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Composite bottom panel slamming of a fast planing hull via tightly coupled fluid-structure interaction simulations and sea trials

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ABSTRACT

The paper presents partitioned tightly coupled fluid-structure interaction (FSI) simulations for composite panel slamming of a high-speed planing hull, including comparison with full-scale experiments. Panels with different layout/stiffness are investigated. Computational fluid dynamics (CFD) is performed using the URANS code CFDShip-Iowa. Computational structural dynamics (CSD) uses modal expansion by ANSYS finite elements. One- and two-way tightly coupled FSI is performed. The complexity of sea-trial conditions is reduced by statistical/frequency analysis, allowing for a simplified representation by one regular wave. Simulations provide details of slamming, including correlation of re-entering pressure peaks with motions and strain peaks. Numerical/modeling issues are discussed. Expected value and associated uncertainty of experimental pressure/strain peak and duration are used for validation. The difference of panels' dynamics is well predicted. Validation errors and uncertainties (average 25% and 14%) are quite large. Nevertheless, errors always fall within one standard deviation of experimental-data individual readings. Results are promising especially if compared to earlier slamming studies for regular/irregular waves in controlled towing tank tests, which show average error and validation uncertainty of 25% and 10%. The current study lays the groundwork for research on high-fidelity CFD/CSD FSI of real-world geometry slamming and ultimately multidisciplinary design optimization of structural and hull-form parameters.

1. Introduction

Bottom panels of planing hulls may experience severe slams, especially when operating in rough sea at high speed. The effects of slamming loads include local deformation and vibration of bottom panels. Slamming is regarded as the most common reason for changes in speed and heading by ship operators. Extreme events may lead to damage and structural failure of hull, equipment, and payload, as well as personnel injuries and exhaustion. Slamming force peaks have a super-quadratic probability distribution of exceedance, making extreme events highly severe and difficult to predict (Kapsenberg, 2011). Slamming phenomena involve hydrodynamics and structural dynamics and show a complex physics, which is still not well understood. The complexity of experiments and numerical simulations of fluid-structure interaction (FSI) for ships currently represents a critical issue for the investigation of full-scale slamming in real sea conditions.

The increasing availability of computational resources made numerical methods practicable and attractive for simulating slamming, allowing for the study of complex geometries and conditions. Computational fluid dynamics (CFD) is applied to evaluate hydrodynamic slamming loads, whereas computational structural dynamics (CSD) evaluates the structure response to slamming. Coupling methods of CFD and CSD are core elements of high-fidelity numerical FSI. Monolithic methods regard fluid and structure as a single system of equations and employ a unique solution strategy. For complex problems (with free surface, high Reynolds number and complex geometries), the accuracy of CFD is limited by the use of a unique numerical method for both fluid and solid, often implemented by finite elements (FE). Partitioned methods use separate solvers for fluid and structure, which may be coupled using a one- or two-way approach. A one-way type of coupling is realized by applying the hydrodynamic load, determined for rigid body, on the flexible structure. In the two-way coupling, the structural deformation is fed back into the fluid solver. Hydro-elastic effects due to the coupling of fluid and structural dynamics during slamming are significant, especially for small impact angles, motivating the development and use of two-way coupling techniques.

High-fidelity CFD studies of ship slamming were presented by He et al. (2013) for a high-speed catamaran, Mousaviraad et al. (2015) for

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the Fridsma planing hull, and Fu et al. (2014) for the USNA planing hull, including irregular and regular wave conditions in head sea. CFD/CSD FSI studies for slamming traditionally address simplified problems and geometries, typically wedge drop tests. Piro and Maki (2013) study a water-entry unit problem using OpenFOAM for the fluid, a modal expansion for the solid, and implementing one- and two-way coupling approaches. Stenius et al. (2011) use FE for both fluid and structure achieving a full coupling. Liao et al. (2013) solve the Navier-Stokes equations with a finite difference approach, the structural dynamics of a plate using FE, and realize the coupling using a volume-weighted method based on immersed boundary. De Rosis et al. (2014) couple the lattice Boltzmann method and the Euler-Bernoulli beam theory using a staggered-explicit coupling. CFD/CSD FSI for ship slamming was presented by Paik et al. (2009) using one- and two-way coupling approaches to couple the Reynolds averaged Navier-Stokes equations (RANS) with a modal expansion for the structure. Oberhagemann et al. (2009) study the slamming of a liquefied natural gas carrier, using a one-way coupling method of RANS and FE.

Experimental data for slamming pressure and deformation/strain is essential to the validation of numerical simulations. Most of controlled experiments are conducted in model-scale including idealized (pyramid water entry, Alaoui et al., 2015, wedge, Tveitnes et al., 2008, and Fu et al., 2014, and asymmetric wedge, Shams et al., 2015, water entry), and complex (Fu et al., 2014) geometries. Dessi and Mariani (2008) and Dessi and Ciappi (2013) present towing tank experiments with segmented-hull backbone models addressing slamming of fast ships in regular and irregular waves. Ikeda and Judge (2014) present measurements of slamming pressure focusing on a deterministic approach to the analysis of individual events. The extrapolation of full-scale results from model-scale data is difficult because of the complex physics of the water impact and still represents a critical issue. Furthermore, full-scale experimental data is very limited and often pertains to non-controlled environments with large associated uncertainties.

Volpi et al. (2015) present a preliminary one-way CFD/CSD FSI for full-scale validation of slamming responses during sea trials of the high-speed planing hull “Numerette,” the slamming load test facility (SLTF) designed, built, and operated by Lehigh University and shown in Fig. 1. The study uses experimental data from Thodal (2016) collected in the Atlantic Ocean near the Barnegat Inlet in Barnegat Light (NJ) for the validation of numerical FSI. Results focus on port and starboard bottom panels of bay 4, which are composite sandwich structures stiffened by a steel longeron. The different fiber orientation in the panels allows for assessing the effect of material properties on slamming loads and deformations. The numerical FSI couples CFD (URANS) and CSD (FE) in a one-way fashion without modeling the added mass. The validation included slamming strains. Experimental data for slamming pressure was not included.

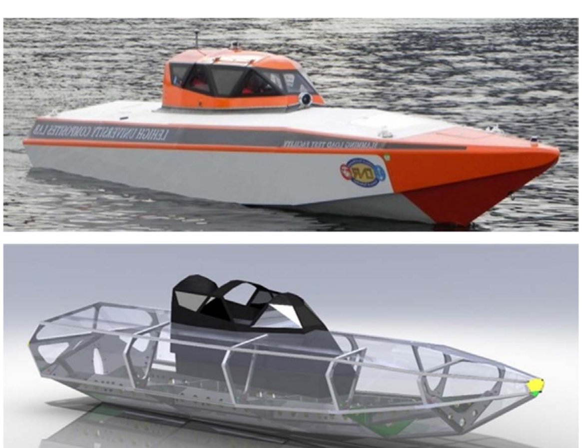

Fig. 1. Slamming load test facility “Numerette”.

The objective of the present work is the extension of the numerical FSI to a high-fidelity tightly coupled two-way approach using URANS and modal expansion based on FE. The solution is based on a partitioned procedure and includes both one- and two-way coupling. The study aims at: (a) providing a better insight on the physics of planing hull slamming, (b) evaluating the effects of structural properties by comparing the behavior of different composite panels, (c) discussing the effects of two-way versus one-way coupling approaches, and (d) assessing the numerical FSI prediction capabilities by comparison to data from sea trials. The latter are replicable only in a statistical sense, provided that detailed information is available. Here, only limited information is known and sea trials are represented using integral statistical estimators associated to average and/or most probable conditions. Nevertheless, these provide a rigorous framework for performing a valuable validation exercise and assess numerical FSI prediction capabilities.

In order to ensure the accuracy of the numerical simulation tools, the full-scale hydrodynamics is firstly validated using captive and free running simulations in calm water. Results and validation can be found in Volpi et al. (2016). Full-scale FSI analysis is performed using captive regular wave simulations, representing significant conditions associated to the sea trials (Thodal, 2016). Simulation conditions include speed, heading, wave height, and wave period. Since the uncertainty for the wave height is large, two wave heights are used and compared, namely average and most probable from the sea state experienced during the experiments. Validation variables include pressure and strain of port and starboard panels of bay 4. The different fiber orientation of the panels provides a larger stiffness for the starboard side. Finally, comparing one- and two-way FSI results addresses the effects of the numerical approach on the prediction of both ship global motions and local loads and deformations. The research was conducted in close collaboration between the University of Iowa and Lehigh University. A preliminary version of this work was presented in Volpi et al. (2016).

2. Computational methods

Monolithic methods potentially achieve full fluid-structure coupling, since this occurs at the governing equations level; for this reason, they are often referred to as full coupling methods. However, the accuracy of the single discipline analysis is limited by using a unique numerical method for both fluid and solid, often implemented by FE. Moreover, ill-conditioning of the system of equations and difficulty in integrating state-of-the-art fluid/structure solvers in a single framework remain open issues. In ship hydrodynamics, Reynolds number and free-surface effects limit significantly the use of monolithic FSI.

In partitioned methods, the solution of the coupled problem is advanced over the separate fluid, structure, and dynamic mesh partitions, in a sequential or parallel fashion. Although generally this approach conserves momentum and energy only in an asymptotic sense (as grid element and time step tend to zero), it offers several appealing features, including the ability to use available high-fidelity tools specifically designed for complex industrial problems, with well-established discretization and solution methods within each discipline, and preservation of software modularity (Farhat et al., 1998). Accuracy and robustness of partitioned methods depends on both the conservation properties at the interface and the convergence properties of the non-linear iterations. It may be noted that ship hydrodynamics convergence of inner iterations is a critical issue also for rigid structures, as CFD is usually coupled with the ship rigid body equation of motion.

The two-way coupling of partitioned solvers can be loose or tight. In a loose coupling (also referred to as weak, staggered, or explicit) the structural deformation is fed back into the CFD only at the beginning of the time step. In a tight coupling, also referred to as strong or implicit, fluid and structure solvers exchange load and deformation in an iterative manner using non-linear inner iterations (such as predictor/