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One-dimensional analytical model for the response of elastic coatings to water blast

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ABSTRACT

In previous studies, the response of sandwich structures to water blast is solved by envisaging the plate adjacent to water as a rigid one, while the effects of the elasticity in the longitudinal direction of the plate are rarely studied. In this paper, a monolithic elastic coating with varying stiffness and thickness is investigated by a one-dimensional analytical approach, based on linear wave motion theory, to reveal the elastic effect of the plate on the incident wave. One side of the coating is loaded by a planar shock wave; on the opposite side, rigid boundary or air-backed boundary is imposed. The fluid–structure interaction (FSI), cavitation phenomenon and large deformation of the coating are taken into account. In particular, the initiation and evolution of cavitation, including the propagations of breaking fronts and closing fronts, as well as the pressure histories of radiated wave by the closing front, are examined. The analytical solution has been compared with finite element (FE) predictions. The results are found to be in excellent agreement for the propagation of breaking front and closing front, as well as the pressure and particle velocity histories at the wet face before the cavitation reaches the wet face. However, when the wet face cavitates, the predictions provided by the analytical method are less accurate and the analytically-computed particle velocity can only be compared in an average sense with the FE predictions. For air-backed case, Taylor's model prior to cavitation becomes a trivial case of the analytical model and the comparison also indicates the validity of the analytical model. The validated analytical model is used to determine the dependence of the peak pressure at the wet face and the impulse transmitted to the coating on the coating properties, including the wave impedance and thickness.

1. Introduction

Nowadays, design of protective structure is of great interests for naval industries. Many protective structures exist for different purposes, including shock/vibration isolation, and sound isolation/absorption, etc. Concerning resistance to underwater blast, there are two aspects to assess the performance of the shock-isolation structures: (i) the effects of such structures on incident wave and (ii) the ability of the structures to store/absorb energy. This paper mainly focuses on the former.

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The first aspect, i.e. the effect of the fluid–structure interaction (FSI), results in a series of complex physical processes, including the wave propagation in different mediums, the deformation of the coating and the cavitation in water. Early theoretical work on this issue dates back to World War II. Taylor (1963) first obtained the solution for a one-dimensional free-standing rigid plate and demonstrated that the momentum transmitted to a rigid plate was reduced greatly due to FSI effects. On the basis of the Taylor's model and its modifications, there are also many theoretical works investigating the response of the protective structure (Fleck and Deshpande, 2004; Xue and Hutchinson, 2004; Deshpande and Fleck, 2005; Liang et al., 2007; McMeeking et al., 2008; Chen et al., 2010; Schiffer et al, 2012; Schiffer and Tagarielli, 2014a). The main feature of these models is that the front face sheet adjacent to water was treated as a rigid one during the loading phase. Generally, the elastic stress waves propagating in the longitudinal direction exist (Reid and Zhou, 2000) for a protective structure. Though the elastic wave does not affect substantially the response of slender elastic plates (Schiffer and Tagarielli, 2014a), the longitudinal stress wave should be taken into consideration for the protective structure with soft elastic material or considerable thickness. The basic theories for the stress wave propagation in the elastic solid can be found in the book by Graff (1975). Hoo Fatt and Palla (2009) proposed a simplified method considering the elastic wave propagation for the case of composite sandwich plates loaded by a prescribed pressure history. Jin et al. (2014) developed an analytical model, based on the linear wave motion theory, to solve the response of elastic double-layer plate to underwater blast. In this model, the pressure jumps at each interface were given explicitly. However, the results can only precisely predict the response of double-layer plate prior to cavitation.

Cavitation plays a quite important role in FSI. The effect of FSI generates the cavitation; conversely, the cavitation may affect the FSI. A considerable amount of research has been conducted to explore this issue. Kennard (1943) described theoretically the cavitation in a bilinear elastic liquid. He found that when the pressure drops below the cavitation limit, cavitation initiates and the boundary of the cavitated region either advances as a breaking front, moving with supersonic velocity, or remains stationary as a free surface, or recedes towards the cavitated region as a closing front, moving with subsonic velocity. Bleich and Sandler (1970) analyzed the response of a rigid plate floating at the surface of a liquid subjected to blast waves by the method of characteristics in which the response of the fluid was described by a bilinear elastic model. Deshpande and Fleck (2005) treated the effect of cavitation by adding the momentum of an attached layer of water between the location of first cavitation and the front face sheet in their analytical model for the response of sandwich plate. The model accurately predicted the momentum transmitted to the sandwich plate at first cavitation; however, the estimation for effects of subsequent wave propagation was not adequate. Thereafter, a more elaborated analytical model which could consider the effects of the cavitated fluid further was developed by Liang et al. (2007) and McMeeking et al. (2008). In this analytical model, first cavitation initiated at a finite distance from the wet face; later on, the cavitation region expanded towards two opposite directions. The cavitated fluid adjacent to the wet face would form a reconstitution wave (closing front) if the cavitation front could not propagate towards the wet face anymore. The model can precisely predict the total momentum transmitted to the front face sheet, and the analytical results were found to be in excellent agreement with finite element (FE) simulations (Liang et al., 2007). Recently, Schiffer et al. (2012) explicitly modeled the propagation of cavitation fronts and closing fronts as well as their interactions with the structure, for the problem of a rigid plate supported by a linear spring, based on the theory of Kennard (1943). The analytical model provides a clear physical picture of initiation, evolution of the cavitation and their effects on the structure response. Later, the model was experimentally validated (Schiffer and Tagarielli, 2012, 2014b, 2015).

Theoretically revealing all the physical processes in underwater explosion problems is very difficult, especially for high-dimensional problems. Hence, numerical solvers are of great interests. Felippa and DeRuntz (1984) developed a cavitating acoustic finite element (CAFE) method. Later, Sprague and Geers (2003, 2004) improved CAFE method and developed a cavitating acoustic spectral element (CASE) method. The methodology of FE simulation performed in ABAQUS/EXPLICIT (2012) in this paper is on the basis of CAFE and CASE method. Nowadays, further improvement on numerical methods for multi-material/multiphase problem is made by many authors (Fedkiw et al., 1999; Liu et al., 2003; Xie et al., 2008; Zhang et al., 2013). Recently, Colicchio et al. (2011, 2015a, 2015b) and Greco et al. (2014) proposed an efficient one-way domain-decomposition strategy, coupling a radial and a three-dimensional solver for compressible multiphase flows. The radial solver was applied at any time in a sub-domain sufficiently far from the region where three-dimensional effects caused by FSI were important, while the three-dimensional solver was used to model the near-body flow. The domain-decomposition strategy significantly limits the computational costs with respect to using a compressible three-dimensional solver over the whole domain and for the entire time evolution, when the explosion bubble was far away from the solids boundaries or free surface.

Though numerical method has the characteristic of generality, analytical method reveals the underlying physics more clearly and is more convenient to perform a parameter analysis. There are few literatures hitherto investigating the response of elastic coatings loaded by underwater blast with an accurate and thorough understanding of the FSI effects. In this paper, we propose an analytical model, which can address the wave propagation in the coating, FSI and cavitation phenomenon, to analyze the effects of the coating elasticity on the incident wave. The theory of Kennard (1943) is adopted to model the details of cavitation in the fluid and its consequent effects on the coating's response. We identify regimes of cavitation behaviors for rigid boundary and air-backed case. According to these behaviors, theoretical predictions are compared with the results from the detailed FE calculations. Furthermore, the effects of the wave impedance and thickness of the elastic coating on the peak pressure and impulse imparted to the elastic coating are explored. Nondimensional performance charts are provided as an insight for the design phase of elastic coated structures exposed to the threat of an underwater blast.