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A numerical study of the second-order wave excitation of ship springing by a higher-order boundary element method

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ABSTRACT: *This paper presents some of the efforts by the authors towards numerical prediction of springing of ships. A time-domain Higher Order Boundary Element Method (HOBEM) based on cubic shape function is first presented to solve a complete second-order problem in terms of wave steepness and ship motions in a consistent manner. In order to avoid high order derivatives on the body surfaces, e.g. mj-terms, a new formulation of the Boundary Value Problem in a body-fixed coordinate system has been proposed instead of traditional formulation in inertial coordinate system. The local steady flow effects on the unsteady waves are taken into account. Double-body flow is used as the basis flow which is an appropriate approximation for ships with moderate forward speed. This numerical model was used to estimate the complete second order wave excitation of springing of a displacement ship at constant forward speeds.*

KEY WORDS: Springing; Weakly nonlinear; Time domain; Boundary element method.

INTRODUCTION

Springing of ships is a steady-state wave-induced global hydroelastic resonant vibration, while whipping is a transient and decaying vibration caused by impulsive loading (i.e. slamming). The linear and nonlinear springing loads on ships may strongly reduce the fatigue life of ships. Storhaug (2007) documented that the springing and whipping may contribute to approximately 50% of the accumulated fatigue damage based on full-scale measurements of a 300 *m* bulk carrier. Wave-induced extreme hull girder loading causes important nonlinearities in the design wave bending moment amidships. See Jensen (2000).

Linear springing of ships in regular waves occurs when the frequency of encounter matches the natural frequency of 2-node vibration. It implies that the response has the same frequency as the encounter frequency of the incident wave. Skjørdal and Faltinsen (1980), Bishop et al. (1977) and Maeda (1980) developed linear springing theories. Skjørdal and Faltinsen (1980) considered head sea and modified Faltinsen's (1971) short wavelength theory, which accounts for important 3D flow effects. They found the hydrodynamic forces by solving the diffraction problem and integrate the pressure over the hull surface. Bishop et al. (1977) and Maeda (1980) found these forces by formulating a reciprocity relationship and solving the radiation (forced oscillation) problem.

Nonlinear springing has also been observed in regular waves in model tests (see e.g. Storhaug, 2007; Slocum and Troesch, 1983; Miyake et al., 2008) when the encounter frequency is equal to 1/n of the structural natural frequencies where n is integer,

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i.e. we can talk about second-order, third-order and so on nonlinearly excited springing. If we consider an irregular sea, second-order springing is associated with sum-frequency effects. Wu et al. (1997) has proposed a 3D nonlinear hydroelasticity theory, where the contributions of the first-order wave potentials and responses to the second-order hydrodynamic actions on a flexible body were formulated. The nonlinearities in the free-surface conditions are not considered. Tian and Wu (2006) has applied this theory to ships traveling in random waves, with a constant forward speed. Vidic-Perunovic and Jensen (2005) studied theoretically non-linear springing due to bidirectional waves. The incident waves are described consistently by second-order theory while a pragmatic second-order strip theory is used to describe the interaction with the ship. The effect of non-linear cross-coupling terms between two long-crested wave systems was added to the second-order terms from each of the two wave systems alone. This was shown to significantly influence the springing-induced response.

It is hard from a numerical point of view to go beyond second-order nonlinearly excited springing by a consistent perturbation scheme. Further, a perturbation scheme becomes increasingly tedious with increasing order of nonlinearly excited springing. If the body surface at rest is not vertical at the free surface, difficulties with flow singularities at the intersections between the mean free surface and body occur. The latter fact limits the possibilities in analyzing higher order than second-order problems for ships with bow flare. When a tank has non-vertical surface in the free-surface zone, Faltinsen and Timokha (2014) demonstrated for the linear eigenvalue problem that singular solutions had to be added at the intersections between the mean free surface and the tank surface to obtain high accuracy in predicting natural sloshing frequencies.

It is now commonly accepted that springing can be excited not only by the linear wave loads but also nonlinear wave loads. Miyake et al. (2008) found experimentally for a modified Wigley model that the springing of super harmonic (n-th) resonance due to the higher-order nonlinear hydrodynamic forces occurred, although the model is a simple mathematical hull form without bulbous bow. The similar phenomenon has been reported by Storhaug (2007) in his model tests of a bulk carrier with different bow shapes.

The wave-induced sectional loads on ships are often analyzed by a blended method, which is based on the linear solution with nonlinear corrections for the Froude-Krylov and the restoring forces. von Graefe et al. (2014) considered the weak nonlinearity of the sectional loads in waves (e.g., hogging-sagging asymmetry) by pressure extrapolation and integration up to the estimated actual water line. Slamming-type of loads may also be added by, for instance, the 2D and 3D generalized Wagner approaches. See Zhao et al. (1996) and Faltinsen and Chezhian (2005). In the generalized Wagner models, the free-surface conditions are the same as in Wagner's outer flow domain, i.e. the dynamic condition is zero velocity potential and the kinematic condition is fully nonlinear. The body-boundary condition is satisfied on the exact body boundary. It is required in the generalized Wagner method that the lateral coordinates of the intersection between body surface and free surface must not decay with time. Therefore, it is not consistent to use the Generalized Wagner approaches in the water exit. Highly accurate and efficient numerical methods to solve the 2D generalized Wagner problem have been developed by, for instance, Helmers and Skeie (2013), Khabakhpasheva et al. (2014) and Korobkin (2011). The coupled seakeeping and 2D generalized Wagner model has been studied by Tuitman and Malenica (2009) and it was shown to be a useful approach from engineering point of view. Further improvements in such coupled model are needed to, for instance, properly take into account the forward speed effects and avoid double counting of the wave forces from wave radiation. In the blended methods, the nonlinearities in the wave radiation and diffraction are only partly considered. How important the neglected nonlinear wave radiation/diffraction is as the excitation of nonlinear ship springing still remains as a mystery. In order to answer this question, it is necessary to solve a complete higher-order problem (e.g. second-order problem) with the presence of forward speed.

The Boundary Value Problems (BVPs) for the linear and higher-order potential-flow solutions for external flows are traditionally formulated in an inertial coordinate system. The body-boundary and free-surface conditions are by Taylor expansions formulated on the mean body and free-surface positions. Because the steady flow does not satisfy the body-boundary condition on the instantaneous body surface, the important m_j-terms occur in the linear body-boundary conditions for ship motions at forward speed. The second-order solution involves second-order derivatives of the first-order unsteady velocity potential and second-order and third-order derivatives of the steady velocity potential on the mean body surface. If the body has sharp corners with interior angles less than 180°, the procedure fails at the sharp corners and flow singularities occur. Use of a body-fixed coordinate system in solving higher-order potential-flow problems does not include any derivatives of the velocity potential on the right-hand side of the body-boundary conditions. Shao and Faltinsen (2010; 2012a; 2012b; 2013; 2014) formulated the boundary value problem in the body-fixed coordinate system in the analysis of the weakly nonlinear wave-