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Modeling fluid-structure interactions during impact loading of water-backed panels

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ABSTRACT

Understanding the response of water-backed panels to impact loading is of paramount importance in the design of marine and aerospace structures. In this theoretical study, we propose a modeling framework to investigate the two-dimensional, nonlinear hydroelastic response of thin structures. Within Euler–Bernoulli beam theory, we account for nonlinear stiffening due to membrane stretching. We demonstrate a closed-form solution for the fluid potential flow, which affords the exact computation of the hydrodynamic loading. The Galerkin discretization is used to cast the governing nonlinear integro-differential equation into a set of nonlinear ordinary differential equations. Two different semi-analytical solutions are established, by using the in-vacuum linear mode shapes of the beam and Hermitian finite element basis functions. Results are verified against full two-dimensional finite element simulations. We conduct a parametric study to elucidate the role of the beam thickness and the functional form of the impact loading. Our results indicate that the water-backing has a critical role on the structural dynamics, which is stronger for thin beams subject to rapid pulses. The model fills a significant gap in the technical literature, holding promise to inform the design of experimental setups and assist in the analysis of observations on water-backed panels.

1. Introduction

The dynamic response of structures to impact loading is of concern in the design of naval, aeronautical, and offshore engineering [1,9,13]. In these applications, understanding the interaction between the fluid flow and the structural deformation is a technical challenge of paramount importance. Such an interaction dramatically influences the structural dynamics, by modulating both the frequency spectrum and the amplitude of the oscillations [42].

Due to the wide spectrum of application of polymer matrix composites in harsh environments [32,37], a number of experimental studies has been devoted to elucidate the dynamic response of composite structures to impact loading in the presence of a fluid [24,26,28,30]. Kwon et al. [24] have proposed an experimental setup to analyze the dynamic response of fully clamped carbon fiber weave and vinyl ester resins laminates. The experimental setup consists of a drop weight impactor, a load transducer, and a number of strain gages at different location on the composite laminates to measure the transient response. The authors examined air- and water-backed panels. An equivalent experimental setup was later used by Kwon and Conner [23], Kwon and Owens [26], and Kwon et al. [28] to elucidate the dynamic response of different composite laminates, including multi-ply symmetric plain weave E-glass skin and symmetric plain weave E-glass fabrics.

Langella et al. [30] have recently proposed an alternative experimental scheme to dynamically load marine panels across a range of experimental temperatures, toward establishing a first understanding of the concurrent role of extreme temperatures. The experimental setup is based on a modified falling weight machine, in which an instrumented impactor falls on a clamped specimen, resting upon a water column, similar to water-backed dry impact considered by Kwon and Conner [23]. The authors have systematically varied the temperature and impact energy to study the dynamic response of air- and water-backed vinyl ester matrix and carbon fibers laminates. They have found that temperature does not have a significant effect on the dynamic response of air-backed laminates, while it plays an important role for water-backed panels. In addition, their results indicate that the presence of the water-backing introduces a secondary peak in the load-displacement curve and sensibly increases the overall load on the

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structure. While experiments by Langella et al. [30] offer some evidence for the role of water-backing, the difference in the test rig used for air- and water-backed samples hamper a precise quantification of water-backing.

In this theoretical study, we propose a new modeling framework to analyze the hydroelastic impact of water-backed clamped panels, accounting for geometric nonlinearities associated with membrane stretching. To isolate the role of fluid-structure interactions and establish a rigorous, physically-based understanding of the impact, we focus on in-plane bending of thin beams. Although experiments are the cornerstone against which composite materials must be tested, theoretical efforts could significantly aid in interpreting experimental results and precisely quantifying the role of water-backing on structural response. The proposed model is expected to assist in the design of experimental platforms to isolate the role of water-backing from other, confounding factors, thereby helping to improve our understanding of marine composites subject to impact in future research.

The problem shares similarities with the dynamic response of floating structures subject to moving loads, which is often studied in the technical literature on ice floes, breakwaters, airports, and bridges [19,47]. For example, Korobkin [21] utilized Euler–Bernoulli beam theory and potential flow to study two-dimensional (2D) deformations of floating plates. While matched asymptotic expansions were utilized to predict the response of very long floating structures (VLFS), a semi-analytical solution based on the method of assumed modes was presented for the analysis of short floating plates. Kashiwagi [18] analyzed the elastic response of a pontoon-type VLFS subject to arbitrary loads. A plate formulation was used to describe the VLFS kinematics and the hydrodynamic loading was modeled similar to [21], by considering both added mass and memory effects related to the time-history of the plate motion. Sturova [48] studied the response of floating beams by combining Euler–Bernoulli beam theory and the hydrodynamic force proposed by Kashiwagi [18]. Similarly, Fleischer and Park [10] considered hydroelastic vibrations of a floating beam subject to a moving load, within a 2D potential flow solution for the fluid.

In addition to these semi-analytical studies, a few authors have put forward computational schemes to elucidate the dynamic response of floating structures. The key advantage of these approaches lies in the ability to consider more complicated geometries [6]. Qiu [41] utilized the finite element method to study a floating platform subject to impulsive and moving loads. Therein, the flow is assumed to be compressible, inviscid, and irrotational, and a pressure-based formulation is used to reduce the number of unknowns and simplify the extraction of the hydrodynamic loading on the structure. A mixed mode function-boundary element method was adopted by Jin and Xing [17] to numerically analyze the response of a landing beam, within the context of potential flow and Euler Bernoulli beam theories. Cheng et al. [6] proposed a 3D formulation to study the dynamic response of a VLFS subject to external loads and incident waves, through a boundary element method for the fluid flow along with an assumed mode solution for the structure. The predictions of most of these computation and semi-analytical approaches have been validated against experiments by Endo and Yago [8] on a prototype VLFS. Beyond these studies on floating structures, Kwon [25] and Kwon and Plessas [27] computationally modeled the dynamic response of clamped structures in the presence or absence of water-backing for harmonic or impulsive loading. Therein, the structure is modeled through the finite element method and the fluid is described as an acoustic medium using cellular automata [52].

While these studies have greatly aided in the design of floating structures, they are not directly applicable to modeling the experimental setups considered in [24,28], which have been motivated by the need of simulating the response of panels in marine vessels and underwater structures. Here, we extend the formulation proposed by Shams and Porfiri [46] for the study of water impact of flexible wedges to investigate the hydroelastic impact of water-backed panels. Compared to theoretical studies on floating structures [6,18,21], the approach proposed by Shams and Porfiri [46] affords the formulation of a computationally-inexpensive, mathematically-tractable problem. The panel is described using nonlinear Euler–Bernoulli beam theory to incorporate von Kármán nonlinearity. The fluid flow is modeled using the classical solution of Wagner [50], which is based on potential flow theory and a linearized treatment of the boundary conditions.

By following the approach proposed by Shams and Porfiri [46], we formulate a mixed boundary value problem to obtain the velocity potential as a function of the structural deformations, and we find an exact solution for the pressure exerted on the structure in terms of the beam acceleration. This methodology allows for effectively solving the fluid-structure interaction and formulating the problem as a single nonlinear integro-differential equation for the beam deflection. We utilize a Galerkin discretization the governing equation into a set of coupled nonlinear ordinary differential equations and derive semi-analytical solutions.

We consider both a set of polynomial basis functions approximating the linear in-vacuum mode shapes of the beam (assumed modes method) and the classical Hermitian finite element basis (1D finite element method). The former approach follows from Shams and Porfiri [46] and enables the exact computation of all the influence coefficients in the hydrodynamic pressure. The latter approach does not yield an exact expression for the hydrodynamic loading, although it is expected to be more easily generalizable to complex geometries and damage models [14,36]. A Newmark-type integration scheme is combined with the modified Newton–Raphson method to march forward in time and predict the structural response. A parametric study is conducted to elucidate the role of the key physical factors controlling the dynamic response of panels subject to different impact loads. Given the lack of experimental results on which we could validate our model, we resort to a 2D finite element simulation of the impact problem to generate reliable synthetic data using the commercial software COMSOL Multiphysics®. Different than the proposed modeling framework, the simulation accounts for viscosity, large structural deformation, and nonlinear boundary conditions at the fluid-solid interface, thereby offering a more realistic representation of the problem on which to verify our semi-analytical findings.

The main contributions of this study are: (i) a new mathematically-tractable, versatile, modeling framework to investigate the dynamic response of water-backed panels subject to impact loading; (ii) the verification of the accuracy of the framework against direct finite element simulations that constitute the current practice in the analysis of fluid-structure interaction problems [6,27,41]; (iii) the precise quantification of the specific role of membrane stretching and added mass through extensive parametric studies, entailing systematic variations of geometric and physical parameters.

The rest of the paper is organized as follows. In Section 2, we present the modeling framework and the governing equations. In Section 3, we illustrate both solution methods based on the assumed modes and 1D finite element method, and we describe a Newmark-type integration scheme to compute the dynamic response of the beam. In Section 4, we specialize our results to vinyl ester resins and verify model findings against 2D finite element simulations. A parametric study is also conducted to identify the role of salient nondimensional numbers on the dynamic response of the beam. In Section 5, the main conclusions of this theoretical study are summarized, identifying potential, indirect, experimental evidence that support our claims. Therein, we also lay out a plan for future experimental validation. Further, in