The Effect of Resistance on Rocket Injector Acoustics

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Introduction: Combustion instability, where unsteady heat release couples with acoustic modes, has long been an area of concern in liquid rocket engines. Accurate modeling of the acoustic normal modes of the combustion chamber is important to understanding and preventing combustion instability. The injector resistance can have a significant influence on the chamber normal mode shape, and hence on the system stability.

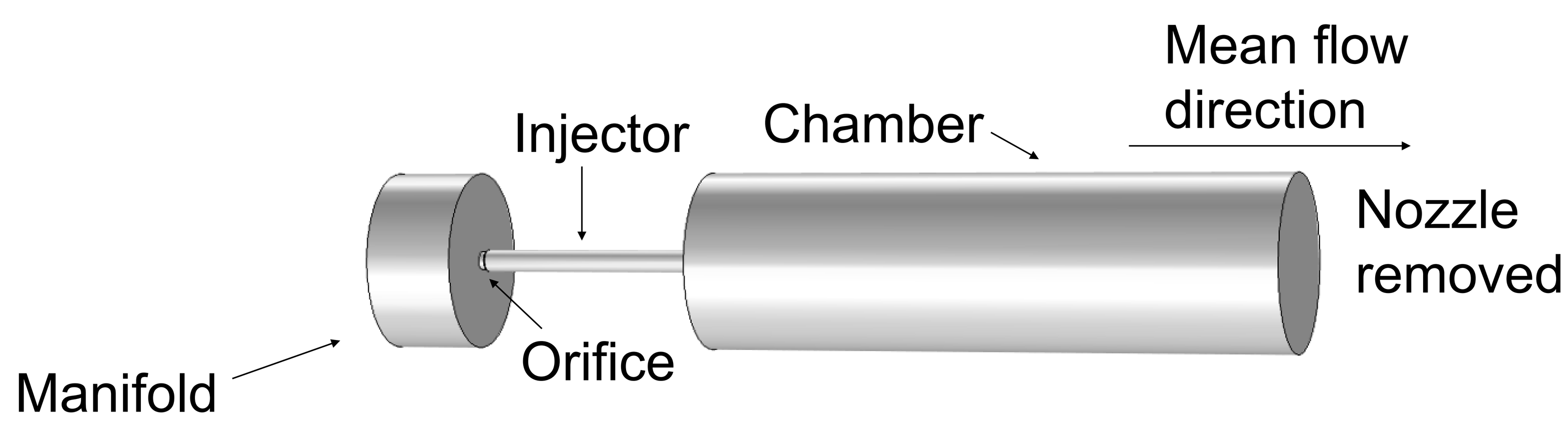


Figure 1. System geometry

Computational Methods: This study evaluates the effect of injector resistance on the mode shapes and complex eigenfrequencies of an injector/combustion chamber system by defining a high Mach-flow, potential flow form of the convective wave equation (see Eq. 1) in COMSOL Multiphysic's Coefficient Form PDE Mathematics Module. The form of the wave equation shown in Eq. 1 is based off of a similar form derived by Campos in Ref. [1]. The additional terms in Eq. 1 are modeled by adding source terms to COMSOL's base governing equation. The pressure mode shape is determined using Eq. 3.

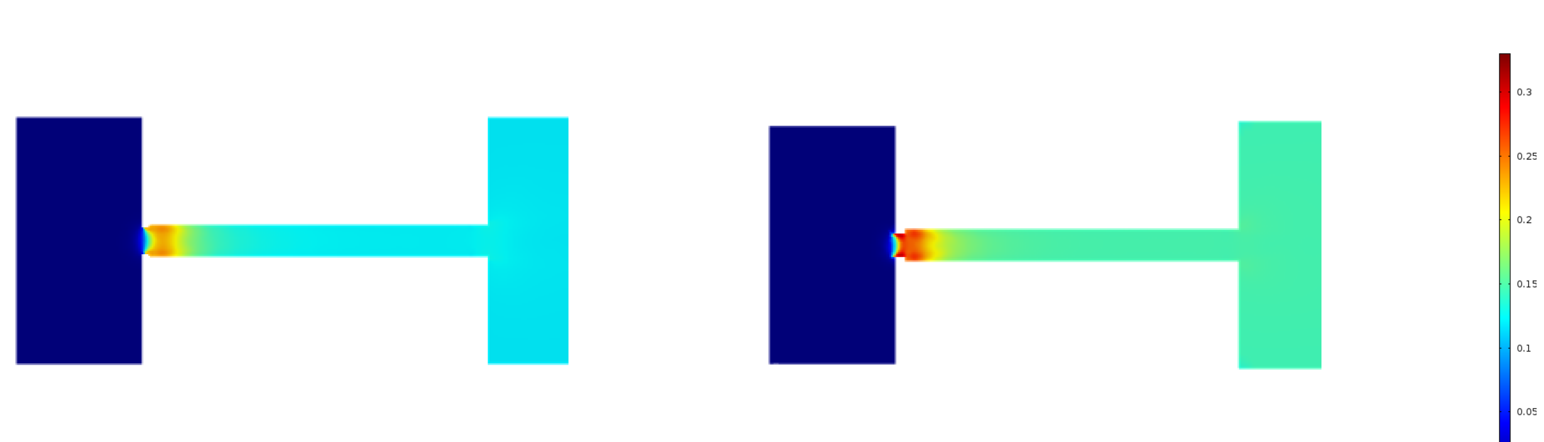
$$\frac{\lambda^2}{c_o^2}\psi - \nabla^2\psi = \frac{2\lambda}{c_o^2}(\vec{v}_o \cdot \nabla\psi) - \frac{1}{c_o^2}(\vec{v}_o \cdot \nabla)(\vec{v}_o \cdot \nabla\psi) + \frac{1}{\rho_o}\nabla\psi \cdot \nabla\rho_o - \frac{2\lambda}{c_o^2}\psi(\vec{v}_o \cdot \nabla)\log(c_o) + \frac{2}{c_o^2}(\vec{v}_o \cdot \nabla\psi)(\vec{v}_o \cdot \nabla)\log(c_o) \qquad \textbf{Eq. 1}$$

$$-\mathbf{n} \cdot \nabla\psi = 0 \qquad \textbf{Eq. 2}$$

$$p = -\rho_o(\omega\psi + \vec{v}_o \cdot \nabla\psi) \qquad \textbf{Eq. 3}$$

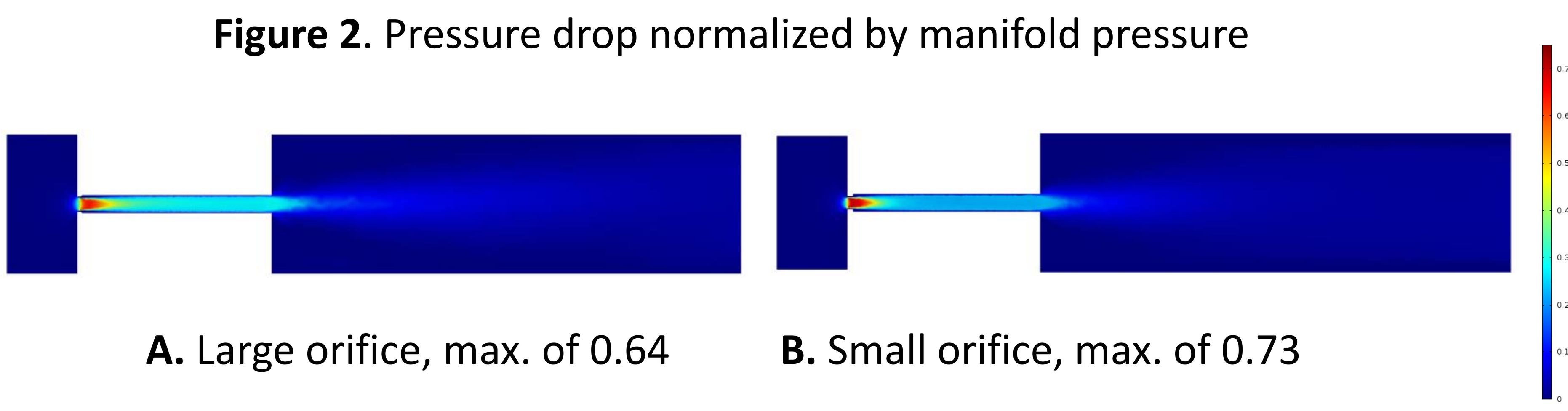
c_o = Speed of sound
ρ_o = Density
$\vec{v}_o$ = Velocity vector
$\lambda = \alpha + i\omega$, Complex eigenvalue
$\psi = \psi^r + i\psi^i$, Complex velocity potential
$p = p^r + ip^i$, Complex pressure perturbation

Background steady-state flow conditions are determined through a NASA Marshall Space Flight Center in-house computational fluid dynamics model, and interpolated onto the COMSOL mesh. Two cases are investigated, one with an injector orifice diameter of 6.502 mm (0.256 in), and the other with a diameter of 5.613 mm (0.221 in). As shown in Figure 2, the larger orifice leads to a 28% drop in pressure with respect to manifold pressure, while the smaller orifice provides a 33% drop.



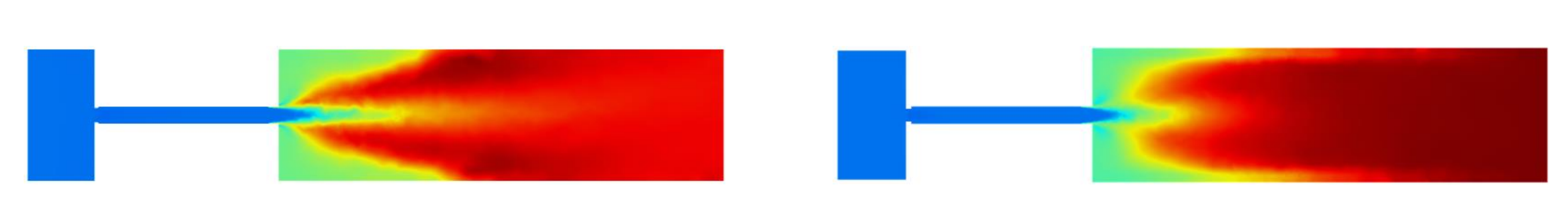
A. Large orifice **B.** Small orifice

Figure 2. Pressure drop normalized by manifold pressure



A. Large orifice, max. of 0.64 **B.** Small orifice, max. of 0.73

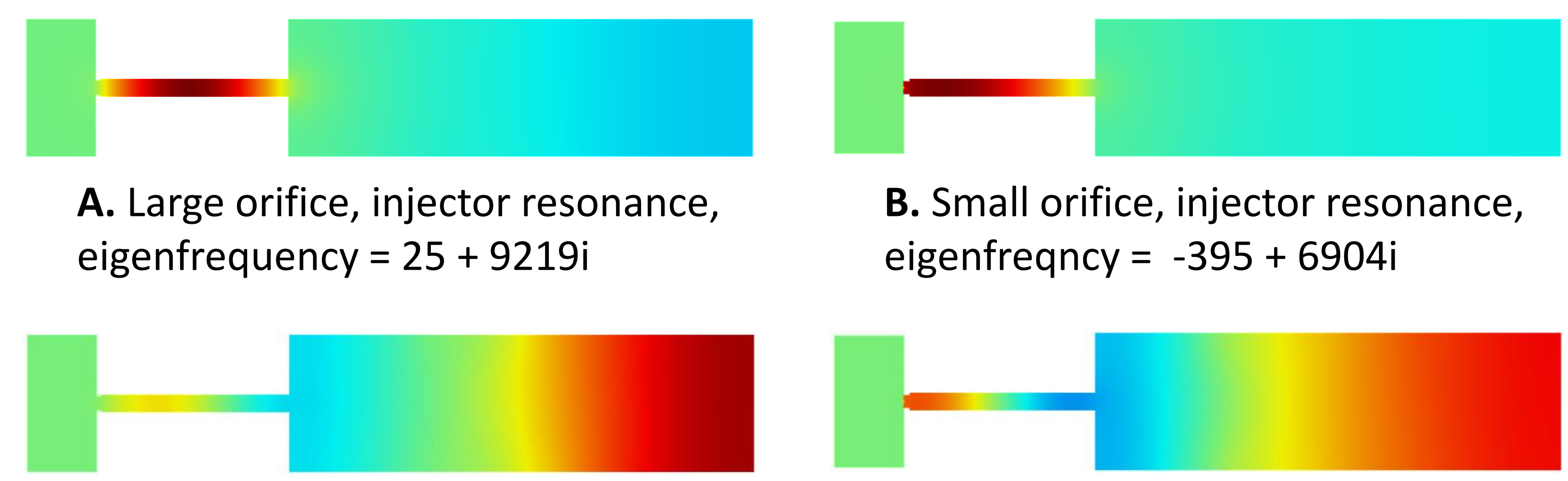
Figure 3. Mach number



A. Large orifice **B.** Small orifice

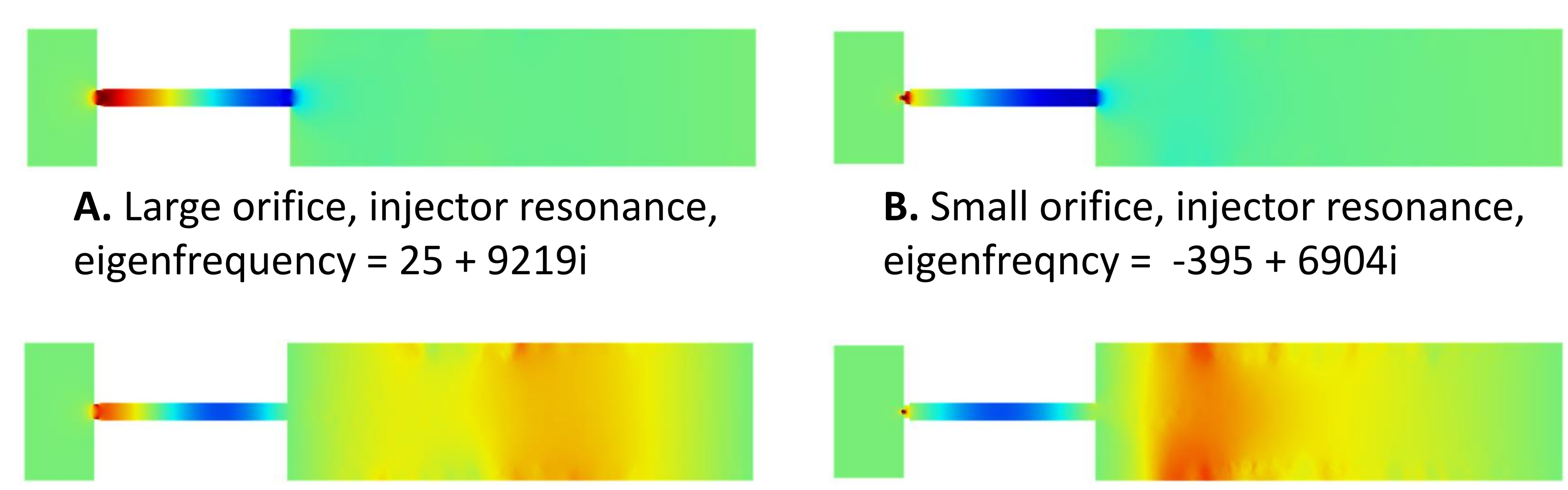
Figure 4. Speed of sound, normalized by maximum

Results: A larger pressure drop across the orifice leads to higher acoustical resistance. Although there is only a 5% difference in pressure drop between the two cases, there is a significant impact on the normal mode shape of the system. For the low resistance case, the manifold/injector boundary behaves similar to an acoustically open boundary, while for the high resistance case it behaves closer to acoustically closed. Additionally, increasing the resistance across the injector leads to a change in both the real and imaginary components of the complex eigenfrequencies. The impact on the normal mode shape and complex eigenfrequencies can be seen in Figures 5, 6, and 7.



A. Large orifice, injector resonance, eigenfrequency = 25 + 9219i
B. Small orifice, injector resonance, eigenfreqncy = -395 + 6904i
C. Large orifice, chamber resonance, eigenfrequency = 106 + 14411i
D. Small orifice, chamber resonance, eigenfrequency = -70 + 12547i

Figure 5. Velocity potential mode shapes for the small and large orifice cases



A. Large orifice, injector resonance, eigenfrequency = 25 + 9219i
B. Small orifice, injector resonance, eigenfreqncy = -395 + 6904i
C. Large orifice, chamber resonance, eigenfrequency = 106 + 14411i
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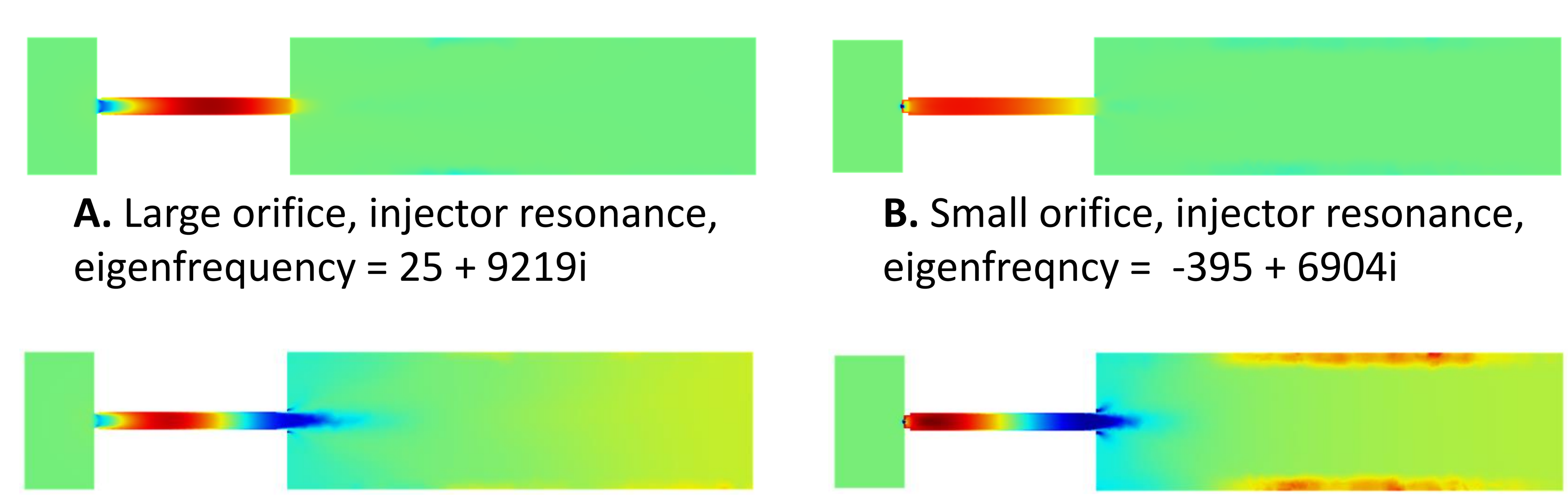
Figure 6. Velocity mode shapes for the small and large orifice cases



A. Large orifice, injector resonance, eigenfrequency = 25 + 9219i
B. Small orifice, injector resonance, eigenfreqncy = -395 + 6904i
C. Large orifice, chamber resonance, eigenfrequency = 106 + 14411i
D. Small orifice, chamber resonance, eigenfrequency = -70 + 12547i

Figure 7. Pressure mode shapes for the small and large orifice cases

Conclusions: The knowledge gained through this model can be used during future design cycles to favorably shape the combustion chamber mode shape, and to determine the complex eigenfrequencies in an effort to predict which modes are susceptible to instability.

References:

1. L. M. B. C. Campos, "On 36 Forms of the Acoustic Wave Equation in Potential Flows and Inhomogeneous Media," *Applied Mechanics Reviews*, vol. 60, pp. 149-171, (2007).