VI International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2015
B. Schrefler, E. Oñate and M. Papadrakakis (Eds)

VALIDATION OF HIGH FIDELITY CFD/FE FSI FOR FULL-SCALE HIGH-SPEED PLANING HULL WITH COMPOSITE BOTTOM PANELS SLAMMING

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Key words: slamming, fluid structure interaction, computational fluid dynamics, finite elements

Abstract. High fidelity CFD/FE FSI (Computational Fluid Dynamics/Finite Element Fluid-Structure Interaction) code development and validation by full-scale experiments is presented, for the analysis of hydrodynamic and structural slamming responses. A fully instrumented 9 meter high speed-planing hull with sterndrive is used. Starboard and port bottom panels are constructed with different composite materials and fiber orientations, allowing for study of the relation between structural properties and slamming. The code CFDShip-Iowa is employed for CFD simulations and the commercial FE code ANSYS is used as structural solver. The hydrodynamic simulations include captive (2DOF without sterndrive) and 6DOF free running conditions for various Froude numbers in calm water and regular waves. Calm water simulations compares well with the experimental data and 1D empirical data provided by the sterndrive manufacturer for resistance, heave, pitch and roll motions. Numerical one-way coupling FSI is performed in head and following regular waves representative of sea-trial conditions, using FE models for two bottom panels. The resulting strains are compared with experimental data showing a good qualitative and quantitative agreement.

1 INTRODUCTION

Slamming impact loads are a critical factor in the structural design, performance and safety of ships, especially for high speed planing hulls. The complex physics of the fluid-structure interactions are not well understood. Experimental studies have primarily involved wedge drop tests, while model or full-scale ship test data is limited. USNA model planing hull slamming pressures and accelerations are reported in [1]. Current prediction methods are largely empirical or use analytical [2] or potential flow-FE methods, often for 2D sections or idealized geometries. Studies have demonstrated the effectiveness of CFD in slamming analysis, including uncertainty quantification for regular/irregular waves using the Delft catamaran [3] and validation for regular/irregular waves for Fridsma model [4] and USNA model including slamming pressures [5]. Most slams show both primary re-entering (the bow enters the wave face) and secondary emerging (the bow impacts the wave crest) pressure peaks, whereas some show only re-entering pressure peaks, which is more typical of wedge drop and full-scale displacement ship test data. Extreme event slams (about twice standard deviation) correlate with three consecutive incoming wave lengths close to ship length with large steepness. Accelerations and pressure display Froude scaling.

The present collaborative research utilizes an instrumented slamming load test facility (high-speed planing hull - Numerette) for full-scale experimental validation of high-fidelity CFD/FE fluid-structure interaction.

The simulation environmental conditions model the experiments for head and following waves. Hydrodynamic calm water and seakeeping validation uses limited Numerette data along with 1D Mecury Marine system based predictions and other planing hull data, respectively. Initial one-way coupling fluid-structure interaction validation uses Numerette strain data from strain gages embedded in bottom composite sandwich panels, collected by an onboard data acquisition system.

Figure 1: Slamming load test facility

2 COMPUTATIONAL METHODS

The FSI study is performed by means of CFD/FE coupling routines. One-way coupling is realized by application of the hydrodynamic loads on the structure. CFDShip-Iowa V4.5 [6] is used as high-fidelity solver for the flow field, whereas ANSYS Mechanical APDL V14.5 is used to solve the structural displacements and strains.

The CFDShip-Iowa is an overset, block structured CFD solver designed for ship applications. Absolute inertial earth-fixed coordinates are employed with turbulence model k-ε/k-ω based isotropic and anisotropic RANS. A single-phase level-set method is used for free-surface capturing. Dynamic overset grids use SUGGAR to compute the domain connectivity.

ANSYS Mechanical is a comprehensive commercial code for structural FE analysis. A fully transient dynamic analysis is used to determine the dynamic response of the structure under the action of time-dependent loads. It includes structural nonlinearities and utilizes the Newmark time integration method to solve the FE equations.

The one-way coupling method consists of computing the forces acting on the structure using CFD, assuming rigid-body motion of the entire ship, and then applying the forces on the elastic model of the panels. The response is determined in one way, since the deformed geometry is not fed back into the CFD solver. In a two-way coupling approach, the flow field and the elastic deformations are computed by feeding back the elastic motions of the structure into the CFD solver. A tradeoff between one- and two-way coupling methods consists in extending the former, using the wet elastic modes of the structure. This requires the modeling of added mass and damping due to the elastic deformation of the body in water. The acceleration of the water due to the body deformation is not taken into account in the CFD solver. In general, the use of a feedback (two-way coupling) is required when large deformation significantly affects the flow field. In this work, the one-way coupling method is used for preliminary qualitative/quantitative analysis and comparison with experimental data.

Specifically, CFDShip-Iowa provides the hydrodynamic loads in terms of distribution of force per unit area over the ship hull surface. The force distribution is given for the CFD grid points and in the CFD coordinate system. A coordinate transformation is applied in order to provide the force distribution on the FE model, which has its own coordinate system. The interpolation of the loads on the FE grid points is carried out using Gaussian quadrature. The structural problem is solved by ANSYS for displacements, strains and stresses. CFD/FE numerical results are validated by comparison with experimental strain data.

3 EXPERIMENTAL SETUP

The slamming load test facility is a 9 meter long 1.9 meter wide steel/composite boat designed and manufactured by Grenestedt [7]. The boat structure consists of a welded AL-6XN stainless steel frame and composite sandwich panels. The boat has a top speed of approximately 27 m/s and a full load displacement of 2450kg.

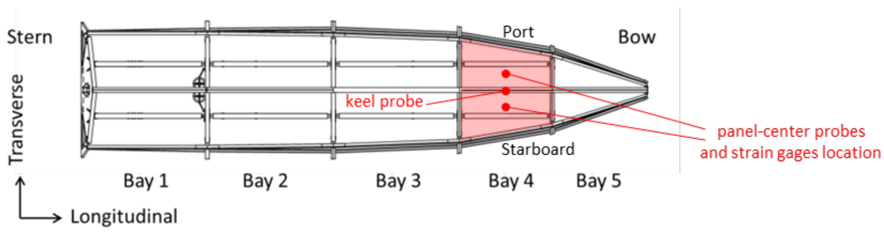

Figure 2: Slamming load test facility layup

To facilitate comparison of different panel constructions, the 10 bottom panels have varied composite layups. All bottom panels are vacuum infused with vinyl ester resin and use a Divinycell H250 foam core but vary in both reinforcement types and fiber direction. The results presented will focus on the behavior of panels in bay 4. The layup of these panels is given in Table 1.

Table 1: Slamming load test facility bay 4 bottom panel layup

	Bay 4 Port Panel	**Bay 4 Starboard Panel**
Top	2 layers DBL700 (0°, ±45°)*	2 layers DBL700 (0°, ±45°)**
↓	Divinycell H250 Foam core	Divinycell H250 Foam core
	3 layers DBL700 (0°, ±45°)*	3 layers DBL700 (0°, ±45°)**
Bottom	1 layer L(X) 440-C10 (0°)*	1 layer L(X) 440-C10 (0°)*

* 0° parallel to keel
** 0° perpendicular to keel

Devold AMT DBL700 triaxial carbon and L(X) 440-C10 unidirectional carbon reinforcements are used in both port and starboard bay 4 panels, but the orientation of the DBL700 differs resulting in a large difference in stiffness.

The slamming load test facility is instrumented with strain gages on both inner and outer skins of the bay 4 bottom panels. Vishay CEA-06-250UN-350/P2 and CEA-06-250UT-

350/P2 gages were used in quarter bridge configuration to measure strain parallel and perpendicular to the keel in the center of each panel. National Instruments NI-9237 signal conditioning and ADC modules were used to acquire 24 bit strain data at 50 kHz per channel. This data was filtered to 5 kHz in post processing.

Modal tests of the dry structure were conducted by exciting the panels at a number of grid points using an instrumented impact hammer and measuring the response with an accelerometer. The least squares complex exponential method was used to extract modal parameters. A National Instruments NI-9234 signal conditioner was used with the PCB Piezotronics 086c03 modal analysis impact hammer and 352c04 accelerometer.

Sea trials were conducted in the Atlantic Ocean near the Barnegat Inlet in Barnegat Light, NJ. Multiple tests, each with duration of 5-10 minutes, were performed. The strain gages were zeroed when the craft was at rest before each test sequence. The vessel was then accelerated to the maximum speed allowable in the conditions. Steering input was used to achieve as close to neutral roll angle as possible. The vessel has since been outfitted with a trim tab to control roll angle. Test segments consisted of a single loop. Data acquisition was stopped when the vessel returned to the approximate starting position.

4 COMPUTATIONAL SETUP

The total number of grid points for CFD simulations with sterndrive is 18.2 M (Figure 3). For bare hull simulations, symmetry with respect to the longitudinal plane is imposed; accordingly, the grid includes only the starboard side of bare hull and half-domain background with 6.94 M grid points.

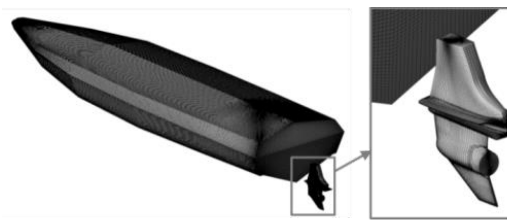

Figure 3: CFD model of Numerette with detailed view of the sterndrive

During the experimental tests, the ship experiences irregular wave, variable heading, and variable speed. A CFD captive regular-wave simulation is used to model the irregular wave pertaining to real-sea conditions [3]. Available information about test conditions includes: sea state 3 conditions; nearly head waves in the first segment of the trial; ship trajectory and speed.

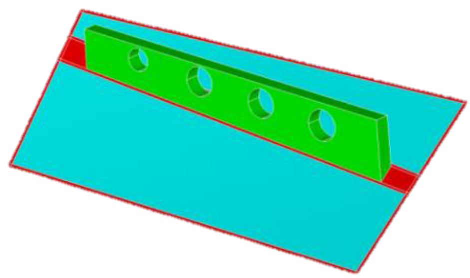

Figure 4: FE model of a Bay 4 panel showing cored sandwich areas (blue), single skin areas (red) and hollow steel longeron (green)

Since the sea trial consists of a single loop, two segments are selected that present alignment between the ship trajectory and the wave direction. The segments are used to model a regular head wave (S1) and following wave (S2) simulations and they are taken as a benchmark for validation. The speed used in S1 and S2 is the average speed $\bar{V}$ of the trial within the selected segments. The wave height is defined as the most probable condition associated to the Bretschneider spectrum, representing a fully-formed sea state 3 (see, e.g., [3]). The wave angular frequency ω is derived by $\omega_e = \omega - (\omega^2 \bar{V}/g) cos\bar{\theta}$, where ω_e is the encounter angular frequency determined as the frequency associated with the FFT-peak of the experimental strain, g is the gravity acceleration, and $\bar{\theta}$ is the heading angle ($\bar{\theta} = 0$ for following seas), which is approximated assuming the ship longitudinal axis always aligned with the trajectory.

Finite element models were developed for the slamming load test facility port and starboard bay 4 composite sandwich bottom panels extending from the keel to the chine and from the aft vertical bulkhead in bay 4 to the fore vertical bulkhead in bay 4 (Figure 4). The panel model consists of a sandwich cored region, a perimeter with only composite skins and the stainless steel longeron. All areas were modelled with Shell99 elements in ANSYS. The model is constrained in X,Y,Z displacement at the keel and chines, Y,Z displacement at the bulkheads and Y,Z displacement at the ends of the longerons. The total number of grid points is 51,648. The model was validated by comparison with experimental modal tests and static displacement tests.

5 EXPERIMENTAL ANALYSIS

Experimental data collected from operation of the slamming load test facility during a 400 second duration test is presented here. The position track and speed over the duration of the tests are shown in Figure 5. Head (S1) and following (S2) wave segments are also identified.

The transverse and longitudinal strains measured at the center of the port panel are shown in Figure 6. The port panel strain waveforms for a typical single slamming event are shown in Figure 7. Also shown are the maximum strains for the 100 highest slamming events, used for comparison with CFD/FE results from regular wave simulations.

The highest magnitude strains are seen on the inner skins transverse to the keel. Strains on the inner skins are primarily in tension indicated by positive strain, while the outer skins are under compression indicated by negative strain. The mean value of the highest 1/3 strain peak strains identified during the S1 head wave segment, S2 following wave segment and full test duration are indicated in Table 2.

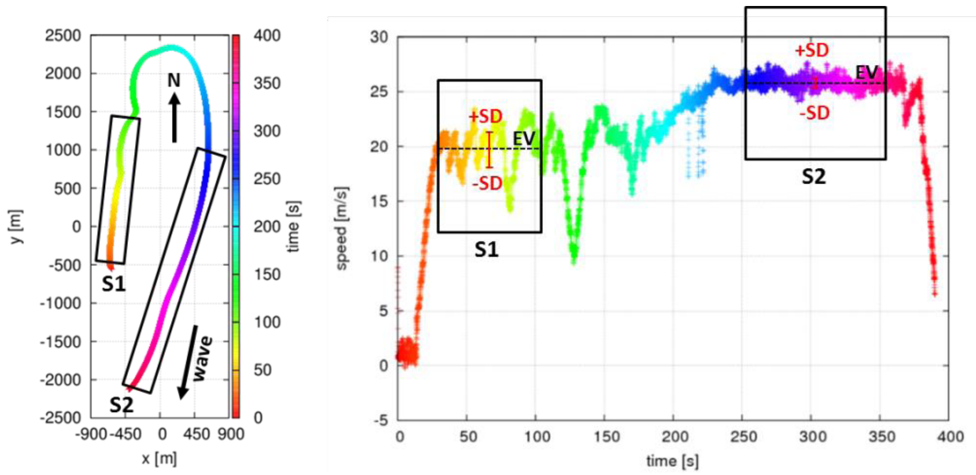

Figure 5: Sea trial trajectory and speed with color mapping for time

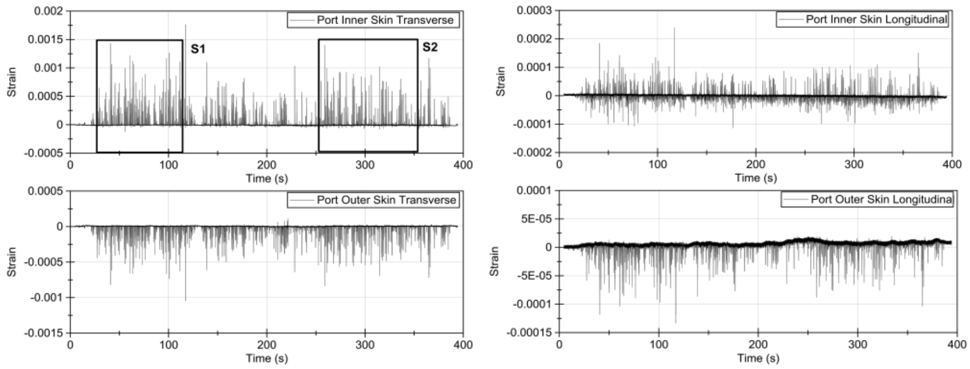

Figure 6: Port bay 4 panel transverse (left) and longitudinal (right) strains

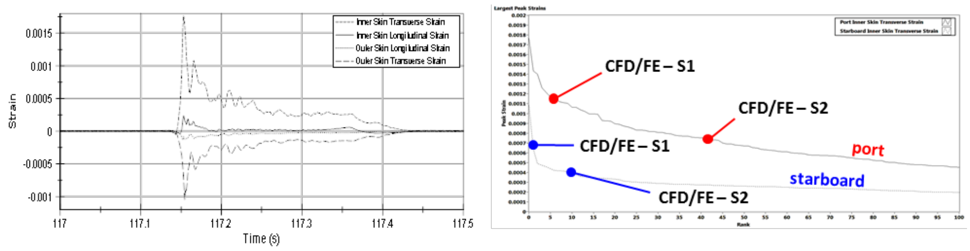

Figure 7: Typical slamming event strain waveforms and maximum strains for the 100 most severe slamming events (note that regular wave CFD/FE gives one value per simulation).

Table 2: Average of highest 1/3 peak strains in port and starboard bay 4 panels for full test duration and S1, S2 wave segments

	Port Transverse Strain	**Starboard Transverse Strain**
Full Test Duration	8.04×10^{-4}	3.11×10^{-4}
Head Wave Segment S1	8.89×10^{-4}	2.70×10^{-4}
Following Wave Segment S2	8.40×10^{-4}	3.83×10^{-4}

6 HYDRODYNAMIC ANALYSIS

The calm water simulations are conducted for both a captive and a free running model. The captive simulations are conducted for a wide range of Fr for the bare hull model free to heave and pitch. The free running simulations are conducted at Fr=1.1, 1.9 and 2.7 for the model appended with sterndrive and body force propeller. The free running model has 6DOF.

Figure 8 shows the comparison of steady state values for both captive and free running simulations, compared with the experimental data. Heave and pitch motions are slightly larger for free running simulation, but the trends versus Fr are similar for both captive and free running simulations. The maximum pitch is for Fr=1.1 (3.6 and 4.2 deg for captive and free running simulations, respectively). Compared to the available experimental pitch data, the comparison errors E=(D-S)%D (D and S are the experimental and simulation values, respectively) for captive and free running simulations are E=6.4 and -8.9%D, respectively. Roll motion is only predicted for the free running model. The roll angle increases by Fr and it is about 2.5 deg for the highest speed, very close to the available experimental value at Fr=2.7 (E=0.8%D). The propeller RPS shows the same trend as EFD, however, it is over predicted for high Fr (E=-12%D). Since the experimental resistance could not be measured for the full scale Numerette, it is estimated from the propeller input power computed using both the engine curve and propeller open water torque curve. The estimated experimental resistance based on engine curve shows similar resistance for low and high Fr, while open water curve estimates very small resistance at high speeds. The captive CFD simulations show E=58%, 49%, and 13% for Fr=1.1, 1.9, and 2.7, respectively. Corresponding errors for free running simulation are 49%, 36%, and -9%. The study of the free running results show that the pressure resistance of the sterndrive is comparable with the resistance of the bare hull. Therefore, captive simulations for the bare hull geometry with no sterndrive under predicted the resistance significantly. Figure 8 also shows the comparison of CFD results with 1D simulation results, provided by Mercury Marine. The propeller RPS, sterndrive resistance and total resistance show fairly good agreement with CFD free running simulations. However, the 1D simulation predicts larger trim angle as no model was used for the stepped bottom of the boat. CFD free surface and pressure distribution on the hull are shown in Figure 9 for Fr = 2.1 and 2.7, i.e. same as used later for regular wave simulations (S1 and S2, respectively).

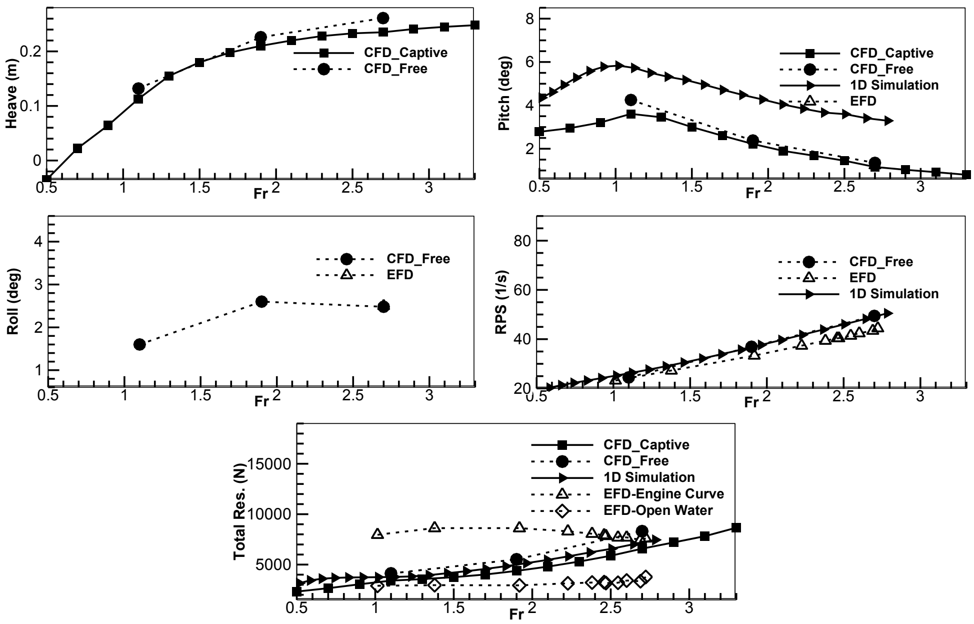

Figure 8: Comparison of CFD and EFD results in calm water

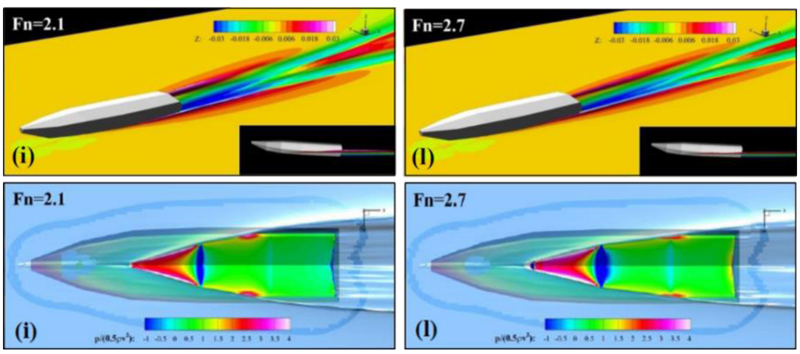

Figure 9: Free surface and pressure distribution for calm water simulation at Fr = 2.1 and 2.7

Figure 10 shows comparison of the captive simulations with the results for other ship hulls including USNA, USCG and Fridsma model. All geometries show similar non-dimensional resistance at high speed. The non-dimensional heave motion is smaller for Numerette, but it follows the same trend as for other geometries. The largest heave motion is for Fridsma, which has the shortest length among all geometries (L=4.5 ft). For pitch motion, Numerette and USNA show similar values for high speed and both show smaller values compared to those for USCG and Fridsma. The trends for pitch motion are the same for all geometries, i.e. there is a peak for pitch motion around Fv=$V/\sqrt{\Delta^{1/3}g}$=2.5-3.0.

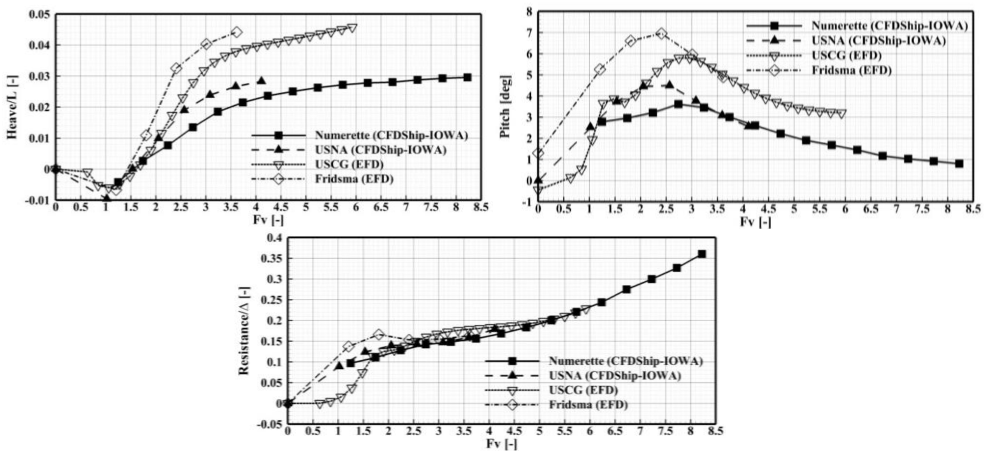

Figure 10: Comparison of motions and resistance against USNA (CFD), USCG (EFD) and Fridsma (EFD)

The speed values used for S1 and S2 are based on Figure 11, which is a close-up of Figure 5, including running mean and RMS. The corresponding inputs for S1 are: Fr equal to 2.15, wave height equal to 0.587 m, with a frequency of the encounter equal to 0.9625 Hz (corresponding to a wave frequency equal to 0.2380 Hz, λ/L equal to 3.120 and H/λ = 1/47). For S2, Fr equals 2.77, the wave height is 0.587 m, and the (negative) frequency of the encounter is 0.9331 (corresponding to a wave frequency equal to 0.2700 Hz, λ/L equal to 2.424 and H/λ = 1/37).

The resistance coefficient, heave and pitch motions indicate satisfactory convergence, as shown in Figure 12 and Figure 13, for S1 and S2 respectively. The response is highly nonlinear. Figure 14 shows the slamming pressures for the keel and panel center, as shown in Figure 2. Note that the experimental strains are measured at the panel center. The slamming pressures for S1 panel center and S2 keel are similar to those described earlier. For S1 keel, the emerging phase has two peaks, which requires more study. For S2, the panel center is not wetted. The re-entering peak is in correspondence with minimum pitch, whereas the emerging peak(s) occurs when the heave starts rising, as shown in Figure 15. The re-entering peaks on the keel for S1 and S2 are comparable in magnitude, and close to 140 kPa.

The results of current regular wave simulations are compared to other planing hulls. Specifically, the 1st harmonic amplitude of heave and pitch motions is compared to Fridsma and USNA models in Figure 16. For Fridsma, x_3/A increases gradually by decreasing the encounter frequency and reaches 1 for long waves. The peak is found near a wavelength corresponding to its resonance condition. Fridsma results also show that x_5/Ak increases with decreasing encounter frequency and reaches nearly 1 for long waves, presenting a small peak. The non-dimensional heave and pitch resonance frequencies are nearly 0.6 for Fridsma. Both

USNA and Numerette geometries have data for limited encounter frequencies and thus the peaks of x_3/A and x_5/Ak are not identified. USNA show similar trend i.e. small motions at short wavelength, increasing to $x_3/A=1$ and $x_5/Ak=1$ at long wavelength. However, Numerette data shows small values at long wavelength, which requires more study.

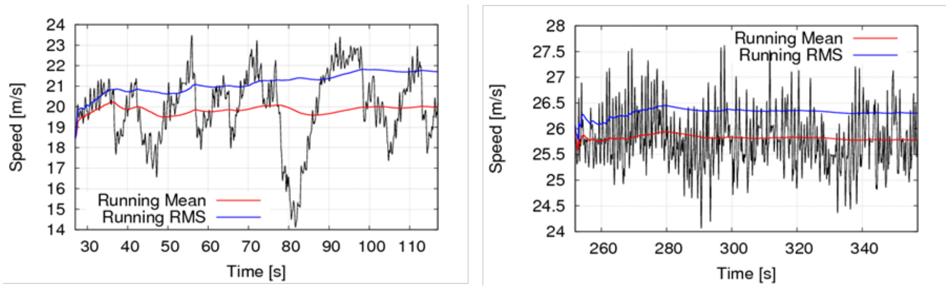

Figure 11: S1 (left) and S2 (right) speed from experiments including running mean and RMS

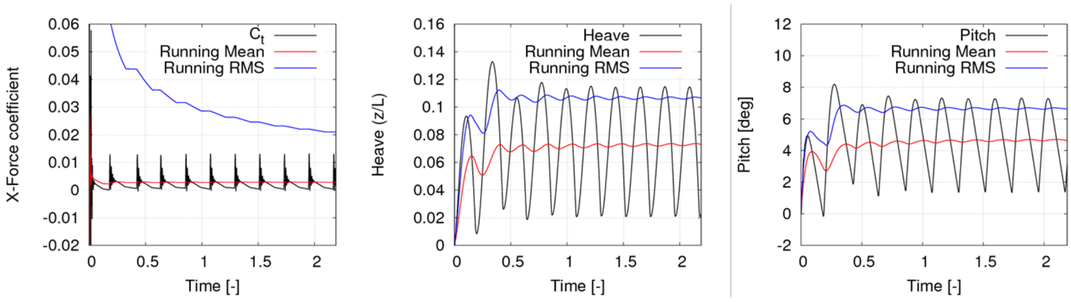

Figure 12: CFD-predicted forces and motions for S1 (time scale=tU/L)

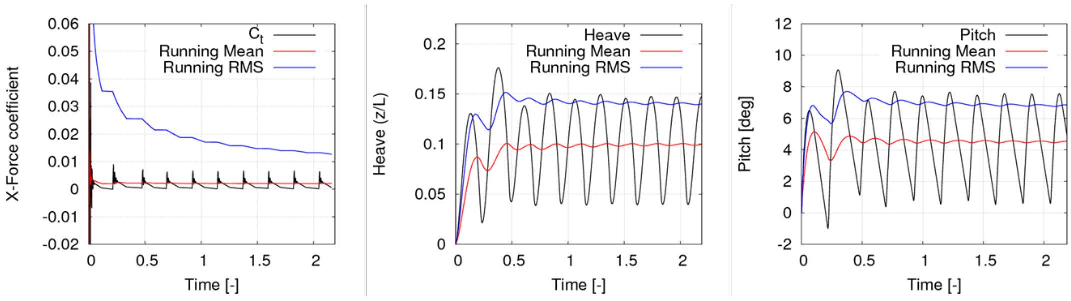

Figure 13: CFD-predicted forces and motions for S2 (time scale=tU/L)

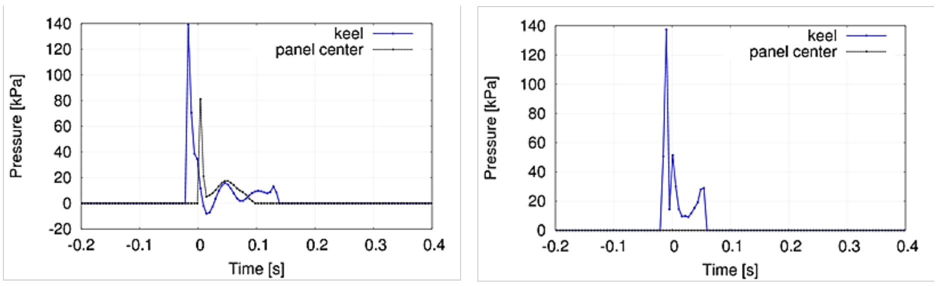

Figure 14: CFD pressure probes location and pressure history for S1 (left) and S2 (right) (time scale=tU/L)

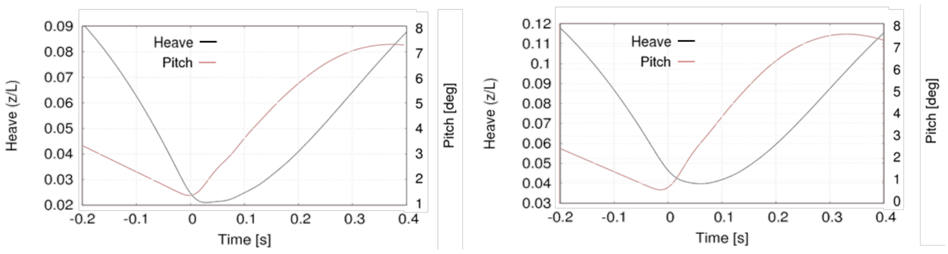

Figure 15: Heave and pitch associated with S1 (left) and S2 (right) simulations

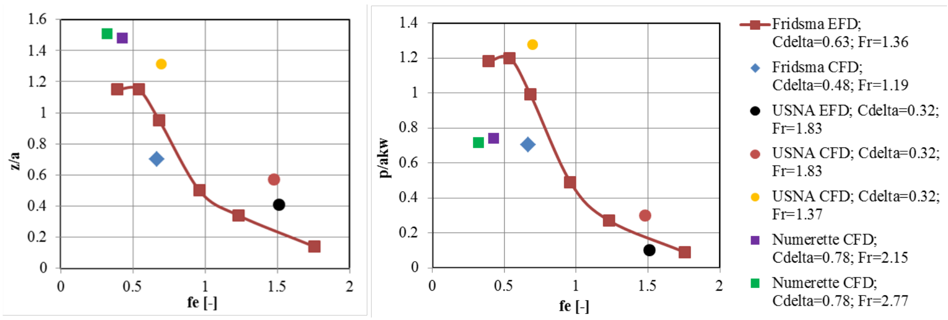

Figure 16: Heave and pitch motions for different geometries

7. FSI ANALYSIS

The CFD/FE slamming strains are validated for S1 and S2, following the approach used for validation of slamming pressures in [5]. Slamming strain events are aligned in time by their re-entering peaks, which provide the expected value EV and standard deviation SD for the peak value and duration, and mean slamming strain. The event duration is defined by the re-entering peak and the signal drop below a given threshold (5% of the peak value). Only strains exceeding the 30% of the highest peak are considered, which is reasonable to detect actual slams from the strain signal. The inner skin transverse strains at the panel center are used for validation, since more severe. The strains are very irregular, however the mean strain is smooth and has a trend similar to typical slamming pressures, as shown in Figure 17.

The CFD/FE slamming strains are also shown in Figure 17, which shows a reasonable agreement with the experiments, especially in consideration of the simulation input approximation to the experimental conditions. The trend of port versus starboard panel strains is well captured by CFD/FE. For S2, peak value and duration are validated since the comparison error E%D is less than the SD%D, as shown in Table 3. The duration is found 0.14 times the encounter period. For S1, the CFD/FE shape is similar to the keel slamming pressure in showing a large re-entering peak and two emerging peaks. The peak E%D is about 3 times larger than SD%D, whereas the duration E%D is less than the SD%D, as shown in Table 3. The duration is found 0.08 times the encounter period.

The comparison of CFD/FE peaks to 1/3 highest experimental peaks average is also provided in Table 3. The average error for the 1/3 highest peaks average is larger for S1 than S2. Overall, the average error is slightly smaller for the 1/3 highest peaks average than that for EV using 30% maximum peak threshold, nevertheless the trend is similar. The identification of the best statistical approach for validation requires irregular wave free-running CFD/FE simulations consistent with the actual experimental conditions. Moreover, the trend of S1 versus S2 depends on head versus following waves, which may be affected by surge and propeller controller, not considered herein (the CFD/FE model is towed at constant speed). S1 and S2 CFD/FE simulation peaks are included in Figure 7, for comparison with the 100 most severe slams from experiments.

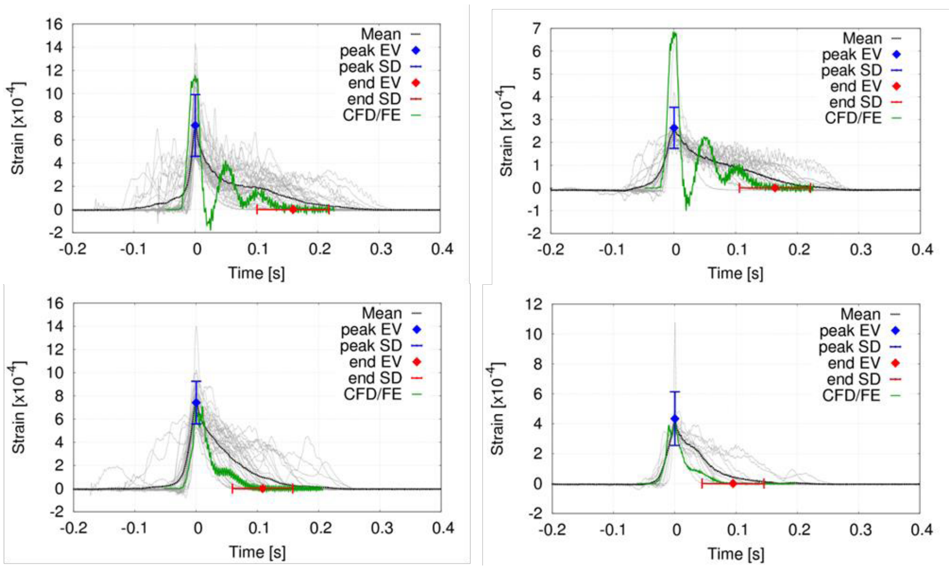

Figure 17: Inner skin transverse strains for port (left) and starboard (right), and S1 (top) and S2 (bottom)

Table 3: Comparison of CFD/FE and EFD results for inner skin transverse strains at panel center

		S1					S2				
		S	EV (D)	E%D		SD%EV (D)	S	EV (D)	E%D		SD%EV (D)
				EV	Ave. 1/3 hst				EV	Ave. 1/3 hst	
Port	Peak	1.19E-03	7.25E-04	-64.3	-34.0	38.0	7.46E-04	7.36E-04	-1.39	11.2	25.5
	Duration	0.15	0.16	6.25		36.8	0.09	0.11	18.2		44.7
Starboard	Peak	6.96E-04	2.56E-04	-172.	-157.	36.0	4.44E-04	4.34E-04	-2.38	-16.0	42.7
	Duration	0.14	0.16	12.5		36.1	0.09	0.10	5.26		52.9
Average absolute	Peak	9.44E-04	4.91E-04	118.	95.9	37.03	5.95E-04	5.85E-04	1.89	13.6	34.15
	Duration	0.15	0.16	9.38		36.48	0.09	0.11	11.72		48.80

7 CONCLUSIONS AND FUTURE RESEARCH

Hydrodynamic slamming on the bottom of a high-speed planing hull was studied experimentally and numerically (CFD). A highly instrumented 9 meter long hull developed for slamming research was used. The bottom of this craft consists of ten separate carbon and glass fiber skin / foam core sandwich panels, each with its unique set of material combinations and fiber layup angles. This allows for study of the influence of bottom stiffness on slamming pressures and deformations. The code CFDShip-Iowa was employed for CFD simulations and the commercial FE code ANSYS was used as structural solver. The hydrodynamic simulations included captive (2DOF without sterndrive) and 6DOF free running conditions for various Froude numbers in calm water and regular waves. Resistance, heave, pitch and roll motions correlated well between experimental operation and numerical simulations for calm water. In offshore sea trials operating in head (S1) and following (S2) waves, strains in two different bottom panels were measured experimentally as well as calculated numerically using one-way coupling (pressures from CFD of rigid hull, applied on dynamic FE model). A few simple parameters such as average peak strains in starboard and port panels were compared; initial indications are that the numerical procedure correctly predicts which panel is straining more, although the error may be on the order of 30-50%.

Future research will focus on: grid and time-step verification for slamming pressure and strains; semi-coupled two-phase free running irregular wave hydrodynamics simulations including sterndrive/propeller/controller and superstructure; and trim tab and asymmetric pressure distribution effect on the slamming strains. Experimentally, bottom pressures will be measured with piezoresistive thick film high-speed sensors at over 100 locations and correlated with numerical analyses. The influence of bottom stiffness on slamming pressures will be studied experimentally and numerically; in particular, an attempt will be made to answer questions such as whether a more compliant bottom leads to lower slamming pressures. Two-way fluid-structure interaction analyses are required for studying such effects, which is of top priority.

ACKNOWLEDGEMENTS

Research was sponsored by the Office of Naval Research (ONR) grants No. N00014-13-1-0616 and N00014-13-1-0617 administered by Dr. Roshdy Barsoum. The authors thank Dr. Maysam Mousaviraad for assisting the comparison with other geometries and John Scherer, technical advisor at Mercury Marine, for providing the required information for CFD simulations and conducting 1D simulation.

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