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Prediction of wave-induced loads on ships: Progress and challenges

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ABSTRACT

The aim of this paper is to critically assess the methods used for the evaluation of wave-induced loads on ships examining analytical, numerical and experimental approaches. The paper focuses on conventional ocean going vessels and loads originating from steady state and transient excitations, namely slamming, sloshing and green water, for the latter, and including extreme or rogue waves, as well as the more occasional loads following damage. The advantages and disadvantages of the relatively simpler potential flow approaches against the more time consuming CFD methods are discussed with reference to accuracy, modeling nonlinear effects, ease of modeling and of coupling with structural assessment procedures, suitability for long term response prediction and suitability for integration within design and operational decision making. The paper also assesses the uncertainties involved in predicting wave-induced loads and the probabilistic approaches used for the evaluation of long term response and fatigue analysis. The current design practice is reviewed and the role of numerical prediction methods within the classification framework and goal based design approach discussed. Finally the suitability of current developments in prediction methods to meet the needs of the industry and future challenges is assessed.

1. Introduction

The structural integrity of vessels operating at sea, more often than not in extreme weather, is of paramount importance in order to ensure the safety of passengers and crew, the timely and safe delivery of cargo and avoid adverse environmental consequences due to catastrophic or nearly catastrophic failures. The designer has to ensure that global structural strength, as well as local structural details, are capable of withstanding operational and environmental loads over the life time of the ship, whilst balancing these requirements against economic and environmental emission driven pressures calling for lighter and more efficient ship structures and structural arrangements. The largely deterministic approach to global structural strength, involving static equilibrium of the ship on a trochoidal wave crest and trough, is no longer fit for purpose. The structural design of ships to detailed classification requirements is gradually displaced by risk or goal based approaches, leading to designs of quantifiable safety level verified by validated numerical methods. The drivers for such change include drastic changes in ship type, size and complexity, increased knowledge and more data on the environment, more data on model and real ship behavior in waves, a wide range of numerical models capable of simulating the physics of ship behavior, even under extreme conditions, and ever increasing computational power enhancing the suitability of these methods in design applications. The fundamental factor fueling these developments is the ability to acquire and generate more data, and the trends are pointing to increasingly more data.

This state of affairs informed the discussions of the ISSC

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(International Ship and Offshore Structures Congress) Committee I.2: Loads in the past three years or so (ISSC, 2015a). The Committee comprises academics and practitioners, providing an ideal background to ponder on a range of issues. These are, for example, the accuracy of predictions from nonlinear potential flow methods compared to RANS methods and, the so called, hybrid methods driven by balancing accuracy against numerical efficiency. Other issues are, the versatility of available numerical methods to successfully, or not as the case may be, simulate the phenomena associated with seakeeping and wave loads and the relative weaknesses with reference to realistic environmental modeling (ISSC, 2015b). Furthermore, the gradual move towards simulating the *complete performance* of the vessel in waves, rather than just individual aspects such as rigid body response, slamming, sloshing, green water etc are issues of interest. In addition, the necessity of simulating loads due to extreme events, the suitability of numerical methods to provide accurate input to long term predictions and the usefulness of data acquired from measurements and numerical predictions, with its associated uncertainties, are issues that dominated the discussions of the committee. We firmly believe that these are issues of great importance to researchers and designers alike, from the viewpoint of providing guidance to the researcher on where to focus future efforts and to the designer on navigating through a plethora of methods and data.

In this paper we will endeavor to deal with these issues by reviewing progress made in the past 3 years in the subject area of wave-induced loads. The structure of this paper follows along traditional lines to direct readers to their area of interest. Nevertheless, it should be noted that (i) the versatility of numerical methods to model more than one phenomenon, e.g. sloshing and slamming, and (ii) the focus of investigations in dealing with as complete fluid–structure interaction modeling as possible, results in some overlaps between the sections of this paper. The generic computational methods are discussed in Sections 2 and 3, with the latter focusing on hydroelasticity. The transient loads relating to slamming, green water and sloshing, and, where applicable their coupling to the rigid body response, are reviewed in Sections 4–6. The loads in abnormal or freak waves are examined in Section 7. Section 8 is focused on experimental and full-scale measurements, whilst the particular loads due to damage following collision or grounding are in Section 9. The life-time related issues, namely probabilistic methods, design waves and fatigue loads are discussed in Sections 10 and 11, including weather routing. Finally Section 12 investigates uncertainties in loads and loading conditions, with conclusive remarks in Section 13.

2. Computational methods for evaluating wave-induced loads

Thanks to dramatic advances of computer science and technology during recent years, the numerical wave tank has attracted great interest from researchers. Computational Fluid Dynamics (CFD) making use of the Reynolds Averaged Navier Stokes (RANS) equations, although computationally intensive, features significantly in many investigations. Nonlinear potential flow solutions continue to be developed and used. Most of the numerical investigations deal with two-dimensional (2D) problems due to constraints from computational resources and/or CPU time consumption associated with three-dimensional (3D) modeling. This is particularly so when dealing with fully nonlinear modeling and irregular waves.

The problem of wave-induced loads on ships with forward speed is one of the most demanding in ship hydrodynamics, especially when considering the excitation by moderate or large amplitude waves. In theoretical/numerical approaches, this requires the proper consideration of the forward speed effects on ship motions and loads and of a variety of nonlinearities related to the large amplitude ship motions and to ship's actual wetted surface, as well to the change of the free surface of the incoming waves and their interaction with the moving ship. Due to the complications of the above set problem, simplifications and *engineering* solutions are often adopted. This implies that the exact nonlinear seakeeping and large amplitude wave-induced loads problem may be still considered unsolved, except for special cases. A brief review of related theoretical and numerical methods is outlined in this section.

Greco and Lugni (2012) developed a 3D seakeeping numerical solver to handle occurrence and effects of water-on-deck and bottom slamming. It couples (A) the rigid ship motions with (B) the water flowing along the deck and (C) bottom slamming events. Problem A is studied with a 3D weakly nonlinear potential flow solver based on the weak-scatterer hypothesis. Problem B, and so local and global induced green water loads, are investigated by assuming shallow water conditions onto the deck. Problem C is examined through a Wagner type wedge impact analysis. For coupling between A and B, the external seakeeping problem furnishes the initial and boundary conditions to the in-deck solver in terms of water level and velocity along the deck profile; in return, the shallow water problem makes available to the seakeeping solver the green water loads to be introduced as additional loads into the rigid motion equations. For the coupling between A and C, the instantaneous ship configuration and its kinematic and dynamic conditions with respect to the incident waves fix the parameters for the local impact problem; in return, the slamming and water entry pressures are integrated on the vessel region of interest and introduced as additional loads into the rigid motion equations. The developed solver has been applied to the problems of a dam breaking inside a closed tank and to the wave-ship interaction problem with/without water-on-deck occurrence for validation. Obtained results are compared with experimental data. Subsequently, Greco et al. (2012) carried out experimental and numerical investigations on a patrol boat at rest or traveling in head regular and irregular waves. In these studies motion RAOs, relative motions and occurrence, features and loads of water-on-deck, bottom slamming and flare slamming events, as well as added resistance in waves, were investigated. The analysis is systematic covering a range of Froude numbers, wave length (λ) to ship length (L_{PP}) ratios and wave steepness values. The main parameters that affect the global and local quantities are identified and possible issues in terms of, for example, water-on-deck severity and structural consequences are determined. Different slamming behaviors were identified, depending on the spatial location of the impact on the vessel, namely single-peak, church-roof and double-peak behaviors. A bottom slamming criterion is assessed. Predicted and measured bottom pressures at Section 18 (Section 20 corresponding to FP) of the boat are shown in Fig. 1 when the vessel is traveling at Froude number 0.189, for three different wave lengths and wave steepness 0.15. The major discrepancies with the experiments are discussed, and the importance of viscous hull damping and flare impact for the most violent conditions is emphasized. Inclusion of these effects has improved the numerical solution.

Hanninen et al. (2012) studied an interface capturing VOF (Volume of Fluid) solution for a passenger ship advancing in steep ($kA=0.24$, k: wave number, A: wave amplitude) and short waves ($\lambda/L_{PP}=0.16$), with the focus on estimating quantitative uncertainties for the longitudinal distributions of the first-third harmonic wave loads in the bow region. The computations were performed with the commercial flow solver ISIS-CFD. The uncertainty distributions obtained reveal that even the uncertainty of the first harmonic wave load varies significantly along the bow region. It is shown that the largest local uncertainties of the first

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