Solid Rocket Motor Combustion Instability Modeling in COMSOL Multiphysics® Software

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Abstract

Combustion instability modeling of Solid Rocket Motors (SRM) remains a topic of active research. Many rockets display violent fluctuations in pressure, velocity, and temperature originating from the complex interactions between the combustion process, acoustics, and steady-state gas dynamics. Recent advances in defining the energy transport of disturbances within steady flow-fields have been applied by combustion stability modelers to improve the analysis framework [1, 2, 3]. Employing this more accurate global energy balance requires a higher fidelity model of the SRM flow-field and acoustic mode shapes. The current industry standard analysis tool utilizes a one dimensional analysis of the time dependent fluid dynamics along with a quasi-three dimensional propellant grain regression model to determine the SRM ballistics. The code then couples with another application that calculates the eigenvalues of the one dimensional homogenous wave equation. The mean flow parameters and acoustic normal modes are coupled to evaluate the stability theory developed and popularized by Culick [4, 5]. The assumption of a linear, non-dissipative wave in a quiescent fluid remains valid while acoustic amplitudes are small and local gas velocities stay below Mach 0.2.

The current study employs the COMSOL Multiphysics® software and its finite element framework to model the steady flow-field parameters and acoustic normal modes of a generic SRM.

This work builds upon previous efforts to verify the use of the acoustic velocity potential equation (AVPE) laid out by Campos [6, 7]. The acoustic velocity potential (ψ) describing the acoustic wave motion in the presence of an inhomogeneous steady high-speed flow is defined by,

$$\nabla^2 \psi - (\lambda/c)^2 \psi - M \cdot [M \cdot \nabla(\nabla \psi)] - 2(\lambda M/c + M \cdot \nabla M) \cdot \nabla \psi - 2\lambda \psi [M \cdot \nabla(1/c)] = 0 \quad (1)$$

with M as the Mach vector, c as the speed of sound, and λ as the complex eigenvalue. The study requires one way coupling of the High Mach Number Flow (HMNF) and mathematics models. The HMNF model evaluates the gas flow inside of a SRM using St. Robert's law to model the solid propellant burn rate, slip boundary conditions, and the supersonic outflow condition. Results from the HMNF model are verified by comparing the pertinent ballistics parameters with the industry standard code outputs (i.e. pressure drop, axial velocity, exit velocity). These results

are then used by the coefficient form of the mathematics model to determine the complex eigenvalues of the AVPE. The mathematics model is truncated at the nozzle sonic line, where a zero flux boundary condition is self-satisfying. The remaining boundaries are modeled with a zero flux boundary condition, assuming zero acoustic absorption on all surfaces. The one way coupled analysis is perform four times utilizing geometries determined through traditional SRM modeling procedures.

The results of the steady-state CFD and AVPE analyses are used to calculate the linear acoustic growth rate as is defined by Flandro and Jacob [2, 3]. In order to verify the process implemented within the COMSOL software we first employ the Culick theory and compare the results with the industry standard. After the process is verified, the Flandro/Jacob energy balance theory is employed and results displayed.

Reference

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Figures used in the abstract

Figure 1

Figure 2

Figure 3

Figure 4