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Fluid–solid coupled simulation of the ignition transient of solid rocket motor

Qiang Li*, Peijin Liu, Guoqiang He

Science and Technology on Combustion, Internal Flow and Thermal-Structure Laboratory, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, PR China

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ABSTRACT

The first period of the solid rocket motor operation is the ignition transient, which involves complex processes and, according to chronological sequence, can be divided into several stages, namely, igniter jet injection, propellant heating and ignition, flame spreading, chamber pressurization and solid propellant deformation. The ignition transient should be comprehensively analyzed because it significantly influences the overall performance of the solid rocket motor. A numerical approach is presented in this paper for simulating the fluid–solid interaction problems in the ignition transient of the solid rocket motor. In the proposed procedure, the time-dependent numerical solutions of the governing equations of internal compressible fluid flow are loosely coupled with those of the geometrical nonlinearity problems to determine the propellant mechanical response and deformation. The well-known Zeldovich–Novozhilov model was employed to model propellant ignition and combustion. The fluid–solid coupling interface data interpolation scheme and coupling instance for different computational agents were also reported. Finally, numerical validation was performed, and the proposed approach was applied to the ignition transient of one laboratory-scale solid rocket motor. For the application, the internal ballistics were obtained from the ground hot firing test, and comparisons were made. Results show that the integrated framework allows us to perform coupled simulations of the propellant ignition, strong unsteady internal fluid flow, and propellant mechanical response in SRMs with satisfactory stability and efficiency and presents a reliable and accurate solution to complex multi-physics problems.

1. Introduction

The ignition transient of solid rocket motor (SRM) operation is complex, and it involves time-dependent processes that advance in time in a strongly coupled manner [1,2]. For example, in a real-world SRM with complex propellant configuration, the hot igniter jet injected from the igniter flows down the chamber bore and heats up the solid propellant. Once the propellant surface temperature reaches the critical temperature, the propellant is ignited locally, and high-temperature gaseous combustion products are released from the propellant surface and injected into the combustion chamber. The time-dependent internal flow field, propellant heating and ignition, and flame spreading are fully coupled because the development of the internal flow field in the combustion chamber governs the convective and radiative heat transfer from the high-temperature combustion products to the propellant solid and the propellant ignition, which determines the flame spreading speed and the propellant burning surface ignition sequence, and in turn,

* Corresponding author. Fax: +86 2988494163.
E-mail address: leeqiang@nwpu.edu.cn (Q. Li).

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the evolution of the internal flow field. Furthermore, in the ignition transient, the motor chamber pressurization loadings applied on the propellant surface cause deformations to the solid propellant that change the geometrical configurations of both the fluid subdomain and the solid subdomain. Thus, the development of internal flow field and the mechanical response of the propellant are tightly coupled.

Previous studies that have investigated the ignition transient of SRMs can be classified into two main categories. In the first category, the internal flow fields in the motor ignition transient were numerically simulated with propellant ignition models of different complexities, and the mechanical responses of the solid propellant were not considered [1–3]. In the second category, the unsteady numerical calculations of the motor ignition transient were not conducted, and the mechanical responses of the solid propellant were simulated with different ignition pressurization loadings [4–6] that were applied on the propellant burning surface. These previous works serve as valuable references values by establishing novel scientific ideas that future studies could apply both in their methodology and theoretical analysis. However, few studies have been reported on the fluid–solid fully coupled simulation of the motor ignition transient.

The key problems for fluid–solid fully coupled simulation of the SRM ignition transient consist of a precise and robust solver for the strong unsteady compressible flow; an ignition model with satisfactory accuracy for predicting the ignition sequence of the propellant burning surface and flame spreading in the chamber; a mesh smoothing technique for maintaining and improving the quality of unstructured volume meshes with severe deformations; an interpolation scheme with satisfactory accuracy and low cost for interpolating data conservatively across the fluid–solid coupling interfaces; and a coupling procedure for handling the coupling of different agents (fluid flow, solid mechanics, propellant ignition, and fluid–solid coupling interface data transfer) at different time and spatial scales as well as for improving the stability and efficiency of the simulations [7].

This study focuses on the mathematical models and numerical strategies for the fluid–solid fully coupled simulation of the ignition transient of SRM. The remainder of this paper is organized as follows. Section 2 revisits the governing equations and numerical methods employed for the compressible flow and solid mechanics in SRMs. Section 3 introduces the ignition model used. Section 4 documents the fluid–solid coupling procedure. Section 5 reports the validation of the numerical strategies and the application and numerical results of a laboratory-scale SRM.

2. Governing equations and numerical methods

2.1. Fluid subdomain

In the fluid–solid coupled simulation of the motor ignition transient, the governing equations for the fluid flow must be formulated to address the compressible flow on moving meshes caused by the dynamic changes in the fluid subdomain geometry.

The application of the arbitrary-Lagrangian–Eulerian (ALE) formulation allows computation of these equations. The set of governing equations for the compressible viscous flow in the ALE formulation can be expressed as [8–11]

$$\frac{\partial}{\partial t}\int_{\Omega} \mathrm{U}\, d\Omega + \oint_{\partial\Omega} \mathrm{F}_c\, dS = \oint_{\partial\Omega} \mathrm{F}_v\, dS \tag{1}$$

where Ω is the control volume, $\partial\Omega$ is the boundary of Ω, U is the vector of the conservative variables, and F_c is the convective flux vector and can be written as follows:

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{bmatrix} \tag{2}$$

$$\mathrm{F}_c = \begin{bmatrix} \rho V \\ \rho u V + n_x p \\ \rho v V + n_y p \\ \rho w V + n_z p \\ \rho H V + V_g p \end{bmatrix} \tag{3}$$

where ρ and p are the fluid density and pressure; $u,\ v,\ w$ are the fluid velocity components; and V is the velocity of fluid flow relative to the computational mesh and can be expressed by the following equation:

$$V = n_x u + n_y v + n_z w - V_g \tag{4}$$

where n_x, n_y, and n_z are the unit normal vector components of the control volume face; V_g is the grid velocity in the normal direction of the control volume face; E is the specific total energy of the fluid; and H is the specific stagnation enthalpy of the fluid. The viscous flux vector can be written as follows:

$$\mathrm{F}_v = \begin{bmatrix} 0 \\ n_x\tau_{xx} + n_y\tau_{xy} + n_z\tau_{xz} \\ n_x\tau_{yx} + n_y\tau_{yy} + n_z\tau_{yz} \\ n_x\tau_{zx} + n_y\tau_{zy} + n_z\tau_{zz} \\ n_x\theta_x + n_y\theta_y + n_z\theta_z \end{bmatrix} \tag{5}$$

where τ_{ij} represents the viscous stresses. It can be written as follows:

$$\tau_{ij} = \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) - \left(\frac{2\mu}{3}\right)\frac{\partial v_k}{\partial x_k}\delta_{ij} \tag{6}$$

Moreover,

$$\begin{aligned} \theta_x &= u\tau_{xx} + v\tau_{xy} + w\tau_{xz} + k\frac{\partial T}{\partial x} \\ \theta_y &= u\tau_{yx} + v\tau_{yy} + w\tau_{yz} + k\frac{\partial T}{\partial y} \\ \theta_z &= u\tau_{zx} + v\tau_{zy} + w\tau_{zz} + k\frac{\partial T}{\partial z} \end{aligned} \tag{7}$$

are terms describing the work of viscous stresses and heat conduction in the fluid. In this paper, μ and k are the viscosity and thermal conductivity of the combustion gases in the SRM, T is the fluid temperature and δ_{ij} is the Dirac function. For the governing equations, the Spalart–Allmaras one-equation turbulence model, which is of satisfactory