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Dynamic response of a flat plate subjected to compression force during vertical and oblique impacts with calm water

Hashem Moradi[a], Ahmad Rahbar Ranji[a], Hassan Haddadpour[b]

[a] Department of Ocean Engineering, Amirkabir University of Technology, Tehran 15914, Iran
[b] Department of Aerospace Engineering, Sharif University of Technology, Tehran 11115-8639, Iran

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ABSTRACT

An existing hydroelastic model is extended for a flat plate subjected to a compression force with spiral spring boundary conditions during water entry. Both vertical and oblique impacts of the plate into calm water are investigated. A longitudinal strip of the plate is analyzed by fully coupling hydrodynamic pressure with elastic responses. Hydrodynamic pressure is determined by potential flow theory and plate deflections are expressed in terms of dry normal modes. The plate deflections are validated through comparison with available asymptotic models, semi-analytical and experimental results. The effect of compression force on the plate deflection is investigated at the midpoint considering different horizontal velocities and inclination angles. Dry and wet frequencies and the minimum threshold values of the compression forces are obtained for plates with different boundary conditions during vertical and oblique impacts. The results show that the plate responses may reach the plastic region at low compression force and high horizontal velocity. It is also found that for all the cases studied yielding occurs before buckling during water impact of the plate.

1. Introduction

The modeling of hydroelastic impact is a challenging problem in the slamming of advanced marine vehicles and the water landing of aerospace structures [1]. During water impact, a rapid transient interaction occurs between fluid flow and structural deformation, which complicates the modeling of the problem both analytically and numerically. Although the use of computational methods in fluid-structure interaction provides valuable details of the fluid flow, it is very time-consuming and costly, especially in the fully coupled approaches [2]. Analytical or semi-analytical models which reduce the computational time and the duration of the pre-design stage are preferred.

One of the practical applications of the hydroelastic model is wet deck slamming. Wet deck is the lowest horizontal structural part that connects the sides of a multihull vessel and frequently affected by impact loads. In the last three decades, a number of researchers have studied the wet deck slamming. Kaplan [3] showed that the wet deck impact loads could be as high as the weight of the structure. Zhao and Faltinsen [4] demonstrated that the heave and pitch motions of a catamaran are affected by wet deck slamming. Robinson and Matveev [5] have experimentally studied vertical water entry of a flat-bottomed catamaran hull and found that an acceleration of 10–15 times of the gravitational acceleration is exerted upon the hull bottom within a time interval in the order of 0.01 s. Numerical results also proved such very large acceleration in a short time [6]. Large slamming forces experienced within a short interval lead to considerable elastic responses of the deck structure, and the consequent deflection changes the distribution of hydrodynamic forces. The induced vibrations in this strongly coupled problem may cause high local and global response (whipping) of the structure which leads to structural cracks due to fatigue [7].

Several scientists studied the local structural response during the water impact [8–10]. Faltinsen and co-workers extensively investigated the local responses of the wet deck only in vertical impact by modeling the wet deck as a flat plate with spiral spring boundary conditions (BCs) [11–14]. They indicated that local hydroelastic effects are significant in wet deck slamming and should be considered in the design process. So far, most of the local hydroelastic analyses have been conducted on vertical impact of horizontal plates, and few of them have been considered the oblique impact of an inclined plate [15,16]. However, vessels move with a trim angle and, in some multihull vessels, the bottom panel is designed with an inclination angle, which consequently leads to the impact of an inclined plate with water. More importantly, in marine and aerospace engineering problems, in addition to vertical velocity, horizontal velocity is also involved.

In the hogging cases of a vessel, the wave crest is placed in the middle of the vessel which imposes a global effect on the vessel and produces local compression force in the hull bottom, Fig. 1(a). The

E-mail address: rahbar@aut.ac.ir (A. Rahbar Ranji).

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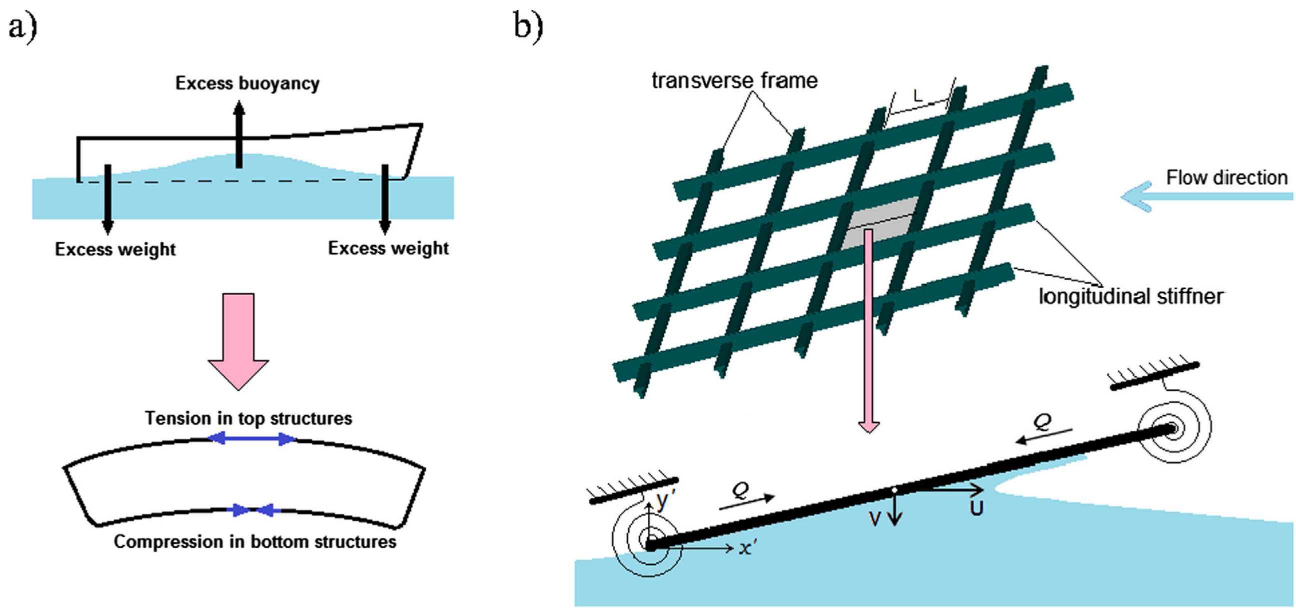

Fig. 1. Schematic depiction of (a) the compression force at the bottom structures due to wave-induced hogging, (b) wet deck structure of a multihull vessel (a strip of the shaded part is modeled).

effect of compression force on the floating plate vibrations was analytically solved by Bukatov [17] based on the potential flow equation. Wang, et al. [18] employed an asymptotic approach to study vibration of a horizontal flat plate subjected to a compression force in vertical impact. They also included horizontal velocity in the analysis of hydroelastic impact and obtained the critical compression force and the critical horizontal velocity [19,20]. They used a simple velocity potential proposed in Kvalsvold and Faltinsen [14] and Faltinsen [21] to obtain hydrodynamic pressure regardless of the Kutta's condition at the trailing edge. However, the Kutta's condition should be applied when horizontal velocity is non-zero [22,23]. Additionally, their analysis was conducted for a zero inclination angle of the plate.

Reinhard, et al. [16] and Reinhard [24] presented a two-dimensional semi-analytical model for the hydroelastic impact of a free-free flat plate in vertical and oblique impacts. They also imposed the Kutta's condition at the trailing edge in oblique impact. Their model is suitable for kinematic conditions including vertical and horizontal velocities, and inclination angle (angle of attack) while the vertical and inclination angle can be time-varying. Although Reinhard's hydroelastic model can cover disadvantages of Wang's model, it was only proposed for free-free BCs of the plate without compression force.

The present research is intended to study the local dynamic or hydroelastic response of wet deck slamming using fully coupled semi-analytical model. In this way, Reinhard's hydroelastic model is extended for a plate subjected to a compression force with spiral spring BCs, considering the importance of the compression force on the local response of the plate [18,19] and the application of the spiral spring supports as a more realistic BCs for the bottom panel of multihull vessels [12,14,19]. A constant compression force is applied to the plate, and a modal basis is used to approximate the dry mode shapes of the plate with spiral springs ends. The hydrodynamic loading integrals are computed in the close-forms which are complicated by adding the compression force. A fourth-order Runge-Kutta time integration is utilized to solve the hydroelastic coupled equations.

This paper is organized as follows: In Section 2, the mathematical formulation of the problem is presented. In Section 3, a system of hydroelastic differential equations is derived for an inclined plate subjected to a compression force during vertical and oblique impacts. In Section 4, the hydroelastic model is validated and then the effect of longitudinal compression force on the plate deflection is investigated. Furthermore, the dry and wet frequencies are calculated, as well as the critical compression forces are determined for a plate with spiral spring supported, clamped-clamped and simply supported ends. Maximum stress during water impact is also compared with yield stress. The main conclusions are drawn in Section 5.

2. Problem statement and mathematical formulation

A typical wet deck structure of multihull vessels is demonstrated in Fig. 1(b). It is assumed that transverse frames have the higher stiffness than the longitudinal stiffeners so that the vertical deflections of the two transverse edges of the plate panel can be neglected. In order to account the restoring moment of the part of the wet deck which was not considered in the model, two spiral springs were applied at both ends [14]. The deflected shape of the plate can be assumed to be cylindrical in the longitudinal direction (two dimensional) with regard to the structural BCs and constant hydrodynamic pressure in the transverse direction.

Consider a strip of the plate with the inclination angle, ε, length, L, thickness, h, constant density, ρ_s, Poisson's ratio, ν, and flexural bending rigidity per unit width, $D = Eh^3/12(1-\nu^2)$. The position of the plate is expressed by $y' = w(x', t')$ for $0 \le x' \le L$ and includes rigid motions, $w_r(x', t')$, and elastic deflections, $w_e(x', t')$. For small elastic deflections and thin plate, the transverse vibration of the strip of the plate under constant compression force is determined using the following equation [25]

$$\rho_s h \frac{\partial^2 w_e}{\partial t'^2} + D\frac{\partial^4 w_e}{\partial x'^4} + Q\frac{\partial^2 w_e}{\partial x'^2} = F(x', t'), \tag{1}$$

where $F(x', t')$ is the external force per unit area and Q denotes the longitudinal compression force per unit width. The external force (hydrodynamic loading) will be presented based on the classical Wagner approach [26] for the case of small angles $\varepsilon \ll 1$. In this approach, the first-order of the solution, $O(\varepsilon)$, was considered and it is important that the horizontal axis and the axis along the plate are identical with an accuracy of $O(\varepsilon^2)$ [27]. Therefore, the hydrodynamic loading and the plate deflection are determined with an accuracy of $O(\varepsilon)$ under the assumption $\varepsilon \ll 1$.

The dimensionless variables are defined as follows: