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Development of vertical second harmonic wave loads of a large cruise ship in short and steep head waves

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ABSTRACT

The reliable prediction of springing excitation requires a detailed understanding of the origin of exciting wave loads. This study clarifies the origin of the second harmonic wave loads that can excite the springing of a large cruise ship (roughly 300 m long) in short and steep head waves. The findings are based on the analysis of previously validated numerical simulations (RANS-VOF) of the flow around a rigid hull. The accumulation of the loading is presented both along the length and the depth of the hull. The results show that the second harmonic vertical loading originates mainly in the foremost part of the ship, where the whole depth of the hull matters. The analysis focuses on the effect of the phase and the amplitude of second harmonic local loading. The irregular variation of the phase of the local loading with respect to that of the freely propagating wave demonstrates a serious deformation of the waves encountered in the area where the second harmonic total loading of the hull mainly originates. The analysis of the temporal behaviour of local loads indicates that the magnitude of the local second harmonic loading relates to the rise time of the respective local loads.

1. Introduction

Springing is a serious matter for ship builders and operators, because long-lasting vibration puts freighters at risk of fatigue damage and because it may affect the comfort of the passengers on a large cruise ship. The scientific community can help control the effects of springing by providing information on its origin and by providing tools that can predict springing in the design stage. A crucial question relating to the numerical prediction of springing is what the behaviour of the exciting wave loads is like from the hydrodynamic point of view. This study clarifies this matter by describing the development of the second harmonic wave loads that can cause springing (so-called second-order springing) in the case of a large cruise ship.

When searching for a numerical tool that can predict springing or another phenomenon, it is typical to conduct numerical simulations with a selected tool and to compare the numerical results against the corresponding experimental ones. Such comparisons provide information on the relevant physical phenomena, too. If the numerical and experimental results are similar, we can assume that the physics modelled by the numerical tool agree with the physics that matter for the phenomenon or vice versa. In the case of springing-type vibrations, the most authentic comparisons between the numerical and experimental results are the ones where the numerical simulations are compared against the vibratory response measured on board a full-scale ship. In such a case, the benchmark study of Storhaug et al. (2003) concluded that traditional seakeeping methods are not capable of predicting the springing response of a bulk carrier in realistic sea states. The methods that were tested in Storhaug et al. (2003) were different strip theories and one linear 3-D Rankine method. Soon afterwards, Vidic-Perunovic (2005) and Vidic-Perunovic and Jensen (2005) showed that the prediction of the springing response is improved when the effect of the bi-directional waves is included in a second-order strip theory. The capability of strip theories to predict springing is of interest from the point of view of practical design work, because strip theories require only scant computational resources in comparison to the other numerical tools: 3-D potential codes and Navier–Stokes solvers. From the point of view of physics, one challenge of strip theories is their limited capability to predict diffraction. For instance, Vidic-Perunovic (2010) pointed out the significance of the linear excitation caused by diffracted waves in the case of the springing of a container ship.

Overall, studying springing in the context of realistic sea states is a great challenge. The physics involved can be very complex for a ship advancing through irregular waves. Furthermore, the information on the prevailing sea state during the measurements may be vague, but it is needed as an input for the numerical simulations. The situation becomes more controlled and more

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simplified when regular waves are studied by means of numerical simulations and model tests. When springing in regular waves is studied, the waves encountered are typically selected in such a way that linear wave loading or a multiple of the encounter frequency (ω_e) resonates with an eigenmode of the hull (ω_{hull}). This study focuses on the second harmonic wave loads ($2\cdot\omega_e = \omega_{hull}$), which can excite the springing of a large cruise ship. Springing excited by second harmonic wave loads is often called *second-order resonant springing* in the literature.

In the previous literature, second-order springing has been studied e.g. by comparing numerical and experimental results and by varying different case parameters such as the velocity of the ship and the height of the waves that are encountered. Kim et al. (2012), Lee et al. (2012), and Oberhagemann and el Moctar (2012), for instance, presented comparisons of the numerical and experimental results for a container ship using a Rankine panel method with a Timoshenko beam, a 3-D hydroelastic code with a 2-D beam model, and a RANS solver coupled with a model decomposition approach, respectively. They all report that the numerical results agree or are comparable with the experimental ones. From a theoretical point of view on hydrodynamics, the capability of a potential code to predict wave loads depends on the non-linear terms that are included in the model, while a RANS-VOF solver does not set any theoretical limitations on the non-linearity of the wave loads that can be predicted. The case parameters can matter for the significance of predicting different non-linear terms and for the requirements concerning the resolutions in RANS simulations. For instance, both an increase in the speed of the ship and an increase in the steepness of the waves encountered are reported to increase the second-order resonant springing. The effect of the speed of the ship has been demonstrated e.g. with experimental results in Storhaug and Moan (2007) and with numerical results in Shao and Faltinsen (2012). As for the wave height, the importance of the increasing wave height was demonstrated in the experimental studies of Slocum and Troesch (1983) and Miyake et al. (2008).

To conclude our overview of the existing knowledge on the matter of second-order resonant springing, the previous studies showed encouraging agreement between the numerical and experimental results and gave ideas about the significance of different case parameters. However, more detailed information on the development of second-order resonant springing is needed in order to understand the requirements for a tool that can predict exciting wave loads in the case of arbitrary case parameters. Such information is needed when selecting a tool for the reliable prediction of springing in realistic sea states as well.

This study describes what matters for the development of the second harmonic wave loads, which can excite the springing of a large cruise ship in one type of regular wave conditions. The findings are based on the analysis of the behaviour of the forces acting at stations on the ship. The data to be analysed was obtained by conducting numerical simulations with a RANS-VOF solver. The structural responses were omitted because of the low amplitude of vibration relating to the stiffness of cruise ships, which is greater than that of some other ship types.

The simulation results that form the basis of the analysis presented in this paper were verified and validated against experimental data in Hänninen et al. (2014) and in Hänninen (2014). The conclusions from these studies are that the numerical uncertainty is insignificant from the point of view of the present analysis and that in the selected case the modelling approach can capture the essential features of the development of the pressure impact at the bow. The validation was performed by comparing the computed time histories of the pressure at 10 locations against data which was obtained by conducting dedicated model tests. The numerical uncertainty of the computed pressure histories used in the validation is assessed in Hänninen et al. (2014) and in Hänninen (2014) by systematically studying the influence of grid and time resolution and the influence of the number of iterations within each time step. The verification of the time histories of the vertical forces acting at selected stations and the distribution of the second harmonic amplitude and phase of this force along the length of the hull is presented in Hänninen (2014). Additionally, the verification of the distributions of the first–third harmonic amplitude of the vertical forces acting at the stations for a similar computation is addressed in Hänninen et al. (2012). The requirements concerning the numerical simulation of a similar flow case are also considered in Hänninen and Mikkola (2008) and Hänninen et al. (2011). In this paper, the focus is on the physical phenomena only as the verification and the validation of the computation were done before.

2. Study case

The study case describes a large cruise ship that is advancing through short and steep head waves. The hull form is one of the development versions of a real ship which was constructed. The length of the ship is 328 m. The encounter period of the ship and waves was selected to be such that the second harmonic component of the wave loads resonates with the two-node vertical mode of the ship.

The computation is performed on the model scale 1:49. The ship frames are shown in Fig. 1 and the case parameters are presented in Table 1. The origin of the coordinate system is located at the aft perpendicular of the ship at the level of the design waterline. The positive z-axis points upwards and the positive x-axis from the stern towards the bow of the ship.

The setup applied in studying this case includes two assumptions about the physics of the flow. First, it is assumed that the motions of the ship are negligible, which implies that the effect of the radiation forces can be ignored. The validity of this assumption was confirmed by the measured data of the motions of the ship in the model tests (Hänninen et al., 2014; Hänninen, 2014). Second, it is assumed that the deformation of the hull (springing vibration) does not significantly affect the main features of the flow. As a consequence, the hull is considered rigid. The reasoning that underpins this assumption is that the order of magnitude of the vibration amplitude is about 1% of the wave height in this case.

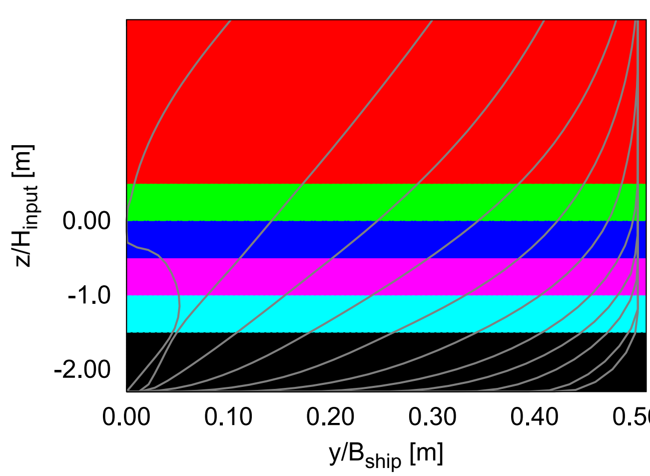

Fig. 1. Ship frames between the fore perpendicular and the midship. The colour zones are used in Section 5.2. (For interpretation of the colours in this figure, the reader is referred to the web version of this paper.)