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Simplified approach to dynamic responses of elastic wedges impacting with water

Shan Wang, C. Guedes Soares *

Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico Universidade de Lisboa, Portugal

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ABSTRACT

A simplified method is proposed to model the water impact of an elastic wedge, by combining a modal analysis for the structural deflection and an analytical model for the hydrodynamic pressure on a rigid body. The structural deflections are expressed by wet modes shapes of the beam, and are calculated using modal superposition and Duhamel integral method. The results from the simplified approach are compared with the calculations by using a fully coupled numerical method. The fully coupled simulation is based on an Arbitrary-Lagrangian-Eulerian formulation included in the commercial software LS-DYNA. The Lagrangian formulation is used to describe plane-strain deformations of the structure, and the Eulerian formulation is applied to analyze the changes of the fluid. The structural deflections of wedges with different deadrise angles from the simplified method are compared with published results of theoretical method and fully coupled BEM/FEM method, showing a very significant reduction of required computation time. The convergence of the modal shapes is also investigated. The deflections of flexible wedges with various deadrise angles, impact velocities, and edge boundary conditions are computed and discussed.

1. Introduction

The hydrodynamic impact between marine structures and waves may induce impulsive pressure loads, which consequently affects the ship structure both locally and globally, due to the large magnitude and short duration. The generated impulsive forces may lead to considerable vibrations and local structural damages and thus the accurate prediction of hydrodynamic forces acting on ship hulls and the associated responses are crucial in the design of marine structures.

The initial approaches to estimate the slamming loads and the associated responses of ship structure treated separately the two time scales involved in this problem. The relative motion between the ship and the waves was determined by time simulations based on linear or non-linear ship motion theories (i.e. Belik et al., 1983; Guedes Soares, 1989; Rajendran et al., 2015). When the location of the water impact and the relative velocity were predicted, the slam induced loads on ship sections can be estimated by analytical models (i.e., Wagner, 1932; Howison et al., 1991; Mei et al., 1999; Korobkin, 2004), experimental studies (i.e., Aarsnes, 1996; Ramos et al., 2000; Hermundstad and Moan, 2005; De Backer et al., 2009; El Malki Alaouietal, 2012) and CFD tools (i.e., Stenius et al., 2006; Veen and Gourlay, 2012; Wang and Guedes Soares, 2013, 2014a). Wagner (1932) has developed the theory of impact, which is based on a flat-disc approximation and potential flow theory for ideal and incompressible liquid. Within this approximation the wetted part of the entering body is substituted with a flat disc, and the Bernoulli equation is linearized and the boundary conditions are imposed on the initial position of the liquid boundary. The higher order terms in Bernoulli equation were taken into account within the generalized Wagner model and the Longinovich model (see Korobkin, 2004), in order to improve the predictions of the classical Wagner theory. Korobkin (2004) suggested that the Modified Longinovich model should be used in more general cases. The review work of Abrate (2013) presented the basic principles and analytical solutions of the water entry problems, including the discussions on the trapped air below a flat body. Wang and Guedes Soares (2013, 2014a) have presented the study of the slamming loads on two-dimensional and three dimensional rigid bodies by using the fully coupled ALE/FEM method. Their results agree well with the experimental studies of Aarsnes (1996) and De Backer et al. (2009). Similarly, a two dimensional SPH algorithm has been developed and applied to the problem of ship keel and bow-flare slamming in Veen and Gourlay (2012), which has shown reasonable agreement with measured values in Hermundstad and Moan (2005) on the slamming pressures. Facci et al. (2015) have implemented a direct computational framework to study the two-dimensional flow physics generated during the water entry of a rigid

* Corresponding author. Avenida Rovisco Pais, Instituto Superior Técnico, 1049-001 Lisboa, Portugal.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

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wedge. Their work show that PIV-based methodology allows for an accurate reconstruction of the pressure field from the measured velocity field, except for early stages of the impact and for a small region close to the free surface.

As mentioned above, these initial studies on the local slamming loads were conducted without considering the effects of elastic responses of the structure. In ship hydrodynamics, the impact velocities are of the order of several meters per second. If the plate thickness is relatively small, then hydroelasticity is a problem even for bodies with moderate deadrise angle (Lu et al., 2000; Faltinsen, 1997; Chen et al., 2006). This hydroelastic problem is still a challenging subject due to the extremely complex flow field on the structural surface during the impact.

Local hydroelastic slamming has been studied theoretical and experimentally for slamming problems on by Faltinsen (1997, 1999, 2000). Their studies show that the effects of hydroelasticity are based on the relationship of the material and geometric properties of the structure, the impact velocity and the relative angle between the water and the structure surface. Lu et al. (2000) have demonstrated a fully coupled analysis of the elastic wedges impacting with water. The fluid flow is solved by the boundary element method (BEM) together with the fully nonlinear free surface condition. The structural response is analyzed based on linear elastic theory using the finite element method (FEM). Korobkin (1998) and Khabakhpasheva (2006) have analyzed the wave impact on a simply supported elastic plate by combining the classical Wagner (1932) theory and Euler–Bernoulli beam theory. Wagner theory is utilized to predict the hydrodynamic loading by linearizing the boundary conditions for the potential flow on the initial water surface and accounting for the structural deformations. Korobkin et al. (2006) and Khabakhpasheva and Korobkin (2013) have developed a similar method that coupled the beam finite element model with Wagner theory of water impact. Because of the flat-disk approximation of Wagner's theory, this method is only applicable to any elastic body with small deadrise angle entering water vertically at moderate velocity. To study the water impact of sandwich composite hulls, Wagner theory in combination with a high-order structural model has been considered by Qin and Batra (2009). Wang et al. (2015) have analyzed the hydroelastic responses of a horizontal plate impacting with the water, by extending the method proposed by Faltinsen (1997) to address forward speeds and compressions on the plate. Besides, some researchers have proposed simplified solutions based on decoupling the structural deformation from the fluid flow, by computing the hydrodynamic loading with the assumption of rigid structures (i.e., Luo et al., 2012; Khabakhpasheva and Korobkin, 2013). Luo et al. (2012) have studied the slamming load and response of one complex 3D steel wedge with stiffened panels on both sides. One uncoupled solution, combining Wagner theory and a FEM code, was presented to predict the stress responses of elastic structures by transient analysis. The predicted results agree well with the measured data from free drop tests, though the effect of elastic response on hydrodynamic pressure is not considered in the simplified solution. Shams and Porfiri (2015) have extended the methodology proposed by Khabakhpasheva and Korobkin (2013) to address arbitrary boundary conditions and free fall impacts. Panciroli and Porfiri (2014) have studied experimentally the hydroelastic impact of an active flexible wedge on an otherwise quiescent fluid, and the measured results are interpreted through a distributed model based on linear plate theory and Wagner's approximate solution for the hydrodynamic load.

Recently, computational solutions have been widely used in hydroelastic slamming problems. Maki et al. (2011) have studied the impact of an elastic wedge onto the free surface by using a loosely coupled method which combines CFD and FEM tools in a one way manner. The CFD is used to assess the loading on a rigid body, and the pressure and stress field is projected onto a structural model. Modal analysis is used to represent the wet structure. Their results agreed well with the calculations of Lu et al. (2000). A fully coupled simulation of an elastic wedge entering into water has been studied by Stenius et al. (2007) using an explicit finite element method. Hydroelastic effects on the structural response are systematically studied for different impact velocities, boundary conditions and structural mass. Their further studies have been presented in Stenius et al. (2011), which includes the calculations from a simplified in-house developed method. The fundamental mechanisms involved in panel-water impact related hydroelastic problems have been extensively investigated, however, comparisons between the method and other theoretical or numerical tools are not found. Similarly, Panciroli et al. (2012) have developed a coupled smoothed particle hydrodynamics finite element method to study water entry of flexible wedges. Wang and Guedes Soares (2014b) have conducted the numerical study on the hydroelastic impact of a flexible wedge by using LS-DYNA, and the results are in good agreement with Lu et al. (2000).

In this work, a simplified method is proposed to study the hydroelastic water entry of a wedge at a constant velocity and the results are validated against a fully coupled simulation method. The simplified method is based on the assumption that the structural deformation doesn't affect the loading on the wetted surface of the structure. Analytical models derived from velocity potential are used for prediction of the hydrodynamic pressure on a rigid body, and the structural responses under the impulse load are calculated by a modal analysis. The present simplified method is validated through the comparison of structural deflection with the results from the fully coupled numerical method, which is based on an Arbitrary-Lagrangian-Eulerian (ALE) formulation implemented in LS-DYNA. Different deadrise angles, beam thicknesses, edge boundary condition and impact velocities of the elastic wedge are considered. Their effects on the hydroelastic deflection of a plate are discussed. Results show that the present simplified method gives satisfactory prediction of the deflection on an elastic wedge when the hydroelastic effect is not significant. This method can be easily derived and solved, and with proper model for the hydrodynamic loading on a rigid wedge, it could be applicable for a wedge with arbitrary deadrise angle and falling velocity. The fully coupled numerical method can be used for hydroelastic water impact problems of an arbitrary geometry body, though high computation effort is required.

2. Methodology

2.1. Simplified method

The symmetric water impact of a wedge with length L and deadrise angle β is illustrated in Fig. 1. The coordinate system (x, z) is used for the calculation of hydrodynamic pressure on the wetted surface, with the origin at the intersection between the initially calm water surface and the symmetric line. The wedge enters into the water at a velocity dh/dt, and the half-wetted length on the structural bottom is denoted as $c(t)$. To

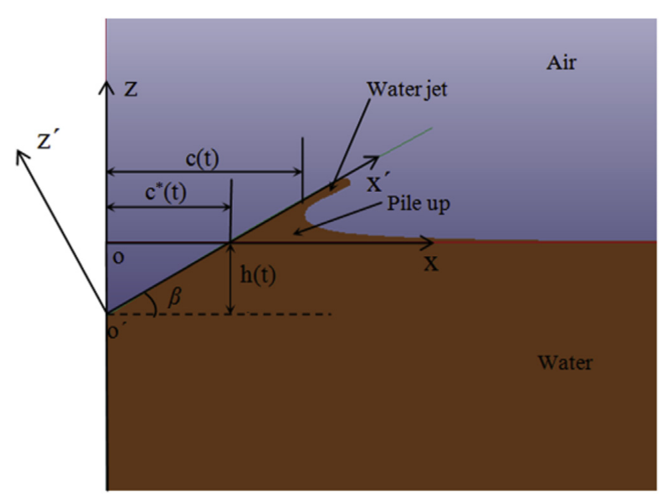

Fig. 1. Coordinate system used for local hydroelastic analysis of a wedge-shape body.

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