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A numerical investigation of the flexible vertical response of an ultra large containership in high seas compared with experiments

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ABSTRACT

The vertical response of an Ultra Large Containership in high seas is analysed by means of numerical methods, which are compared with experiments. The experiment was conducted in a wave tank on a free running model with aluminium back bone and the flexible response of the ship is measured. The ship was tested in regular waves of moderate amplitude to analyse springing, and in severe irregular seas for whipping response. It was found that the flexibility of the model increases the largest sagging peak by up to 32%. The hydroelastic response of the ship is numerically calculated using a body nonlinear time domain method based on strip theory. A practical engineering method is followed for calculating the dependency of the hydrodynamic forces on the geometrical nonlinearity of the wetted hull. The time domain code is coupled with a Finite Element Model and the ship hull is modelled as a non-uniform Timoshenko beam. The ship responses in moderate seas are very well calculated by the numerical method. Even though vertical motions in very high seas are slightly overestimated by the numerical results, the numerical vertical bending moments are reasonably in good agreement with the experimental results.

1. Introduction

Unlike the rigid hull concept where the hydrodynamic analysis and the structural elastic responses are decoupled and analysed separately, the term hydroelasticity of ships implies that the structural deformation changes the radiation field and thus the structural and the hydrodynamic forces are fully coupled. This generally occurs when the hull girder natural frequency lies in the vicinity of the harmonics of the wave loads. The dynamic response of large great lakes bulk carrier has been a great concern to naval architecture community since 1970s (Stiansen and Chen, 1978). Recent huge increase in the demand for longer and larger containerships with capacities varying between 8000 and 14000 TEU and length up to 400 m has reemphasized the importance of hydroelasticity in ship design. Due to their open hull structure and the long hulls, the natural frequency (Eigen frequencies) of the hull girder falls within the vicinity of the wave induced loads. Therefore, the containerships are highly susceptible to springing and whipping, among which the former leads to fatigue failure, and the latter is important for the structural design as it imparts huge impact load on the structure and can also be a cause of fatigue failure. Springing is a phenomenon in which the wave induced loads are able to resonate at the structural natural frequency and the whipping loads results from the slamming of the ship which causes the transient dynamic loading on the ship.

Traditionally, the seakeeping problem, which considers ship as a rigid body, and the transient response of the structure (whipping) due to slamming loads are treated in two stages and solved separately, for e.g., Meyerhoff and Schadachter (1980), Belik et al. (1983) and Guedes Soares (1989). This generally yields good results for small and medium sized vessels as shown by Ramos et al. (2000). Guedes Soares (1989) calculated the transient loading due to slamming based on a linear strip theory method. Time history of the relative motion was used to identify the slamming event and the slamming load was calculated from the rate of change of fluid momentum. The hull was represented using a Timoshenko finite element beam model and the vibratory response was calculated based on modal superposition. Based on Guedes Soares (1989), Ramos and Guedes Soares (1998) used several empirical methods to calculate the slamming loads and compared the slam induced vertical bending moment acting on a containership. The findings were found to be consistent with the experimental results conducted by Ramos et al. (2000). Fonseca et al. (2006) presented a decoupled analysis using 2D nonlinear theory where the rigid body motions were calculated first using a partially nonlinear time domain method (Fonseca and Guedes Soares, 1998) and the hull vibration problem was solved in the next step, which is similar to the approach proposed by Guedes Soares (1989), except that in

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that case a linear strip theory was used. The vertical bending moment (VBM) from the numerical method was compared with the experimental results for a frigate.

The main disadvantage of the aforementioned approach is that the rigid and the flexible modes are not coupled and the equations of motion are solved separately for rigid and elastic responses. Therefore, it is not possible to take into account the steady-state vibration of the hull known as springing, and the effect of slamming loads on the ship motions and the accelerations. These effects are generally considered small and hence negligible for small and medium size ships. However, they are relevant for large containerships, long bulk carriers and LNG carriers. Due to their long hull and open structures, the hull girder natural frequency lies close to the wave induced load frequencies and due to high speed of the containerships, the wave induced loads affect the elastic responses as the encountering frequency approaches the structural natural frequency. Kim et al. (2015) showed that a decoupled analysis will lead to overestimation of the whipping loads because in a fully coupled scenario, the slamming loads will mitigate the pitch motion and the mitigated pitch motion will reduce the slamming loads.

1.1. 2D linear theory

Since the pioneering work of Bishop and Price (1977, 1979), significant developments have been achieved in the methods to calculate the hydroelastic loads acting on ships. Bishop and Price (1977, 1979) proposed method to couple the structural deformation of the hull with the hydrodynamic forces calculated using linear strip theory. Bishop et al. (1978) modified the frequency domain formulation for the calculation of the response in irregular sea by introducing time series simulation.

This method had been extensively used by many researchers in order to study the symmetric and antisymmetric response and other characteristic behaviour of different types of ships. Wu et al. (1991) extended the unified theory for the calculation of hydroelastic response of the slender body. Several other forms of strip theory had been proposed driven by the need to include the hydrodynamic forces acting in the ship's longitudinal direction which facilitated improvement in the calculation of the flexible response of the hull using 3D Finite Element Methods (FEM), Wang et al. (1991) and Che et al. (1994). Hermundstad et al. (1999) extended the high speed strip theory proposed by Faltinsen and Zhao (1991) for the calculation of the hydroelastic response of the fast vessels.

1.2. 2D nonlinear theory

The linear theories provided reasonably agreeable results for engineering application in low to moderate seas. However in extreme seas, the ship response becomes highly nonlinear, and in order to deal the problem, the nonlinear hydroelastic theories were proposed. Yamamoto et al. (1980) presented a nonlinear hydroelastic method in which the hydrodynamic forces were calculated for the instantaneous draft but for a representative frequency. Jensen and Pedersen (1979) proposed nonlinear quadratic strip theory, and later on extended the theory for accurate estimation of the springing response, Jensen and Pedersen (1981). Gu et al. (1988, 1989) introduced a 2D nonlinear model based on generalised strip theory. The radiation solution was presented by a time convolution method and the nonlinear hydrostatic forces and the momentum slamming forces were included. The hydrodynamic model was coupled with a Timoshenko model. Soding (1982) proposed a method to replace the time consuming convolution integral with higher order differential relation between the relative velocity and the corresponding hydrodynamic forces.

Xia et al. (1998) proposed nonlinear hydroelastic theory based on strip theory. The memory functions due to the free surface effect were represented using higher order differential equation, and the body nonlinear hydrodynamic wave excitation forces and slamming forces were calculated. The method was used to calculate the vertical response of a S175m and the agreement with the experimental results was found to be good, particularly for low speed. Wu and Moan (1996) presented a nonlinear hydroelastic method where the linear part is evaluated using a linear strip theory and the nonlinear modification is obtained as the convolution of the linear impulse function and the nonlinear modification force. Mikami and Kashiwagi (2008) derived a nonlinear hydroelasticity method based on strip theory for the calculation of the hull vibratory response in large amplitude waves. Body nonlinear hydrostatic and Froude–Krylov forces were included and the radiation force was represented by memory function and infinite frequency added mass.

1.3. 3D linear and nonlinear theory

In order to examine the behaviour of the non-beam like structures, 3D linear, Wu (1984) and Price and Wu (1985), and nonlinear methods, Wu et al. (1997), have been proposed. Hirdaris et al. (2003) applied a 2D and 3D hydroelastic theory to predict and compare the dynamic behaviour of a bulk carrier. The 2D wet analysis for the fluid structure interaction was carried out by means of Timoshenko beam and strip theory and beam and shell finite element models were combined with a 3D potential flow method in frequency domain for the 3D wet analysis. It was found that the 2D and 3D analysis gave good results for the symmetric responses while difference observed for antisymmetric responses. Wu and Cui (2009) presented a detailed overview of the existing 3D linear and nonlinear methods for the calculation of the hydroelastic response of the ships. Santos et al. (2009a, 2009b) applied hydroelastic theory to determine the limits of applicability of a 2D and 3D linear hydroelastic method in calculating the dynamic response of a fast patrol boat. The fluid structure interaction was modelled using a 3D potential flow method with pulsating source singularity distributed on the mean wetted surface and the structure was modelled using beam and 3D finite element models. Oberhagemann et al. (2012) analysed the bending moment of the same ULCS that is used in this thesis using finite volume method, and concluded on the effect of grid sizing on hydroelastic loads.

Recently, ISSC 2012 (Drummen and Holtmann, 2014) conducted a benchmark study for slamming and whipping, the main objective was to estimate the degree of variation in the results between different numerical methods and their agreement with the experimental results. The participants were free to use any method suitable for them. Most of the participants used 3D panel methods for the calculation of the added mass and lumped it to the structural model, while a participant coupled the structural solver with a Reynolds Averaged Navier Stokes (RANS) solver. A wide range of methods were used for the structural model, which included 2D beam element with links connecting the mass segment, 2D Timoshenko beam and 3D shell elements. It was concluded that the mode shapes and the natural frequency for two, three node vibration of both dry and wet symmetric and antisymmetric distortion were well estimated by most of the participants. However, more complex methods do not necessarily give good results as the more elaborated models included additional uncertainties. Kara (2015) numerically predicted the hydroelastic response of a rectangular barge and a Wigley hull using a direct time domain approximation and the results satisfactorily agreed with the experimental results. The body was discretized using quadrilateral elements and the potential over each element was calculated by solving boundary integral equations in which transient green