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Euler–Lagrange simulation of high pressure shock waves

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HIGHLIGHTS

- We couple Eulerian and Lagrangian FEM to model high pressure generating processes.
- We apply the multi-material Eulerian technique to model air-blast and to predict shock wave propagation.
- We model the overdriven detonation using the penalty method.
- The Euler–Lagrange coupling is shown to manage shock–structure interaction problems.

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ABSTRACT

This paper presents the numerical simulation of overdriven detonation (or O.D.D.) that occurs when a high velocity object impacts an explosive. The pressure and the velocity at this state are higher than those of the Chapman–Jouguet (C–J) state. First, before the simulation of this event, a study of PBX air blast by using multi-material Eulerian method is presented. Pressure peaks are computed for several distances from the explosive. Second, the O.D.D. phenomenon is modeled by the Euler–Lagrange penalty coupling, which permits to couple a Lagrangian mesh of the flyer plate to multi-material Eulerian mesh of explosives and air. This coupling gives us the high detonation velocities in the acceptor explosive and demonstrates that it is able to handle shock–structure interaction problems.

1. Introduction

The application of shock waves in the industrial sector has increased significantly in recent years. For example, the food processing by using shock wave [1,2] is an interesting alternative to the usual heat treatment. This high pressure processing better preserves the food nutrients for a lower cost in energy and time. The explosion welding is another application in the industry [3]. The large energy of these blast loads can also alter the physical properties of some materials like the Sugi wood [4,5]. The permeability and strength of the wood have been showed to be improved after being subjected to an underwater shock wave. These examples are just a few among many other applications. Controlling and improving the shock waves processing has become necessary to meet the industrial demands.

The experimental approach can be used to cope with these requirements. However, experiments are often costly in terms of time and resources, and it is sometimes difficult or impossible to achieve them. Several numerical methods have been developed to solve these problems, which require often to deal with fluid–structure interaction. Many of these problems require to solve interactions between compressible flow and structures. A contact coupling method can be used, where

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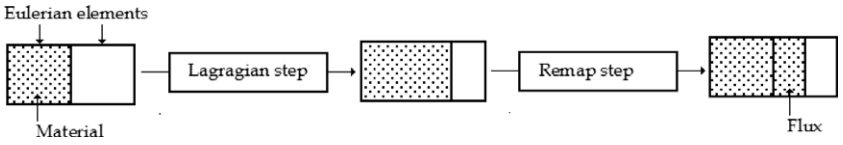

Fig. 1. Split of the time step for an Eulerian method.

both the fluid and structure are discretized by Lagrangian finite elements. This method is suitable for materials with small deformations. However, for fast and dynamic problems like explosions, the Lagrangian method is not appropriate to model the fluid because the severe mesh distortion reduces the accuracy of the solution. In this case, the Euler–Lagrange coupling is used. In this approach, there is no fluid mesh distortion because the mesh is fixed and the material flows through the elements, while the structure is modeled as Lagrangian.

The overdriven detonation is a technique that creates high shock waves. This phenomenon occurs when a metal plate accelerated by the detonation of a first explosive called donor hits a second explosive called acceptor. While the shock wave travels in the donor at a speed limited by the Chapman–Jouguet (C–J) conditions, the high velocity impact of the plate against the acceptor creates a shock wave with speed much higher than the C–J detonation. Experimental results of this approach are carried out by Otsuka et al. [6].

The Euler–Lagrange solvers allow to deal with fluid–structure interaction problems. In this study, an explicit solver LS-DYNA® is used to simulate the overdriven detonation. The ALE formulation implemented in this solver divides each time step into Lagrangian and remap steps. A method applying both steps is usually referred as Eulerian or ALE (Arbitrary Lagrange Euler) while a Lagrangian method is limited to the first step. During the Lagrangian step, the nodal accelerations are calculated from the nodal forces and the nodal masses. The nodal velocities and nodal displacements are calculated from these accelerations. The aim of the second step is to manage this mesh deformation. For materials undergoing large deformations, it is suitable to use the Eulerian formulation. Explosives have large velocities and the mesh can be highly distorted after a few computational time steps. However, a structure like the plate in the overdriven detonation usually has small deformations. So the Lagrangian calculation is sufficient to solve structure dynamics. In an Eulerian method, the remap, or advection step allows the mesh to move back to its initial position as sketched in Fig. 1. The volumes transported between the current and original elements are fluxes and are calculated by a finite volume code. Advection methods such as donor cell or Van Leer scheme are used to determine the transport of physical quantities like mass, momentum, and energy from one element to its neighbors.

The Eulerian method is referred as multi-material. As different materials can be in one element, it is necessary to locate the material interface for the advection. The Youngs method [7] is used to follow the material interfaces by calculating the slope given by the gradient of the volume fractions. Then a finite element code can solve the structure and explosive dynamics during the Lagrangian step. A remap step for the explosive resets the mesh to its initial position and solves the transport problem.

The Lagrangian and remap steps are presented in a Section 2 to better understand the equations and the numerical approaches. A computer study of bomb blast was performed using the multi-material Eulerian formulation in LS-DYNA®. Section 3 describes the contact and Euler–Lagrange coupling methods that deal with the fluid–structure interaction. Section 4 is dedicated to the numerical simulation of the overdriven detonation. The plate and explosive dynamics are respectively solved by the Lagrangian and Eulerian methods and their meshes are distinct. A penalty method is applied to couple these two different computational domains.

2. Lagrangian and Eulerian methods

The Lagrangian approach is used to model fluids with small motion and structures. While when the flow of fluid undergoes large motions, the Eulerian description is appropriate. The ALE method combines the use of these two methods. For example, this technique is recommended when studying structures with large deformations. Thus a description of the multi-material ALE formulation is first presented. Then the Lagrangian method, which is also the first step in the Eulerian formulation, is described. Finally the Eulerian method is presented.

2.1. ALE description of the conservation laws

In the ALE approach, three states are considered [8]: the material domain noted M, the reference domain (or ALE domain) noted R and the spatial domain noted S. The material motion is defined by the map $\vec{\vartheta}$ between the material and spatial domains as shown in Fig. 2. The mesh motion is defined by the map $\vec{\varphi}$ between the reference and spatial domains. The material motion in the referential coordinate system is determined by the map $\vec{\psi}$ between the material and reference domains. The conservation equations are written by Eqs. (1)–(3).

$$\frac{d\rho}{dt} + \rho\, div\,(\vec{v}) = 0 \tag{1}$$