Marine Structures 63 (2019) 215–238

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Hydroelastic analysis on water entry of a constant-velocity wedge with stiffened panels

Pengyao Yu[a], Hui Li[b], Muk Chen Ong[c,*]

[a] College of Naval Architecture and Ocean Engineering, Dalian Maritime University, Dalian, 116026, China
[b] College of Shipbuilding Engineering, Harbin Engineering University, Harbin, 150001, China
[c] Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Stavanger, 4036, Norway

ARTICLE INFO

Keywords:
Water impact
Slamming
Elastic wedge
Hydroelasticity
Mode superposition method

ABSTRACT

This paper presents a hydroelastic analysis on water entry of a constant-velocity wedge with stiffened panels. Incompressible flow and the potential flow theory are considered in the present study. Through revisiting the pressure distribution around the elastic wedge based on the Wagner theory, a semi-analytical hydrodynamic impact theory is expanded to perform the hydrodynamic analysis of elastic wedges. Mode superposition method is adopted to calculate the structural response. Modal displacements of different two-dimensional (2D) sections corresponding to the cross-sectional fluid domain are obtained from the modal analysis of a three-dimensional (3D) structure. Unlike most hydroelastic studies requiring the analytical mode shapes of structures, the coupling analysis of the 2D section between the discrete mode shapes of the finite element model and the impact hydrodynamic forces is realized; and this makes the present numerical method appropriate for complex 3D structures. By integrating the general force of different sections, the governing equation for the hydroelastic analysis of a complex 3D wedge is established.

The numerical scheme of the present method is verified in 2D analysis by comparing with published literature results and the decoupled result of a commercial software. Numerical results show that the present method is more accurate than hydroelastic methods based on the Wagner model, and it can predict the oscillatory response after flow separation, which is usually infeasible in hydroelastic methods based on the Wagner model. By removing the coupled terms in the governing equations, the present method can be used for structural response analysis under the decoupled condition. Then, the numerical scheme is further validated by the comparison with the decoupled result of the commercial software. Through the comparison between coupled and decoupled results of a 3D wedge, it is found that the effect of fluid-structure interaction and the oscillatory response after flow separation are important for predicting the structural responses.

1. Introduction

In rough seas, the impact between ship hulls and waves can induce severe local pressure loads, which may cause local or global structural damages [1]. In order to investigate the fundamental mechanisms during slamming, water entry engineering problems of rigid and elastic bodies have been studied extensively over years using analytical or semi-analytical methods [2–18], numerical methods [18–30] and experiments [31–43].

The theory of the rigid body impact is the foundation of the theory of the elastic body impact. Pioneering work on the rigid impact

* Corresponding author.
E-mail address: muk.c.ong@uis.no (M.C. Ong).

https://doi.org/10.1016/j.marstruc.2018.09.007
Received 1 February 2018; Received in revised form 26 July 2018; Accepted 22 September 2018

had been done by Von Karman [14] and Wagner [15]. With the help of the matched asymptotic expansion method, [2]; Howison et al. [5] and Zhao and Faltinsen [18] corrected the singularity of the contact region edge in the original Wagner model. Logvinovich [44] added some extra terms to the distribution of the velocity potential which made the flow velocity at the edge of the contact region bounded. Korobkin [6] gave a rational derivation of several analytical models, including the Original Logvinovich Model (OLM), the Modified Logvinovich Model (MLM) and the General Wagner Model (GWM). Tassin et al. [12] assessed the accuracy of several analytical models for the prediction of hydrodynamic forces and pressure distributions acting on a body entering initially calm water. During the water entry of a finite wedge, the jet root may detach from the body surface. By introducing a fictitious section, Duan et al. [45] expanded the application of MLM and the vertical entry force of the wedge after the flow separation was calculated. Tassin et al. [13] investigated 2D water entry with separation through different analytical models. This included the separation model suggested by Logvinovich (1972) and the concept of Fictitious Body Continuation (FBC) combined with MLM. By comparing the results of MLM with the numerical result of the commercial explicit FE-code LS-DYNA, Yu et al. [46] proposed a semi-analytical model considering the flow separation and negative pressure correction.

Hydroelastic method is often adopted to better consider the structural elasticity on water entry problems. Based on analytical hydrodynamic impact theory, many hydroelastic methods have been proposed. Kvalsvold and Faltinsen [36] and Faltinsen et al. [4] studied wetdeck slamming using a hydroelastic beam model. By the direct coupling of the finite element method (FEM) with the Wagner theory, Korobkin et al. [47] illustrated a hydroelastic method to evaluate the structural response of elastic wedge in two dimension [48]. presented a numerical method to study water entry of a 2D elastic wedge, which considered the strong coupling conditions between the hydrodynamic loads and the structural response. Shams and Porfiri [49] proposed a numerical model for the analysis of two-dimensional hydroelastic slamming of flexible wedges, in which the wedge kinematics was modeled by Euler–Bernoulli beam theory and the flow domain was studied using the Wanger theory. This model was validated through comparison with available semi-analytical, computational, and experimental results. Datta and Siddiqui [50] presented a theoretical hydroelastic analysis of an axially loaded uniform Timoshenko beam undergoing hydrodynamic impact-induced bottom slamming.

Several fully nonlinear hydrodynamic impact theories are expanded to fully nonlinear methods of elastic body impact. Lu et al. [20] calculated the elastic wedge response by coupling the boundary element method with the finite element method. By using the commercial explicit FE-code LS-DYNA which contains the Arbitrary-Lagrangian Eulerian (ALE) algorithm, Stenius et al. [24, 25] studied the hydroelastic interaction between a 2D elastic wedge and water free surface. A similar analysis has been presented in Das and Batra [51] for sandwich composite hulls. Piro and Maki [23] adopted the open-source computational-fluid dynamics (CFD) library OpenFOAM to solve the fluid domain, and performed the hydroelastic analysis of bodies that enter and exit water.

The 3D stiffened plate with several longitudinal stiffeners and transverse frames is a typical structure in ship and ocean engineering. Although water entry of 2D rigid or elastic wedges has been widely studied, dynamic response of the 3D wedge-shaped stiffened plate under the hydrodynamic impact is only marginally studied. Faltinsen [3] performed a hydroelastic analysis of a 3D wedge during water entry. Therein, the cross-fluid domain was solved by the 2D Wagner theory and the analytical modes of the stiffened plate were solved based on the orthogonal plate theory. The applicability of the orthogonal plate theory was verified by comparing with the finite element method in the quasi-steady analysis. Luo et al. [37] performed an decoupled method to study the impact response of a 3D wedge which consists of two stiffened plates. In this method, the hydrodynamic impacting load was solved by the matched asymptotic theory and the structural response was predicted by the FEM code. Luo et al. [52] also performed a coupled study on the dynamic response of a freefall 3D wedge with the commercial code LS-DYNA. The numerical results were in a good agreement with experimental results. Due to the shallow penetration of the wedge, the vibration response after flow separation was not presented. To our knowledge, the limitations of the previous work about the water entry of the 3D wedge include: (a) the vibration response of the stiffened plate after flow separation was usually not considered; (b) the hydroelastic method based on the analytical hydrodynamic was only suitable for simple structures with analytical modes, such as the orthotropic stiffened plate.

Compared with fully nonlinear hydrodynamic theories, analytical or semi-analytical models are more efficient in the solution of the fluid domain. Inspired by the coupled idea between the cross-sectional fluid domain and the 3D wedge in Faltinsen [3]; a hydroelastic method for the constant velocity water entry of a 3D wedge is proposed. Compared with the previous studies, the present method contains the following improvements.

- A semi-analytical hydrodynamic model is expanded to solve the cross-fluid domain around the elastic wedge. This model is more accurate than the Wanger model for the prediction of impact loads.
- The present method can predict the vibration response of the stiffened plate after flow separation, which is usually infeasible for hydroelastic methods based on the analytical hydrodynamic model.
- Structure vibration modes in the present method are solved using FEM, which is widely used in the ship engineering.

This paper is organized as follows. In section 2, the pressure distribution around a 2D elastic wedge is presented. In Section 3, the expression of general forces in the 2D section by combining hydrodynamic coefficients with principal coordinates is presented. In section 4, a hydroelastic equation of 3D elastic wedges during water entry is established. In Section 5, numerical results of 3D and 2D wedges during water entry are presented and discussed. In Section 6, the main conclusions of the present study are summarized. Furthermore, in Appendix A, the derivation process of the semi-analytical model which considers the correction of the negation pressure and flow separation on the basis of the Modified Logvinovich Model is shown.