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Numerical simulation of the fluid–structure interaction between air blast waves and free-standing plates

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Abstract

A numerical method is used to compute the flow field corresponding to blast waves of different incident profiles propagating in air and impinging on free-standing plates. The method is suitable for the consideration of compressibility effects in the fluid and their influence on the plate dynamics. The history of the pressure experienced by the plate is extracted from numerical simulations for arbitrary blast strengths and plate masses and used to infer the impulse per unit area transmitted to the plate. The numerical results complement some recent analytical solutions in the intermediate range of plate masses and arbitrary blast intensities where exact solutions are not available. The resulting beneficial effect of the fluid–structure interaction (FSI) in reducing transmitted impulse in the presence of compressibility effects is discussed. In particular, it is shown that in order to take advantage of the impulse reduction provided by the FSI effect, large plate displacements are required which, in effect, may limit the practical applicability of exploiting FSI effects in the design of blast-mitigating systems.
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1. Introduction

Recently there has been significant interest in understanding the influence of fluid–structure interaction (FSI) on the blast loading of structures. It was shown in the pioneering work of Taylor [1], that FSI reduces the amount of impulse transmitted to free-standing plates and that this effect is more pronounced for lighter plates. The reduction of transmitted impulse is due to the pressure relief experienced by the structure caused by its motion. Taylor's analysis is restricted to the linear case of incident blast waves of exponential profile in which the pressure wave does not cause any significant changes in the fluid density. This assumption is applicable in the case of underwater explosions, as the pressure level required for water to undergo non-negligible compressibility effects is in the order of 100 kbar, which exceeds conventional situations. The beneficial influence of FSI in potentially mitigating the effect of blast has recently been explored as a basis for the design of sandwich structures with increased blast resistance [2–10].

Although the compressible case is not amenable to analytic treatment for the whole range of plate masses and blast intensities regardless of the blast wave profile, the authors have recently derived some results in the asymptotic limits of very heavy and very light plates for the cases of uniform [11] and exponential [12] incident blast profiles. It is important to emphasize that although the uniform profile has some interest due to its analytic tractability and the exponential profile because it presumably provides a reasonable approximation to blast waves [13,14], neither profile does actually correspond to the exact solution of a blast wave caused by a point explosion, which was derived in closed (implicit) form by von Neumann [15]. Although

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the simplified exponential pressure profile is attractive due to its simplicity, it is not suitable for initializing the flow in numerical simulations, as it is not clear what the corresponding density and velocity fields consistent with the governing differential equations of compressible flow are.

In this paper, we use a numerical method to conduct simulations of the interaction between blast waves of different profiles and intensities with free-standing plates of varying mass. The method is based on a Lagrangian formulation of the equations of compressible flow. In the Lagrangian framework, the dynamic response of the plate and its interaction with the flow can be simply modeled by modifying the governing equations and adding the plate's mass at the material location of the plate. Following the classic approach of von Neumann and Richtmyer [16], a shock capturing scheme based on artificial viscosity is adopted. The numerical method is verified by comparisons with exact solutions in the acoustic and non-linear compressible range in the asymptotic limits where exact solutions have been derived [12,11]. Special attention is then paid to the computation of blast-structure interaction in the intermediate asymptotic range of plate masses where exact solutions are unavailable. The analysis includes the cases of uniform, exponential and planar explosion (von Neumann–Sedov) profiles. The analysis of the role of the structure supports has been omitted purposely, in an attempt to isolate and highlight the role of FSI on impulse transmission to structures, as was originally done by Taylor but in the case of a compressible fluid. Clearly, the role of the supports is to reduce the momentum acquired by the structure, at the expense of creating possible large reaction forces.

The numerical calculations play an important role in complementing recent analytical work [12,11] by providing the necessary values of transmitted impulse which, in combination with the asymptotic results, are used for the development of practical formula encompassing the whole range of behavior.

This paper is organized as follows: In Section 2, the continuum problem is formulated and the numerical method employed is described. Section 3 is devoted to the presentation of numerical results including verification cases and applications. The paper concludes in Section 4 with a summary of findings and conclusions.

2. Problem statement and numerical approach

The problem of interest concerns the interaction of a shock wave traveling in compressible medium with a free-standing plate of thickness h_p and density ρ_p (Fig. 1). The plate is positioned initially at $x = 0$ while the fluid medium on its left side is assumed to be an ideal calorically-perfect gas at rest with density ρ_0 and pressure p_0. A constant pressure p_0 is applied on the right (free) side of the plate at all times in order to balance the loading until the arrival of the wave. Three different wave shapes are considered: uniform, exponential and planar explosion.

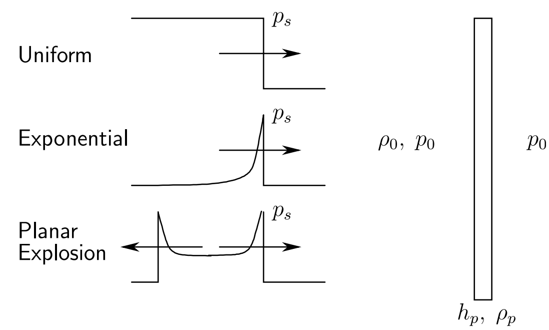

Fig. 1. Problem of interest: a wave with peak overpressure p_s traveling through medium with properties p_0 and ρ_0 impinges on a free plate of thickness h_p and density ρ_p. Initial load balance until the shock arrival is provided by the pressure p_0 applied on the right side of the plate.

The quantities of interest are the pressure histories on the plate's surface, the displacement, velocity and impulse of the plate.

In order to facilitate the description of the dynamics of the plate a Lagrangian formulation for the fluid motion is adopted. In the Lagrangian framework, the continuum equations governing the problem are:

- The kinematic relations for the material velocity and acceleration:

$$V = \frac{\partial x}{\partial t} \quad \text{and} \tag{1}$$

$$A = \frac{\partial V}{\partial t}, \tag{2}$$

  where the Eulerian coordinate x, the velocity V and acceleration A of a material particle are functions of the Lagrangian coordinate X and the time t.
- The momentum conservation equation:

$$\rho_0 A = -\frac{\partial p}{\partial X}, \tag{3}$$

  where ρ_0 is the initial density of the particle with Lagrangian coordinate X and p is the pressure.
- The equation of state, which is modified to include a viscous dissipation term Q:

$$p = \rho R T - Q = (\gamma - 1)\rho_0 \frac{e}{F} - Q, \tag{4}$$

  where R is the ideal gas constant, T is the absolute temperature, $\gamma = \frac{C_p}{C_v}$ is the specific heat ratio, where C_p and C_v are the specific heats at constant pressure and volume, $e = C_v T$ is the internal energy and $F = \frac{\partial x}{\partial X}$ is the deformation gradient. The viscous dissipation term is required for stabilization of the numerical scheme and consists of the original quadratic term of von Neumann and Richtmyer [16] and a linear term due to Kuropatenko [17]:

$$Q = \begin{cases} -\rho_0 (K_1 D \Delta)^2 - \rho_0 a_0 K_2 |D| \Delta, & D < 0, \\ 0, & D \geqslant 0, \end{cases} \tag{5}$$

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