Mean Flow Augmented Acoustics in Rocket Systems

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Abstract

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Oscillatory motion in solid rocket motors and liquid engines has long been a subject of concern. Many rockets display violent fluctuations in pressure, velocity, and temperature originating from the complex interactions between the combustion process and gas dynamics. The customary approach to modeling acoustic waves inside a rocket chamber is to apply the classical inhomogeneous wave equation to the combustion gas. The assumption of a linear, non-dissipative wave in a quiescent fluid remains valid while the acoustic amplitudes are small and local gas velocities stay below Mach 0.2. The converging section of a rocket nozzle, where gradients in pressure, density, and velocity become large, is a notable region where this approach is not applicable. The expulsion of unsteady energy through the nozzle of a rocket is identified as the predominate source of acoustic damping for most rocket systems. An accurate model of the acoustic behavior within this region where acoustic modes are influenced by the presence of a steady mean flow is required for reliable stability predictions. Recently, an approach to address nozzle damping with mean flow effects was implemented by French [1]. This new approach extends the work originated by Sigman and Zinn [2] by solving the acoustic velocity potential equation (AVPE) formulated by perturbing the Euler equations [3]. 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.

French applies the finite volume method to solve the steady flow field within the combustion chamber and nozzle with inviscid walls. The complex eigenvalues and eigenvector are determined with the use of the ARPACK eigensolver. The present study employs the COMSOL Multphysics® framework to solve the coupled eigenvalue problem using the finite element approach. The study requires one way coupling of the CFD High Mach Number Flow (HMNF) and mathematics interfaces. The HMNF interface evaluated the gas flow inside of a solid rocket motor using St. Robert's law modeling solid propellant burn rate, slip boundary conditions, and the supersonic outflow condition. Results from the HMNF model are used by the coefficient form of the mathematics module to determine the 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. Pertinent results from these analyses are the complex valued eigenvalue and eigenvectors. Comparisons are made to the French results to evaluate the modeling approach. A comparison of the French results with that of the present analysis is displayed in figures 1 and 2-3, respectively. The graphic shows the first tangential eigenvector's real (a) and imaginary (b) values.

Reference

J. C. French, Nozzle Acoustic Dynamics and Stability Modeling, vol. 27, Journal of Propulsion and Power, 2011.
R. K. Sigman and B. T. Zinn, A Finitel Element Approach for Predicting Nozzle Admittances, vol. 888, Journal of Sound and Vibration, 1983, pp. 117-131.
L. M. B. C. Campos, On 36 Forms of the Acoustic Wave equation in Potential Flows and Inhomogeneous Media, vol. 60, Applied Mechanics Reviews, 2007, pp. 149-171.

Figures used in the abstract

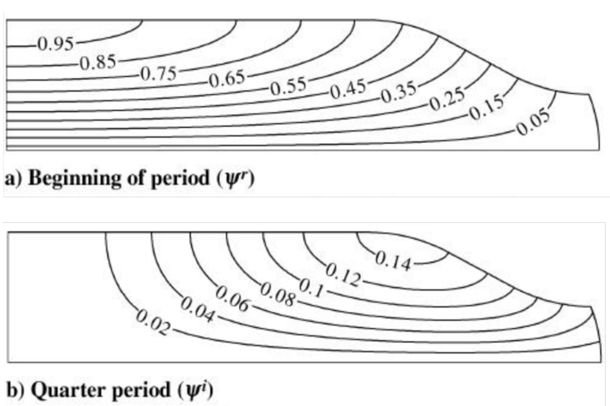

Figure 1: Short motor first tangential acoustic potential mode shape, French analysis [1].

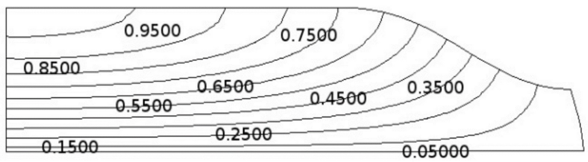

Figure 2: Short motor first tangential acoustic potential mode shape at beginning of period, COMSOL analysis.

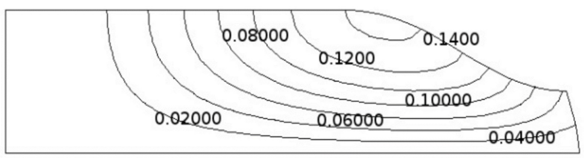

Figure 3: Short motor first tangential acoustic potential mode shape at quarter period, COMSOL analysis.