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Blast response simulation of an elastic structure: Evaluation of the fluid–structure interaction effect

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ABSTRACT

Blast pressure wave interaction with an elastic structure is investigated using a numerical analysis approach, which considers fluid–structure interaction (FSI) within an Arbitrary Lagrange Euler (ALE) framework. Approximate numerical procedures for solving the Riemann problem associated with the shock are implemented within the Godunov finite volume scheme for the fluid domain. The structural displacement predicted by ignoring FSI is larger than the corresponding displacement considering FSI. The influence of the structural and blast pressure wave parameters on the importance of FSI is studied using an analysis of variables. Two non-dimensional parameters corresponding to the ratios of blast duration to the time period of the structure and the velocity of the structure to the particle velocity of the incident blast pressure wave are identified. It is shown that for a given blast pressure wave, the error in the maximum displacement predicted by ignoring FSI effect during structural motion is directly proportional to the ratio of the structure velocity to the particle velocity of the incident blast pressure wave. There is a continuous exchange of energy between the structure and air during the structural motion, which is significant when the structural velocity is significant compared to the particle velocity of incident blast pressure wave. FSI effect become insignificant when the ratio of velocities starts approaching zero.

1. Introduction

In typical air blast analysis, the blast over-pressure, which is determined as the reflected pressure of a fixed rigid surface is imposed on the structure as an external pressure loading with a known evolution in time [1]. The actual pressure variation is further simplified using triangular or exponential functions [1–5]. During the analysis, it is usually assumed that there is no coupling between the fluid and the solid and the response of the solid can be obtained independently of the fluid by directly prescribing a known pressure on to the structural element. The results presented in the literature broadly differ in the level of sophistication adopted for representing the structural element. A popular approach comprises of transient dynamic analysis of the structural element to a prescribed pressure time history using a numerical scheme such as the finite element method. The response of the structure is accurately represented using the appropriate elements and material models at high strain rates. Several examples of this approach for studying the blast response of structural elements such as slabs, walls and beams can be found in the literature [3–5]. The second approach recommended by the U.S. Department of Army in TM5-1300 [1], which is more practice-oriented, is based on substituting the structural element with an equivalent single degree-of-freedom (DOF) spring-mass system. The procedures for obtaining the equivalent stiffness and mass for the single DOF spring are reviewed in detail by Morison [6]. This rather simplistic approach is often preferred because it provides a satisfactory basis for studying the dynamic response of a structural element subjected to transient loading of short duration [7].

In recent years there has been considerable interest in evaluating the role of fluid–structure interaction (FSI) in the blast response of a structure. Fluid–structure interaction occurs when the blast pressure wave causes deformation of the structure and, thus alters the flow of the fluid. In an early attempt, Taylor (1963) studied the momentum transferred to a free-standing plate from a pressure wave with an exponential profile [8]. It was shown that changes in the reflected over-pressure are associated with movement of the boundary which results in a decrease in the

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transmitted impulse from the pressure wave to the free-standing plate. The use of compliant structures in mitigating the influence of underwater shock loading has been explored for developing sandwich-plate structure for improved blast performance [9,10]. The role of FSI, evaluated using Taylor's approach, was shown to be significant in decreasing the transmitted impulse in such structures. Taylor's approach, however, involves simplistic assumptions, such as, no change in the fluid density and linear superposition of waves, which are acceptable for studying weak shock waves. Such an approach is not suitable for studying the interaction of a strong shock wave in air blasts which involves non-linear, finite amplitude disturbances propagating in a compressible medium [11]. Recently, from a numerical evaluation of the response of a free-standing plate subjected to air blast it has been shown that the FSI effect in reducing blast impulse is significant only at large displacements, which limits its practical use [12]. These results however cannot be directly applied to the case of air blast response of structures, where the resistance to motion is derived from both inertial and stiffness effects. A careful evaluation of the role of the structural parameters on determining the influence of FSI in the dynamic response of a structure is required.

A blast pressure wave is associated with a leading shock front, which brings an abrupt finite pressure change, followed by decaying pressure. A simplistic understanding of the role of FSI when a blast pressure wave in a compressible fluid medium is incident upon the surface of a moving boundary can be obtained from the classical work of Courant and Friedrichs on shock waves [13]. In a moving shock wave, the leading shock front is followed by constant pressure. If the shock wave is incident on a fixed rigid boundary, it is assumed a pressure P_{ro} is developed on the surface of the boundary immediately following the reflection of the leading shock front. If the boundary starts to move with a velocity, V_b, the motion of the boundary would alter the pressure at its surface. The relation between the resultant pressure amplitude at the face of the moving boundary, P'_{ro} and the velocity of the boundary, V_b is related by the simple wave relation, given as

$$\frac{P'_{ro}}{P_{ro}} = \left(1+\frac{\gamma-1}{2}\frac{V_b}{a_r}\right)^{\frac{2\gamma}{\gamma-1}} \qquad (1)$$

where a_r is the local sound velocity after the reflected shock, which, can be shown to monotonically increase with the intensity of the shock wave and γ is the ratio of heat capacities of air [13, p. 95]. When the motion of the boundary is away from the direction of reflected shock front, for V_b less than a_r, there will be a decrease in the resultant pressure at the face of the moving boundary, when compared with P_{ro}.

From the simplistic analysis it appears that the pressure on the surface of a moving boundary is dependent on its velocity. If the blast pressure wave is incident on an elastic structure, the velocity of the structure would depend upon the applied pressure loading history and structural parameters such as stiffness and mass. This therefore presents a coupled fluid–structure problem, where the movement of the structure influences the applied pressure, which in turn effects its movement. It is clear that when a blast pressure wave is incident on an elastic structure, the role of FSI depends upon both the blast wave and structural parameters. Conventional analysis ignores this interaction and the reflected pressure obtained from a fixed rigid wall, which assumes that the boundary does not move during the time associated with the passage of the blast wave, is directly prescribed on the structure.

There are some important questions which remain unanswered, such as: (1) when is the FSI effect in air blast incidence on a structure important? (2) what is the error in ignoring the air blast–structure interaction in terms of the predicted stresses and amplitude of displacements in the structural element? and (3) what are the structural and blast parameters which help to decide when the role of FSI is important? Answers to these questions are investigated using a single DOF spring-mass system within a framework which considers the change in the fluid domain due to the deformation of the solid and the variation in the blast overpressure due to movement of the solid–fluid boundary. A numerical analysis framework for predicting the response of a 1-DOF structure, which considers solid–fluid interaction within an Arbitrary Lagrange Euler (ALE) framework, was developed. An accurate Riemann Solver with appropriate spatial and temporal discretization was implemented for capturing the singularity associated with the shock. Numerical simulations were performed to study the interaction between a blast pressure wave and an elastic structure.

2. Objectives

The objectives of this paper are:

1. To develop a numerical framework for studying the response of an elastic structure subjected to an incident blast pressure wave considering FSI.
2. To determine the relationship between the structure and blast parameters for which the influence of FSI is important.
3. To develop a procedure to estimate the difference between the structural response parameters when FSI is not considered in the analysis.

3. Problem statement

The FSI was studied using a 1-DOF structure placed in the path of an incoming blast pressure wave generated using a shock-tube arrangement as shown in Fig. 1. A spring-mass system was used to represent the elastic structure. The mass is idealized as a piston in the path of an incoming shock front (Fig. 1a). The piston is assumed to fit perfectly inside the tube, which is frictionless. In this one-dimensional idealization, the shock front is planar and there is no flux of air perpendicular to the direction of blast wave propagation. The analysis is performed considering

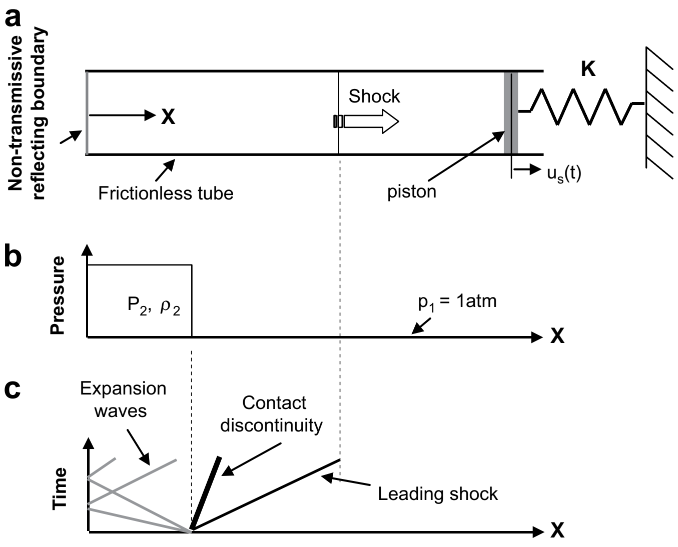

Fig. 1. The configuration used for evaluating 1-D response of the structure subjected to blast pressure wave: (a) initial conditions for creating the blast pressure wave; (b) X–*t* diagram showing the formation of the blast pressure wave; and (c) the spring-mass system in a shock-tube arrangement.