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Multi-domain simulations of shock wave interaction with aerodynamic obstacles in cylindrical implosions

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ABSTRACT

A multi-domain finite-volume approach is presented to simulate the interaction of converging shock waves and aerodynamic obstacles for dilute gases. The so-called reshaping process, in which the cylindrical shock is reshaped into a polygonal shock due to the presence of obstacles along the shock path, is studied. To accurately capture the diverse spatial scales of the problem, the computational domain is divided into three sub-domains, namely, the far-field region, the obstacle region and the focus region. Shock propagation in the far-field region is simulated under the axisymmetric, namely, one-dimensional approximation. The obstacle region is described by a fully two-dimensional model, in which initial conditions are interpolated from the far-field. The solution in the obstacle region is then interpolated into the focus region surrounding the center of the imploding shock. These two regions partially overlap to allow for linear interpolation. Numerical results are presented for air in dilute conditions and for four, eight, sixteen and twenty four aerodynamic obstacles. The proposed multi-domain solution technique is found to be capable of describing the complex gas dynamics of the shock propagation and reshaping, while reducing the computational burden for a large number of obstacles of one order of magnitude with respect to fully two-dimensional simulations.

1. Introduction

The knowledge about converging shock waves is relevant to both theoretical gas dynamics – in e.g. the study of the instability of the shock front and of sonoluminescence – and to industrial applications, including Inertial Confinement Fusion (ICF) [1]. In ICF applications, large values of temperature and pressure are required to trigger thermonuclear reactions and are expected to be observed in the close proximity of the shock focus point. Unfortunately, to attain high energy concentration at the focus point, it is mandatory to cope with the intrinsic instability of imploding cylindrical shock waves. Shock front instability may be triggered in certain thermodynamic [2] or flow [3] conditions. The main consequence of the deviation of the shock shape from regularity is a reduction of its effectiveness in terms of the maximum values of the pressure and temperature at the focus point.

To prevent the onset of shock instabilities, one can force the shock to interact with a number of obstacles placed along its propagation path. The multiple reflections of the shock eventually modify its shape into a more stable one. For symmetrically arranged and suitably shaped obstacles, the final shock shape is prismatic, which corresponds to a more stable configuration [4,5]. On the other hand, the obstacle arrangement is to be optimized to reduce losses due to shock/obstacle interaction [6]. Numerical simulations were used to determine the optimal design of the obstacle shape and arrangements.

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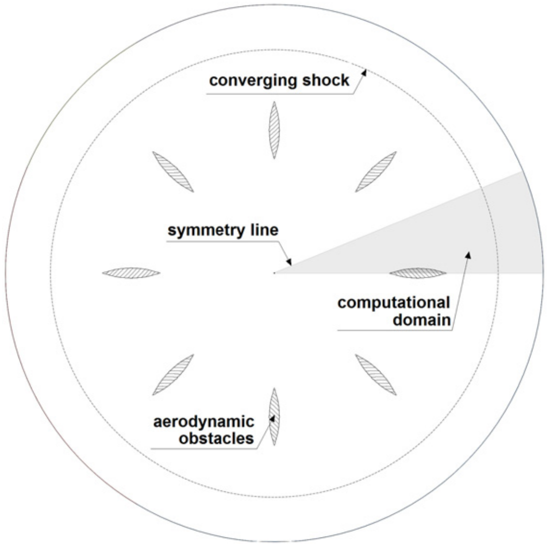

Fig. 1. Sketch of the problem geometry. The shaded region is the computational domain corresponding to the obstacle region.

In particular, aerodynamic obstacles were proposed to reduce shock/obstacle interaction losses [7]. Due to the diverse time and space scales involved, the numerical simulations of the reshaping process and shock focusing are not trivial.

In the present work, a multi-domain approach is proposed to reduce the computational effort required by shock reshaping simulations while preserving an overall accuracy that is sufficient to capture the relevant flow features, including the temperature peak at the focus point. Differently from Ref. [4], where the complete configuration is simulated, the diverse symmetries of the problem are exploited here in order to reduce the size of the computational domain: a one-dimensional axisymmetrical simulation is performed far from the obstacle region where the implosion can be represented by a shock wave with cylindrical symmetry. Then, two concentric two-dimensional numerical domains are used to represent respectively the reshaping phenomenon, which is the core of the investigation, and the focusing of the shock at the origin. Each simulation is initialized with the results of the previous one. To this purpose, a 1D/2D and a 2D/2D interpolation procedure is devised and implemented in the FlowMesh software of the Department of Aerospace Science and Technology of Politecnico di Milano [8,9]. In the FlowMesh solver, the fluid-dynamic governing equations are solved in the Arbitrary Eulerian–Lagrangian formulation, based upon a Finite Volumes space discretization.

This paper consists of three sections: the first one presents an overview of the physical problem and of its most relevant features. Section 2 illustrates the procedure adopted in the setup of the numerical simulations, with particular reference to the decomposition of the problem and the interface-matching technique. Section 3 presents numerical results obtained by applying the different strategies to the simulation of the reshaping of cylindrical shocks. In the last section, final remarks and future development of the present work are presented.

2. Physics of the interaction process

The present section briefly outlines the relevant features of the physical problem of interest. The obstacle arrangement and an overview of the considered problem geometry are depicted in Fig. 1, where the three-dimensional cylindrical shock front is represented in a two-dimensional plane that is normal to the symmetry axis. In Fig. 1, the dashed line indicates the shock position before interacting with the obstacle leading edges. As it moves towards the origin, the shock interacts with the aerodynamic obstacles which are placed around the origin in a symmetric fashion. The final goal is to reshape the curved shock wave into a polygonal shock, whose piece-wise straight front is more stable with respect to surface corrugations [10]. According to previous investigations [5], the best results are obtained for symmetrical obstacle arrangements. In this case, the number of edges of the final configuration is equal to the number of obstacles (or twice as many) and the vertices of the polygonal shock are located along symmetry lines, namely, along the obstacle axes or the median lines separating each couple of obstacles.

Thanks to the symmetric arrangement of the obstacles, the shock dynamics can be conveniently described in a reduced domain, labeled sub-domain in Fig. 1, which spans an angular sector of π/n_{obs}—where n_{obs} is the number of obstacles.

In Fig. 2, the reflection patterns causing the shock reshaping are sketched. The first reflection occurs at the obstacle leading edge (Fig. 2(a)) and for the investigated obstacle geometry it is known to be of Mach type, characterized by the presence of a triple point, moving towards the median symmetry line, where the incident shock front and the two reflected waves (the Mach stem and the simple reflection, namely wave A) intersect. The second step is the reflection at the symmetry surface (Fig. 2(b)), which produces a second Mach reflection followed by a second simple reflection, identified as wave B (Fig. 2(c)).