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Hydroelasticity of marine vessels advancing in a seaway

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ABSTRACT

An important branch of hydroelasticity deals with the dynamic interactions between elastic structures and ocean waves. While the modal superposition method has been the primary approach in hydroelastic analysis of marine vessels, we present a directly coupled approach in the frequency domain with a rigorous treatment of the vessel forward speed. The formulation adopts a translating coordinate system with the free surface boundary conditions accounting for the double-body flow around the vessel and the radiation condition taking into account the Doppler shift of the scattered waves. A boundary element model, based on the Rankine source formulation, describes the potential flow and the hydrodynamic pressure on the vessel. A finite element model relates the vessel response to the hydrodynamic pressure through a kinematic and a dynamic boundary condition on the wetted hull surface. This direct coupling of the structural and hydrodynamic systems leads to an equation of motion in terms of the nodal displacement of the finite elements. The results are evaluated against predictions from a seakeeping model with forward speed and the modal superposition method at zero speed. A parametric study of a Wigley hull shows that forward speed introduces new resonance modes, which amplify the elastic response of the vessel in a seaway.

1. Introduction

Hydroelasticity assumes greater importance in the design of modern-day marine vessels such as multi-hull ships, container ships, oil tankers, and bulk carriers (Hirdaris and Temarel, 2009; Hirdaris et al., 2011). The unique hull designs and lightweight construction result in a relatively flexible ship structure under the action of ocean waves. Cheung et al. (1998) showed the coupling of the rigid-body and elastic responses with the inertia, hydrostatic, and hydrodynamic forces might produce stress concentrations and extreme loads that would otherwise not be detected by conventional design procedures. The forward speed of a vessel in rough seas is an important design and operation consideration, but does not receive the same level of attention in hydroelastic analysis. The steady flow relative to the vessel introduces a Doppler shift of the scattered wave field that modifies the hydrodynamic coefficients and excitation force (Das and Cheung, 2012). The changes in the added mass, damping, and excitation force alter the response and resonance characteristics of a rigid vessel and their effects on a flexible hull are not known with certainty.

The modal superposition method has been the primary approach in hydroelastic analysis of marine vessels since the seminal work of Bishop and Price (1979). With the assumption of a slender ship, they approximated the hull deformation as a series of free oscillation modes of an equivalent beam in vacuo and the hydrodynamic loads on a series of cross sections from strip theory. Bishop et al. (1986) subsequently generalized this approach to full three-dimensional, in which

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the finite element method determines the resonance modes of the ship structure and a distribution of pulsating sources on the wetted hull surface provides the hydrodynamic loads. Their work has provided the capability to evaluate the hydroelastic response of SWATH ships, container ships, and bulk carriers at zero forward speed in ocean waves (e.g., Reane et al., 1991; Cheung et al., 1998; Hirdaris et al., 2003; Senjanović et al., 2008; Hirdaris, 2009). A drawback in the implementation of the modal superposition method is the lack of established criteria for truncation of the infinite series of free oscillation modes. While a truncated series generally reproduces the overall hydroelastic response, some of the high-frequency modes might be necessary to resolve local stress concentrations (Cheung et al., 1998).

An alternate approach is to couple the structural and hydrodynamic systems directly in the frequency domain. This approach provides a complete linear solution and becomes necessary when the structure does not have a definitive shape or free vibration modes in vacuo such as the case of flexible, fluid-filled membranes in ocean waves (e.g., Ohyama et al., 1989; Zhao, 1995; Zhao and Aarsnes, 1998; Phadke and Cheung, 1999, 2001). The formulations of these two-dimensional numerical models are similar, in which the elastic model of the membrane and the Rankine source models of the internal and external fluids are directly coupled through a force-equilibrium relation. Das and Cheung (2009) extended the approach to analyze three-dimensional motions of a fluid-filled membrane in practical applications. The method of direct coupling has also been implemented with pulsating sources for response of deformable structure in waves (e.g., Cheung et al., 2000; Eatock Taylor, 2009). This approach solves the coupled structural and hydrodynamic problem only once at the incident wave frequency versus the modal superposition method that requires solutions of the hydrodynamic problem at a series of frequencies.

Forward speed effects have been considered in the modal superposition and direct coupling approaches of hydroelasticity. Du et al. (1998) extended the method of Bishop et al. (1986) to include vessel forward speed through the use of a translating, pulsating source in the hydrodynamic formulation. This approach, however, introduces non-physical oscillations of the hydrodynamic coefficients with frequency that hampers its use even in general seakeeping (Du et al., 2011). Kim et al. (2009) directly coupled a Rankine source model of the fluid and a simplified Vlasov beam model to investigate hydroelasticity of ships with forward speed. In the absence of a proper radiation condition, their solution is obtained in the time domain as commonly done in the research community (e.g., Cheung et al., 1996; Büchmann et al., 1998; Kring, 1998). Das and Cheung (2012) recently developed a radiation condition for the Rankine source formulation in the frequency domain that accounts for the Doppler shift of the scattered wave field due to vessel forward speed. The resulting model, which caters to general hull forms and vessel forward speeds above or below the group velocity of the scattered waves, has potential applications to hydroelasticity.

The present study extends the work of Das and Cheung (2009, 2012) to provide an alternate formulation of the hydroelasticity problem through direct coupling of a finite element model of the ship structure and a boundary element model of the steady and oscillatory flows in the frequency domain. This includes reformulation of the body surface boundary condition for a deformable vessel advancing in a seaway and the associated numerical schemes to facilitate transfer of information between the two models. The use of the Rankine source in the boundary element model eliminates problems with irregular frequencies and non-physical oscillations with frequency and allows description of the near-field current in wave scattering through the free surface boundary conditions. There is, however, limited data in the literature for direct verification of hydroelasticity models with vessel forward speed. Instead, we verify the hydrodynamic component with the forward speed results of a rigid vessel from Das and Cheung (2012) and the coupling scheme between the hydrodynamic and structural components at zero forward speed with the modal superposition method of Riggs et al. (2007). Through a parametric study, the model provides a thorough investigation of the rigid-body and elastic responses of a vessel advancing in a seaway that previous models cannot fully elucidate.

2. Hydrodynamic formulation

Potential theory provides the framework to define the fluid flow in the domain and the hydrodynamic loads on the vessel. The fluid is inviscid and incompressible and the irrotational flow satisfies the Laplace equation for the implementation of a boundary integral equation. Small amplitude assumptions of the surface waves and vessel oscillatory motions lead to linearization of the wave scattering problem. This section describes the boundary-value problem of wave scattering around an elastic body with a steady forward speed and its solution through the boundary element method with the Rankine source formulation. The numerical solution in terms of the body surface displacement allows direct coupling with a structural model of the vessel.

2.1. Boundary-value problems

Fig. 1 illustrates the boundary-value problem of a vessel traveling with a steady forward speed U in a seaway. The fluid domain is bounded by the still-water surface S_F, the static equilibrium body surface S_B, the seabed at water depth d, and a control surface S_C truncating the infinite region. Let t denote time and $\mathbf{x}=(x_1, x_2, x_3)$ the position vector with respect to a Cartesian coordinate system fixed to the vessel forward motion. A complex velocity potential provides a description of the irrotational flow as

$$\Phi(\mathbf{x},t)=U[\phi_0(\mathbf{x})-x_1]+[\phi_W(\mathbf{x})+\phi_S(\mathbf{x})]e^{-i\omega_e t}, \tag{1}$$