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Nonlinear computational methods for hydroelastic effects of ships in extreme seas

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ABSTRACT

We present computational methods to assess slamming-induced hull whipping on sectional loads of ships in regular and irregular waves. The numerical methods solved the Reynolds-averaged Navier-Stokes (RANS) equations coupled with the nonlinear rigid body motion equations of the elastic ship hull. We numerically investigated three containerships in regular waves, in random irregular long crested waves, and in deterministic wave sequences. Comparisons to experimental measurements agreed favorably. We relied on different wave models, including second order Stokes waves and nonlinear wave fields obtained from the solution of nonlinear Schrodinger equations (NLS). Simulations in random irregular waves provided short-term ship response probability distributions under sea state conditions relevant for design loads.

1. Introduction

Assessing the structural integrity of ship hull structures requires a reliable prediction of loads in extreme seas. In this regard, hydroelastic effects on wave-induced loads and structural responses have grown in importance over the last years because they contribute to the life cycle load spectra of wave-induced hull girder stresses. Long-term full-scale measurement campaigns of, e.g., Kahl and Menzel (2008), Storhaug et al. (2003), Storhaug (2007), and Vidic-Perunovic and Jensen (2005) support this point of view, also shown by the comparative total (unfiltered) and wave encounter frequency (low-pass filtered) stress spectra in Fig. 1, measured on board a Panamax containership. The risk associated with ships encountering extreme waves is not negligible as shown by the frequency distribution of ship losses presented in Fig. 2, i.e., a ship's structural integrity and stability may be endangered when the master cannot avoid these extreme seas. Ship accident statistics and related risk analysis may be found in Kelangath et al. (2012). Generally, design guidelines and Classification Society rules specify safety factors to account for dynamic load effects on the elastic ship hull. However, improved and validated numerical tools which consider nonlinear hydrodynamics could help quantify dynamic loads directly, thereby not only providing an improved technique to evaluate unconventional ship designs, but also serving as a guide to adjust safety factors in regulations.

The influence of hydroelastic effects on maritime structures was already investigated in the 1970s. Among others, Bishop and Price (1979) developed an hydroelastic theory based on linear fluid structure interaction. They employed a beam model to idealize the ship's structure. Bishop et al. (1986) extended their model, using dry eigenmodes to represent the ship's structure. Aksu et al. (1991) compared two- and three-dimensional hydroelasticity theories. Hirdaris and Temarel (2009) documented the progress achieved to evaluate hydroelastic effects of ships.

Numerous numerical approaches exist to assess wave-ship interaction, ranging from advanced strip theory methods (e.g., Newman, 1978; Salvesen et al., 1970; Faltinsen, 1990; Söding, 1987; Jensen, 2001; Fonseca and Guedes Soares, 1998; and Vidic-Perunovic and Jensen, 2005) to boundary element methods (e.g., Söding et al., 2014; Kim et al., 2009; Sclavounos, 2012; Shao and Faltinsen, 2011; Papanikolaou and Schellin, 1991) and field methods based the solution the Navier-Stokes equations (e.g., el Moctar et al., 2004, 2006a, 2006b, 2011; Oberhagemann and el Moctar, 2007; Oberhagemann et al., 2012a, 2012b, 2012c; Oberhagemann, 2016; Ley et al., 2011, 2013, 2014; Ley and el Moctar, 2014; Paik et al., 2009; Seng and Jensen, 2012; Stern et al., 2015; Craig et al., 2015; and Robert et al., 2015). Hirdaris et al. (2014) presented a current and extensive overview of methods for wave-induced global and impact loads on ships and offshore structures. Most recently, Hirdaris et al. (2016) investigated the influence of hydrodynamic nonlinearities on wave-induced motions and loads which act, as usual, not only amidships, but also at the ship ends. They validated their results against experimental measurements obtained from model tests of a 10,000 TEU containership investigated

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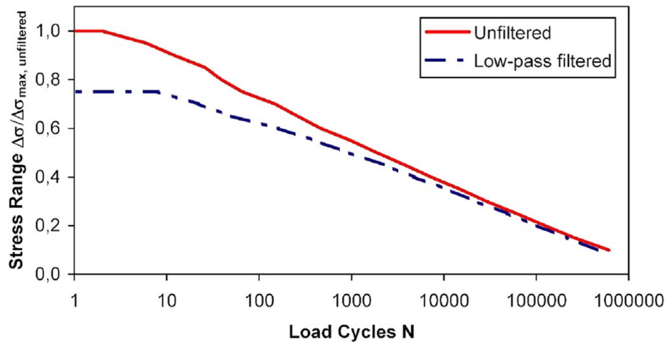

Fig. 1. Comparison of total (unfiltered) and wave encounter frequency (low-pass filtered) stress spectra, measured on board a Panamax containership, Kahl and Menzel (2008).

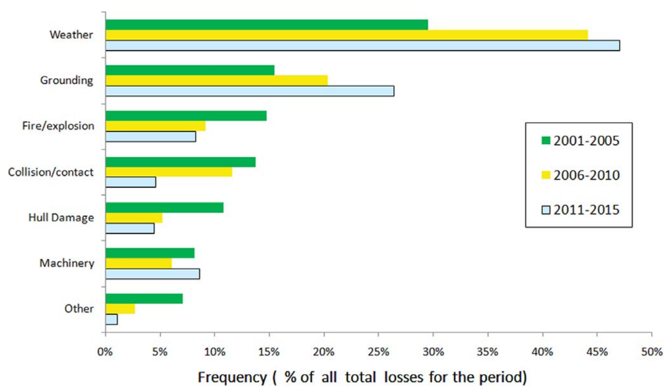

Fig. 2. Frequency distribution of ship losses (2001–2015, ships larger than 500GT), International Union of Marine Insurance (2016).

within the scope of a joint industry project WILS (Hong, 2009, 2010, 2013) conducted between shipyards and classification societies, Lee et al., 2012. The authors demonstrated that weakly nonlinear fluid structure interaction methods may be useful to compute wave-induced motions and vertical loads. However, they emphasized the importance of validating the radiation and diffraction forces when dealing with a strongly time varying wetted surface.

The flow around a ship in extreme seas is characterized by high nonlinearities, wave breaking, air trapping, slamming, etc. Navier-Stokes-Equations are better suited to describe these physical phenomena. Furthermore, they are becoming more accessible to the engineering community to assess wave-structure interaction. However, direct long-term simulations covering the entire ship's life are unrealistic within the foreseeable future, because available resources only allow for simulations of selected seaways.

We present approaches that couple Navier-Stokes equations with nonlinear ship motion equations and linear elastic structural deformation equations to simulate ship responses in nonlinear seaways and to predict corresponding nonlinear wave-induced motions and loads. We identified ship dependent relevant scenarios and analyzed different wave models, e.g., second order Stokes waves and nonlinear wave fields obtained from the solution of the nonlinear Schrödinger equation (NLS). We also examined the associated wave propagation in these wave fields (Ley et al., 2013). The nonlinear Schrödinger equation has a number of exact analytical solutions, known as breathers, which are prototypes of rogue waves (Osborne et al., 2000). Such waves are relevant because they may emerge spontaneously from a random seaway, provided the spectrum is sufficiently narrow and waves, on average, are sufficiently steep (Onorato et al., 2001, 2006).

Physical model tests of a containership were performed within an international benchmark study, Kim and Kim (2016). Its aim was to assess the accuracy/reliability of current numerical methods and to evaluate the international state-of-the-art in the study field. This benchmark study, jointly organized by the International Towing Tank Conference (ITTC) and the International Ship and Offshore Structures Congress (ISSC), provided valuable comparative experimental data, Kim and Kim (2016).

We also used model test results of two additional containerships. Comparisons between model test measurements and numerical simulations validated the numerical methods. Not only regular waves, but also irregular long-crested seaways and deterministic wave trains which incorporated rogue waves were numerically investigated and compared with experimental data. One of the objectives was to obtain statistical information on the probability of occurrence of extreme waves and the corresponding ship responses.

Finally, we determined conditioned wave sequences based on the so-called Most Likely Response Wave (MLRW) concept of Dietz (2004). These wave sequences induced a linear vertical bending moment response, corresponding to the long-term expected maximum according to spectral moment statistics. Subsequent CFD simulations in these wave sequences provided nonlinear corrections of linear responses.

2. Numerical methods

We relied on a straight forward and intuitive approach to solve the fluid-structure interaction problems, namely, by separating the solution domain into a fluid domain and a structural domain and then solving both problems alternatingly. To achieve a consistent naming convention, we based our CFD (Computational Fluid Dynamics) computations on solving the Reynolds-averaged Navier-Stokes (RANS) equations and our CSD (Computational Structure Dynamics) computations on solving the motion equations of an elastic body. Our fluid dynamic method implemented a finite volume approach (finite volume method, FVM); our structure dynamic method, the finite element method (FEM).

2.1. Fluid dynamics

We restrict the description of our numerical fluid dynamics methods to major features; details may be found in Ferziger and Peric (2008), el Moctar (2001), el Moctar et al. (2004, 2011). The conservation equations for mass and momentum in their integral form serve as the starting point. The fluid is assumed to be viscous. The solution domain is subdivided into a finite number of control volumes which may be of arbitrary shape. The integrals are numerically approximated using the midpoint rule. The mass flux through a cell face is taken from the previous iteration, following a simple Picard iteration approach (Ferziger and Peric, 2008). To obtain a dedicated equation for pressure, the mass conservation equation is combined with the momentum equation, resulting in a pressure correction equation. Solver COMET (Muzaferija and Peric, 1997) achieves an implicit coupling between pressure and velocity using the Semi-Implicit Pressure Linked Equations (SIMPLE) algorithm, while code interDyMFoam (OpenFOAM, 2014) implements a hybrid PIMPLE approach that combines the SIMPLE with the PISO (Pressure Implicit with Splitting of Operators) algorithms. The remaining unknown variables at the center of a cell face are determined by combining a central differencing scheme (CDS) with an upwind differencing scheme (UDS). A second-order central difference scheme (CDS) can lead to unrealistic oscillations if the Peclet number exceeds two and large gradients are involved. On the other hand, an upstream difference scheme (UDS) is unconditionally stable, but leads to higher numerical diffusion. To reach a compromise between accuracy and stability, the schemes are blended. Near the ship hull, the blending factor is chosen between 0.9 and 0.95. The two equation turbulence model SST with wall functions accounts for turbulence (Menter, 1993).

To simulate free-surface flows around a floating ship hull, both RANS methods implement an Eulerian multiphase formulation. An