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Hydroelastic criterion for an inclined flat plate in vertical and oblique impacts

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ABSTRACT

A two-dimensional semi-analytical model is applied for the analysis of hydroelastic effect during vertical and oblique impacts of flexible inclined plates with different boundary conditions (BCs). Hydrodynamic pressure is calculated using Wagner's theory and the structural deformation is presented as a linear combination of dry normal modes. A longitudinal strip is used as an approximation of the longitudinal bending of a plate. Model predictions are validated by comparing with the available experimental data, semi-analytical model, and asymptotic approaches for vertical and oblique impacts of the plate with different BCs. The water impact is analyzed with two viewpoints of rigid and flexible plates. Maximum stress and deflection calculated using hydroelastic and rigid-quasi-static analyses are compared for different BCs. Based on the hydroelastic criterion, validity range of rigid-quasi-static analysis and the importance of dynamic response are determined. The effect of horizontal velocity is discussed. It is found that for a low value of hydroelastic criterion, the hydroelastic analysis yields lower values of maximum stress or deflection than rigid-quasi-static analysis, while for a moderate value of hydroelastic criterion is vice versa. As expected, for a high value of hydroelastic criterion both analyses yield the same results except in the case of a clamped-free plate. Evaluation of the hydroelastic and rigid-quasi-static analyses revealed that hydroelastic criterion and structural BCs are determinant in selecting one of them for the design process.

1. Introduction

Hydroelastic structural responses considerably affect the hydrodynamic loads in problems concerned with water impact. When elastic structural responses are significant, a strong coupling is created between the fluid flow and structural deflections. In this case, the structure should be designed based on hydroelastic analysis, which is complicated and costly. In contrast, when the hydroelastic effects are small, the simple and inexpensive rigid-quasi-static analysis is employed, meaning that the hydrodynamic load is estimated under rigid assumption and then applied to the elastic structure regardless of the structural inertia [1,2]. Therefore, selection between hydroelastic and rigid-quasi-static analyses is a critical step in the design process which has a great impact on cost and the computational time.

As the pioneer of water impact model, Wagner [3] presented a theoretical method for water entry of the two-dimensional rigid structure. Later, researchers extended the studies by assuming the flexible structures. The initial models for hydroelastic impact with liquid free surface were proposed in [4–6]. In this context, many studies have been conducted based on the Wagner's theory to obtain semi-analytical solutions [7–12]. With the development of computational tools and measurement devices, numerous numerical and experimental studies have been devoted to the hydroelastic impact [13–17].

Most of these research efforts focused on identifying the interactions between structural deflections and hydrodynamic loads. However, a few studies have been reported the criteria for considering or not considering the role of hydroelasticity. The first attempts carried out by Haugen and Faltinsen [18] to introduce a criterion for evaluating the importance of the hydroelasticity. They presented a dimensionless hydroelastic parameter R_F as the ratio of the wetting time of the rigid plate impact to the highest wet structural period. This parameter is a function of deadrise angle, vertical velocity, length, flexural bending rigidity, and water density. Faltinsen [19] employed orthotropic plate theory and Wagner's approach and, based on the R_F criterion, showed that smaller deadrise angles and higher impact velocities increase the hydroelastic effects. Bereznitski [20,21] numerically investigated the role of hydroelasticity in slamming problems and proposed the ratio of impact time to the highest dry structural period (R_B) as the key factor in

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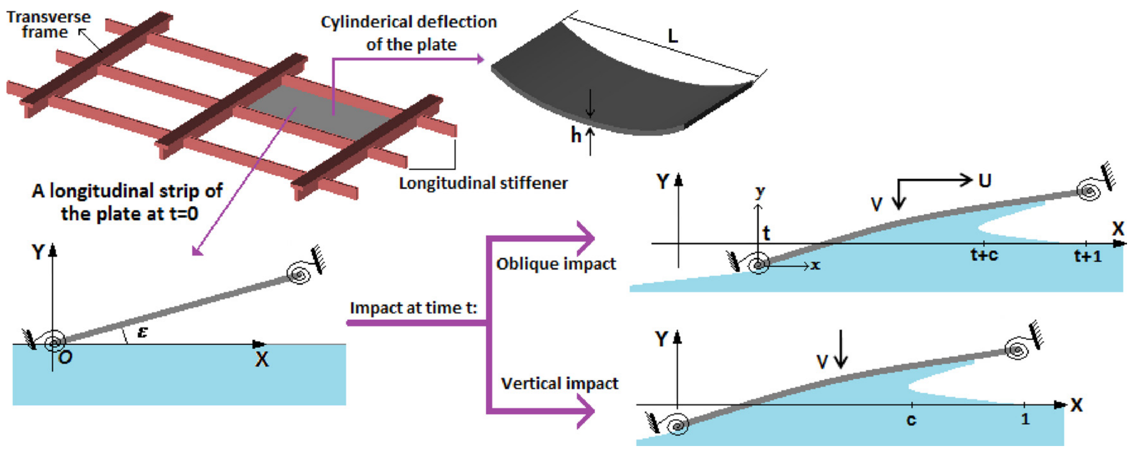

Fig. 1. Schematic illustration of the bottom panel of a multihull vessel during oblique and vertical impacts. ***XOY*** and ***xoy*** are, respectively, inertial and body-fixed Cartesian coordinate systems in dimensionless forms.

taking into account the hydroelastic effects. He used the Finite Element Method (FEM) to solve potential flow theory considering air entrapment on water flow in wedge water entry problem at angles smaller than 10°. Regarding the R_B criterion, he calculated the impact time by applying the triangular approximation to the force distribution in the rigid impact. Bogaert and Kaminski [22] proposed the lumped-mass model to add the effect of rigid body motions to the hydrodynamic loads and structural vibrations.

Stenius et al. [2] conducted a numerical study using LS-DYNA software package investigating the flexible wedge impact at deadrise angles of 20° and 30° with the boundary conditions (BCs) of simply supported (SS), clamped-simply supported (CS), and clamped-clamped (CC) ends. They calculated the wetting time through Wagner's method and presented a relation for R_F criterion, which was different to that of Haugen and Faltinsen [18] in the effect of structural BCs. Wedge water entry at deadrise angles 15° to 35° subjected to clamped-free (CF) BCs was experimentally studied in [23]. The experimental results were used to validate the combined SPH-FE numerical simulation. The wetting time in the R_B criterion was calculated through Wagner's method. Panciroli et al. [24] performed experiments on elastic wedge impact at deadrise angles of 20° to 35° with the BCs of CC, SS, and CF. Based on the Von Karman [25] theory, a relation was derived for R_B criterion which was a function of deadrise angle, vertical velocity, total mass, water pile up, and dry natural frequency. Piro and Maki [1] numerically simulated the wedge impact at a deadrise angle of 10° with simply supported ends for water entry and exit. The Navier-Stokes equations and the modes associated with the natural frequencies were respectively employed for the fluid flow and the structural deflections. Both weak and strong coupling between the numerical solver and the modal decomposition method were established.

Shams and Porfiri [12] extended analytical model proposed by Khabakhpasheva and Korobkin [26] for wedge free fall impacts with arbitrary BCs. They validated hydroelastic model through comparison with available results in the literature for different R_F with the BCs of SS and CF. Recently, Shams et al. [27] experimentally examined the deflection of a composite wedge (syntactic foam) at a deadrise angle of 10° with the CF BCs. In this case, hydroelastic effects were extreme, i.e. R_F was considerably small (less than 0.03). The role of hydroelasticity is clarified by simultaneously measuring the hydrodynamic loads and wedge deflections. Moreover, Shams et al. [28] semi-analytically and experimentally modeled a flexible wedge water entry and exit at an angle of 25° subjected to the CF BCs. Their results revealed that during the water exit, the hydroelastic effect for $R_F < 0.36$ leads to change in the force direction.

These studies have been dedicated to water entry in vertical case. Despite the extensive efforts on the vertical impact of rigid and elastic bodies, few researchers have addressed the problem of oblique impact. Most of which have only focused on the hydrodynamics of rigid bodies [29–34]. The oblique impact of elastic bodies was studied in [35,36]. Reinhard et al. [35] presented an analytical model for an elastic plate with free ends (FF). According to their results, the elasticity of the plate can increase the hydrodynamic loads. Thus, the bending stresses may exceed the yield strength. Iafrati et al. [36] analyzed the hydrodynamic pressures, strains, loads and velocity reduction for an elastic plate at angles 4° and 10°, with high horizontal speeds and the CC BCs.

Although these studies have greatly contributed to developing the knowledge of hydroelastic impact, they have mostly been conducted on angles larger than 10 ° and for vertical impacts. Previous research has shown that hydroelastic effect increases in small angles [19,21]. On the other hand, in some practical cases, the structures are also involved with horizontal velocity (oblique impact) [34,37,38] in addition to vertical velocity (vertical impact). Hence, the purpose of current study is to investigate the hydroelastic response of the plate at small angles during vertical and oblique impacts. To this end, we applied a hydroelastic model for the impact of the plate with different BCs. The stresses and deflections are calculated by the hydroelastic model and rigid-quasi-static analysis. Then, their maximum values are utilized to predict the range of hydroelastic criterion in which the rigid-quasi-static analysis is valid, identify the hydroelastic effects, and examine the effect of structural BCs and horizontal velocity on the hydroelastic criterion.

In the present work, a system of differential equations is initially derived for the impact of the plate with different BCs. Then, the results of the hydroelastic model are compared with experimental data, semi-analytical model and asymptotic approaches. Finally, the dynamic and rigid-quasi-static responses are evaluated based on hydroelastic criterion during vertical and oblique water entries for different BCs.

2. Formulation of the problem

The unsteady coupled problem of an elastic plate with small inclination angle which enters the ideal and incompressible water is considered, see Fig. 1. At time $t'=0$, the plate touches the free surface of the water at a single point and then enters the water vertically or obliquely. The vertical movement is assumed dominant in the oblique entry that gives $V/(\varepsilon U) > 1$. The dimensionless inertial (XOY) and body-fixed (xoy) Cartesian coordinate systems are used to describe the motion of the plate. Note that the dimensional variable is denoted by a prime.

Following [9,10,38,39], assuming that the deformed surface of the plate is cylindrical in the longitudinal direction. Therefore, a longitudinal strip is approximated for analyzing the plate bending with various BCs at the strip ends. However, the most important boundary

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