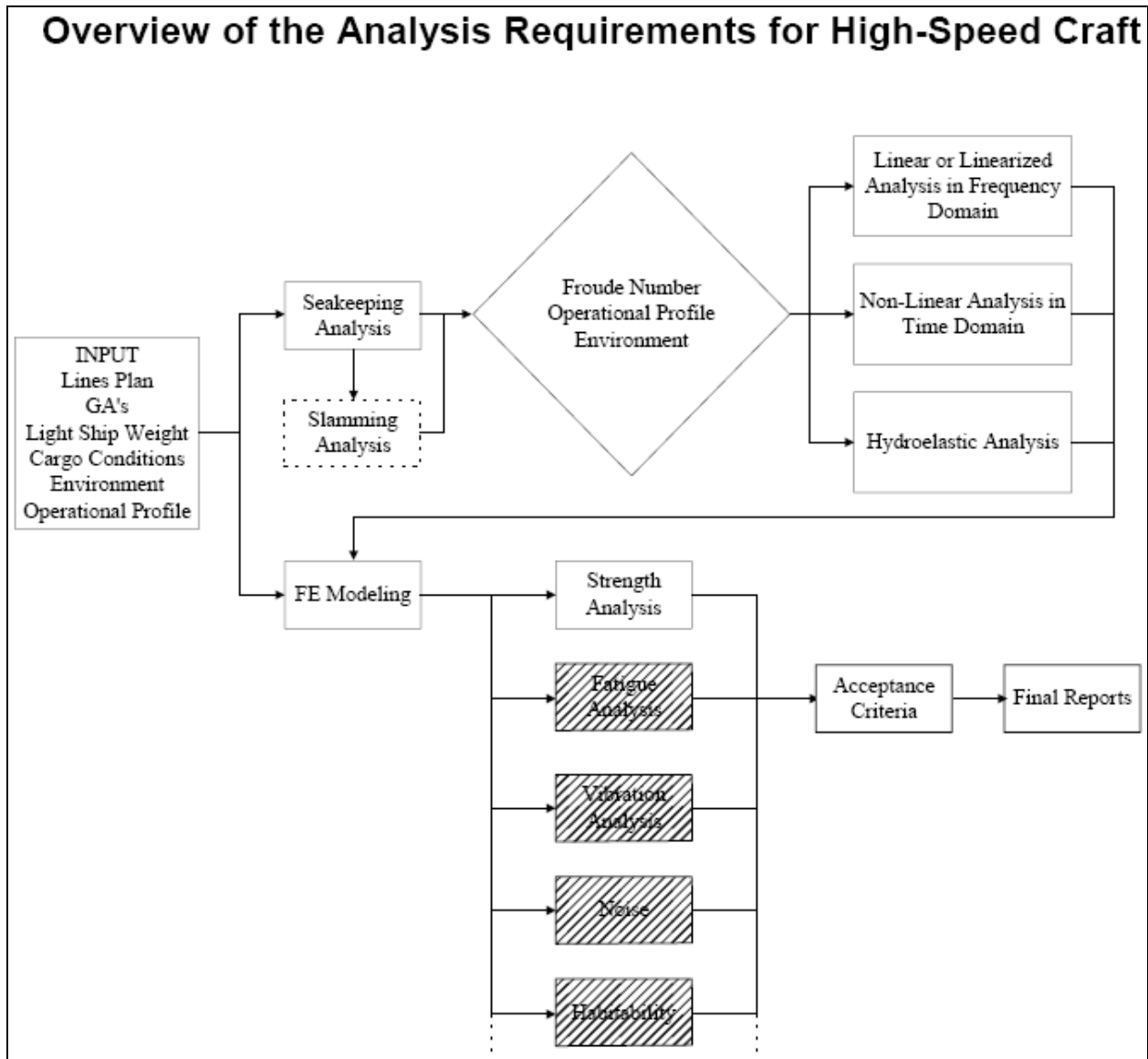


Figure 7. ABS Proposed Direct Analysis Method

Schematic of the DLA Procedure of Alternative Direct Analysis

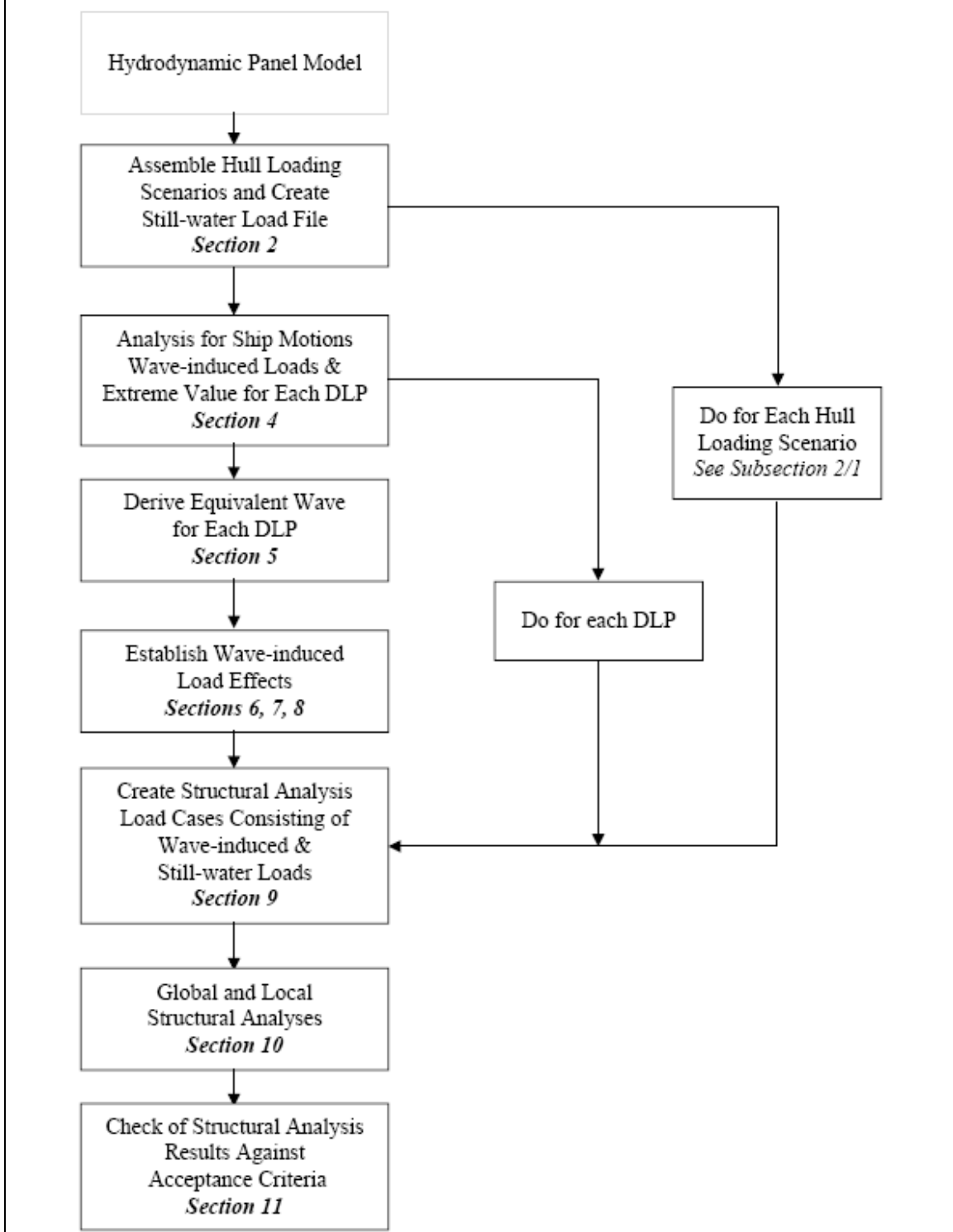


Figure 8. ABS Proposed DLA Procedure

ABS's comments were based on preliminary assessment of the approach, as discussed during the project. ABS will provide further comments and feedback upon review of the final report of the current phase. More importantly, ABS can provide better assessment of the methodology and the associated tools in terms of incorporating it into their rule-making process during the follow-on Phase II-B effort.

6.0 SUMMARY

This report provides a summary of the comparison and verification efforts undertaken in collaboration with NSWC-CD to verify the validity of the seakeeping data generated for the selected hullforms. In addition, it provides the various algorithms developed both for the local seakeeping responses and global loads for all three hullforms. It also provides some initial comments from ABS with respect to the rational dynamic load prediction process and their future involvement as the project progresses to the follow-on phase.

7.0 REFERENCES

1. Allen, R. and R. Jones, "A Simplified Method for Determining Structural Design-Limit Pressures on High Performance Marine Vehicles", AIAA/SNAME paper 78-754, Apr. 1978.
2. Birmingham, J., et al, "Development of a Fatigue Lifetime-Load Spectrum for Large-Scale Aluminum Model", ASTM, ST671, 1979.
3. Sikora, J., with A. Dinsenbacher and J. Beach, "A Method for Estimating Lifetime Loads and Fatigue Lives for SWATH and Conventional Monohull Ships", Naval Eng. Journal, May 1983.
4. Sikora, J., "Cumulative Lifetime Loadings for Naval Ships", 1998 International Mech. Eng. Congress & Exhibition, Anaheim CA, Nov. 1998.
5. Sikora, J. and N. Klontz, "Seaway Load Prediction Algorithms for High-speed Hull Forms", presented at the 2005 Annual Meeting of SNAME, Houston, TX.
6. Det Norske Veritas, "Rules for High Speed, Light Craft and Naval Surface Craft", Part 3, Ch. 1, Sec. 3, July 2003.
7. American Bureau of Shipping, "Guide for High Speed Naval Craft", Part 3, Ch. 1, Sec. 3, 2003.
8. American Bureau of Shipping, "Guide for Naval Vessels", Part 1, Ch. 3, 2004.
9. American Bureau of Shipping, "Guidance Notes on Dynamic Load Approach and Direct Analysis for High Speed Craft", Feb. 2003.