Fastrac Rocket Engine Combustion Chamber Acoustic Cavities

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Introduction

In the design of combustors, stability is often at odds with performance. The determination of stability parameters has been an ongoing process, combining theory with experience. Many of the theoretical variables are difficult to measure and quantify. These are important considerations in the design of acoustic cavities for the combustion chamber. The design of acoustic cavities to ensure combustion stability is heavily dependent on empiricism and experience. Though computational methods are being employed more and more to help understand the details of the combustion processes, the design process and stability rating depend heavily on testing. This was the case with the Fastrac 60,000 pound thrust engine. The subject of this paper is the finite element analysis of the chamber and acoustic cavity acoustics. This small part of the development activity was undertaken to try and understand the three dimensional aspects of combustion chamber acoustic pressure oscillations.

Background

Combustion instability refers to organized oscillations that are sustained and/or amplified by the process of combustion. These combustion system oscillations can be broadly categorized[1] as resulting from gas pulses and due to periodic supply of heat to gas. These two causes of instability are the result of release of chemical energy (heat), flow oscillations and/or acoustic coupling. Combustion stability problems appear during the development of most rocket engines and can produce many undesirable effects such as high vibration levels, heat transfer magnification, and thrust oscillations. The high frequency, high amplitude oscillations can cause major injector or chamber damage in fractions of a second. The instability is best detected with chamber fluctuating pressure measurements, however, fluctuating pressure measurements in the feed-system, and accelerometers on the chamber wall or injector may also show the oscillations.

The simplest approach to the analysis of high frequency combustion instability is to view the system as a vibrating mass of gas with heat addition or subtraction as a destabilizing influence depending on phase. Acoustic interaction between the combustion chamber and acoustic cavities has a significant influence on this process.

Finite Element Method

The finite element method can be used to calculate the natural frequencies and acoustic mode shapes of complex-shaped combustion chambers and cavities. For acoustic problems, the method is based on a variational integral formulation of the wave equation. The pressures within the fluid are discretized by dividing the fluid domain into a finite number of 3D-elements with unknown pressure values at the element corners or nodes. This allows complex geometry to be easily modeled by breaking it into as many finite elements as desired. The result is a set of second order linear ordinary differential equations which can be expressed in matrix form as follows:

$$\mathbf{M}\, d^2\mathbf{P}/dt^2 + \mathbf{K}\,\mathbf{P} = \mathbf{F}(t)$$

where **M** is the fluid mass matrix, **K** is the fluid stiffness matrix, **P** is the vector of unknown nodal pressures, and **F**(t) is a vector containing any externally applied pressures. For determining the acoustic modes, **F**(t) = 0 and the equation above is solved as an eigenvalue problem. For a response analysis, **F**(t) is nonzero and the pressures can be solved for as functions of time or frequency.

Acoustic Cavities

Acoustic cavities are often used to disperse and damp unwanted oscillations in a combustion chamber. The cavities take the form of outer wall slots or perforated liners. These acoustic resonators behave as either Helmholtz resonators or quarter wave tubes. A key requirement for properly sizing resonators is knowledge of the fluid properties in the resonator. These properties are heavily dependent on temperature. Since the temperature in the acoustic cavity may not be known a *rule of thumb* is to size the cavity using $^1/_4$ to $^1/_3$ the main chamber temperature; or another rule of thumb is to size the cavity using half the chamber sound speed. The size of the acoustic cavity opening relative to the combustion chamber is another important consideration. Experience has shown that effective cavities have an area ratio of about 20% of the main chamber area.

The Fastrac thrust chamber (Figure 1) was designed with a large space in each outer quadrant of the injector. The cavity space had an odd shaped port to the combustion chamber that was a 90° bend on inner wall and an approximately 45° diagonal on the outer wall (Figure 2). These cavities of nearly 90° arc (Figure 3) could be fitted with tuning blocks to provide the desired acoustic cavity size and shape or the full space could be used as an acoustic cavity.

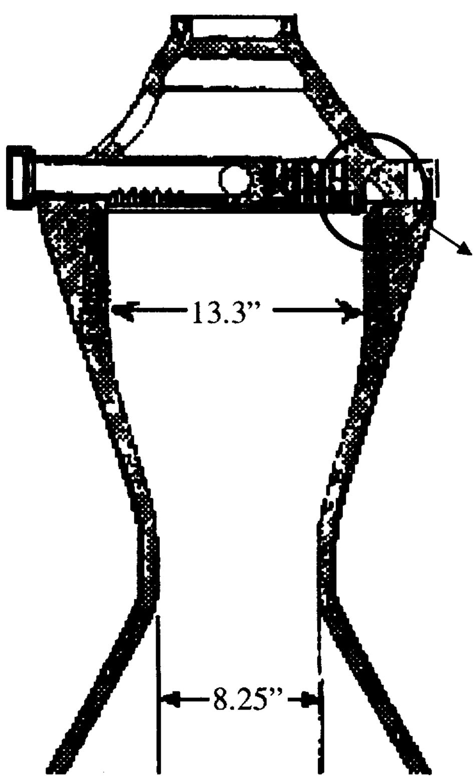

Figure 1 - Fastrac Thrust Chamber

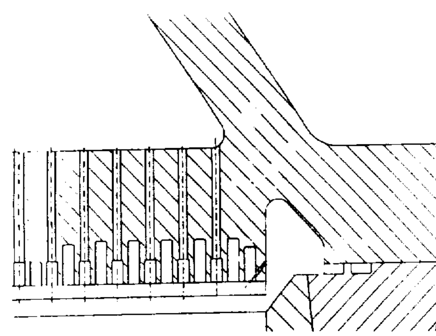

Figure 2. Acoustic Cavity (side)

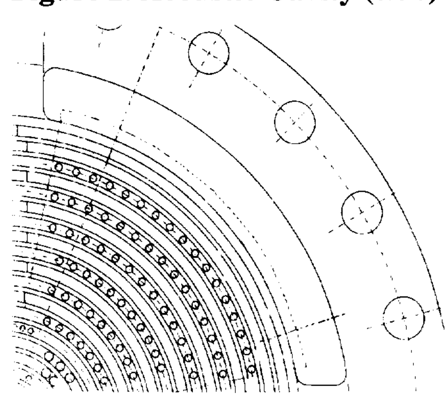

Figure 3. Acoustic Cavity (plan)

The process for designing an effective acoustic cavity typically involves trial and error. First, the chamber acoustic modes are determined. Next, the mode of concern is identified and the acoustic cavity is tuned to this frequency. This is typically the 1T mode. The two acoustic cavity types employed in most chambers are quarter-wave and Helmholtz resonators.

Designing or acoustically tuning the cavity to a certain frequency provides the shape, but, the size and location are also necessary considerations. Tangential modes have highest pressure oscillations at the outer boundary, radial modes have highest oscillations at center, therefore, tangential modes are affected more by boundary layer coolant. Nodal lines occur as far as possible from excitation and therefore spin away from regions of perturbed or intense combustion and conversely the nodal line will spin toward an acoustic resonator. Large area resonators located at the outer boundaries of the chamber will "alter" the acoustic frequencies of the chamber, consequently, the characteristics of the chamber plus cavity must be evaluated. Analysis[2] and test can be performed varying resonator dimensions to identify the optimal acoustic cavity shape. Similarly the number of resonators can be optimized.[3]

As in other chamber development programs, several geometries were tested before arriving at a satisfactory Fastrac design. The initial Fastrac acoustic cavity analysis utilized one dimensional equations to determine the expected frequency.[4] The fluid properties in the cavity were determined using the cooled cavity temperature measured on earlier tests. The first acoustic cavity tested was a quarter wave design. These cavities proved ineffective at damping pyrotechnically induced chamber disturbances during hotfire. The next acoustic cavities tested were small Helmholtz resonators. These were also cooled cavities and did not damp the oscillations. These results brought into question, among other things, the validity of one dimensional frequency calculations and the cavity temperature measurements.

The final configuration tested was a larger Helmholtz resonator using the full acoustic cavity cutout as the resonator volume. Tests were performed with and without coolant flow into the cavities. Again, simple one dimensional acoustic analysis was performed over a range of cavity temperatures. It was now assumed that the actual cavity temperature was unknown. Since the chamber and acoustic cavity geometry did not match the traditional Helmholtz resonator shape, a three dimensional finite element analysis was also performed.

Finite Element Analysis

A MSC/NASTRAN three dimensional model of a 90° segment of the Fastrac chamber fluid volume and the large Helmoltz acoustic cavity fluid volume was created. This was a $^1/_4$ symmetry finite element model with 13,082 elements and 15,110 nodes shown in Figure 4. To determine the natural frequencies of the chamber, a modal analysis was run with all possible symmetry boundary conditions. The modal runs were done using a variable property chamber fluid and three cases for the acoustic cavity fluid properties at temperatures of 2941° R, 2074° R, and 1500° R. These cases were intended to bound the possible fluid properties in the uncooled acoustic cavities. The chamber property variation was based on an axi-symmetric CFD analysis[5] of the Fastrac 60K combustion chamber flow. This analysis shows the combustion chamber fluid properties exhibit a rapid increase in density and therefore sound speed in the first few inches near the injector faceplate.

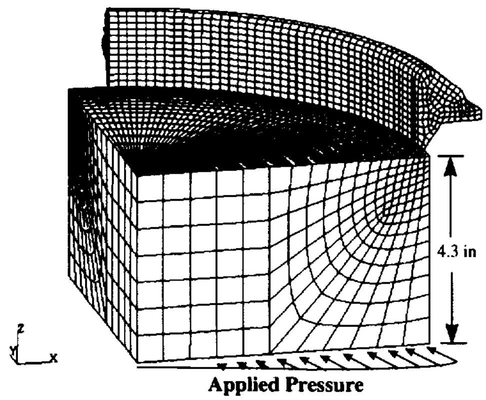

Figure 5 - Acoustic FE Model

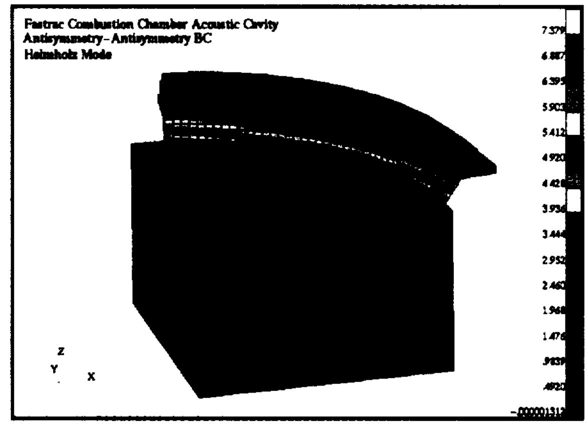

Figure 4 - Helmholtz Type Mode

Four of the cavity modes that should damp the chamber first tangential acoustic mode (1T) were identified from the analysis results (e.g., see Figure 5). A response analysis was then performed using an input excitation oscillatory pressure shaped like the 1T mode on the fluid boundary. The response of the fluid in the chamber and cavity was obtained as a function of frequency of input excitation. The response of the model with and without the acoustic cavity was calculated at several points. The resulting pressures are shown in Figure 6. This plot shows that the frequency and magnitude of the response vary significantly with cavity temperature.

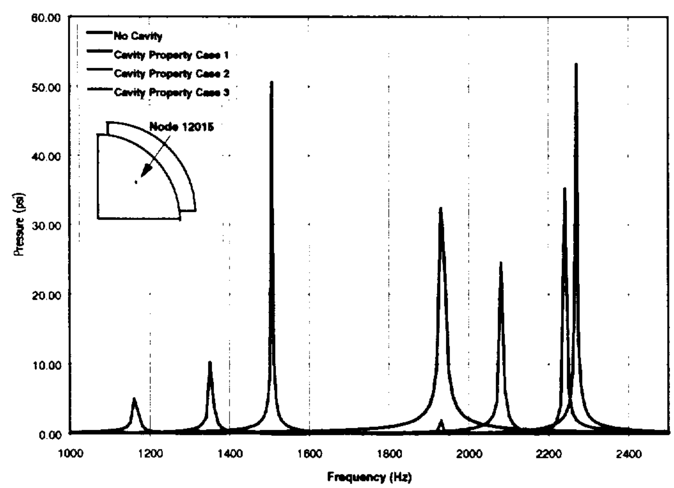

Figure 6 - Response to Sinusoidal Pressure

The "no cavity" chamber responds at an expected 1930 Hz when excited with a 1T oscillatory pressure. The pressure distribution of this response is compared to the 1350 Hz response of "cavity case 2" in Figure 7.

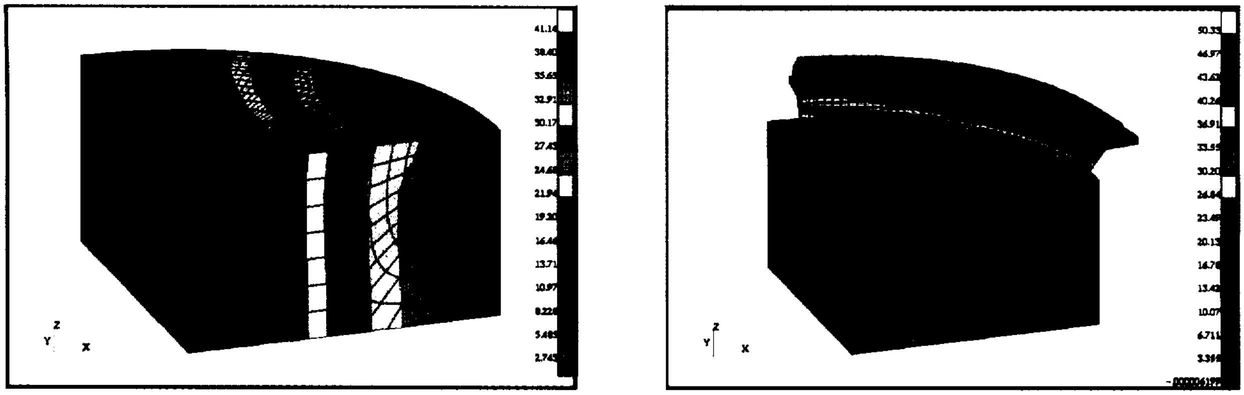

Figure 7 - Pressure Distributions at 1930 Hz and 1350 Hz

Summary of Results

The 60K Fastrac combustion chamber first tangential mode frequency was estimated to be around 1950 Hz at nominal operating conditions. Acoustic cavities were implemented at the outer periphery of the chamber to damp first tangential mode oscillations. In Figure 8, the combustion chamber high frequency pressure power spectral density shows the oscillation response to a small bomb disturbance. This figure illustrates the unstable high amplitude discrete oscillations present when the cavities are cooled (test 13) and broad peaked (damped) response when cavities are not cooled (test 12). The cooled cavity temperature is not known and the uncooled cavity temperature is around 2110° R.

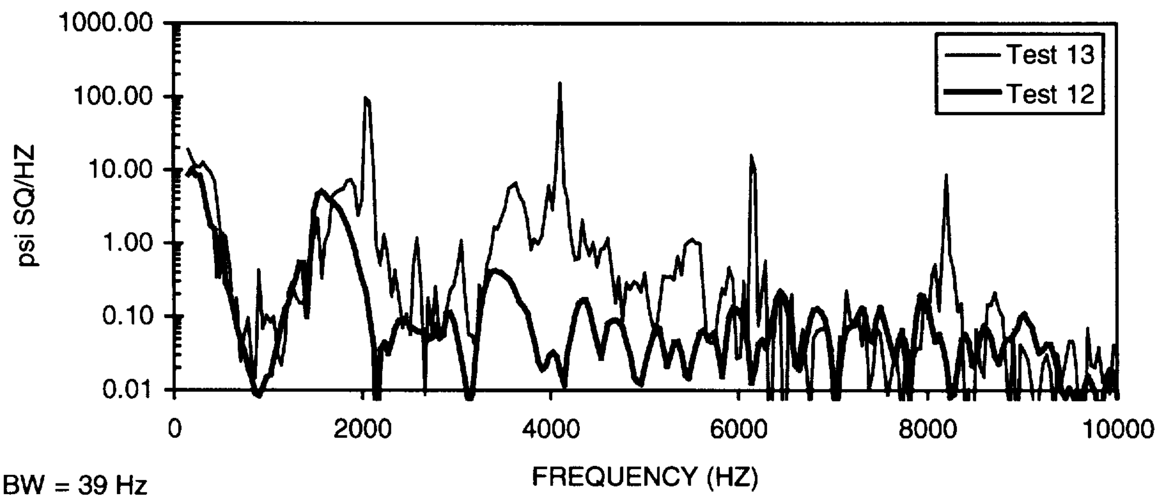

Figure 8. Fastrac Combustion Chamber High Frequency Pressure PSD

Figure 9, shows a comparison of calculated and measured frequencies. The acoustic cavity can behave as a Helmholtz resonator or sustain a cavity tangential frequency. These frequencies were plotted as a function of cavity fluid temperature. The chamber first tangential mode frequency is shown as constant with at the rule of thumb cavity temperature. The finite element model, FEM, results for symmetric, S, and anti-symmetric, A, boundaries are shown. The FEM mode shapes show pure Helmholtz, H, cavity oscillations or Helmholtz with tangential, H/T, cavity oscillations.

Also included on the plot is the measured chamber oscillation frequency at measured cavity temperature.

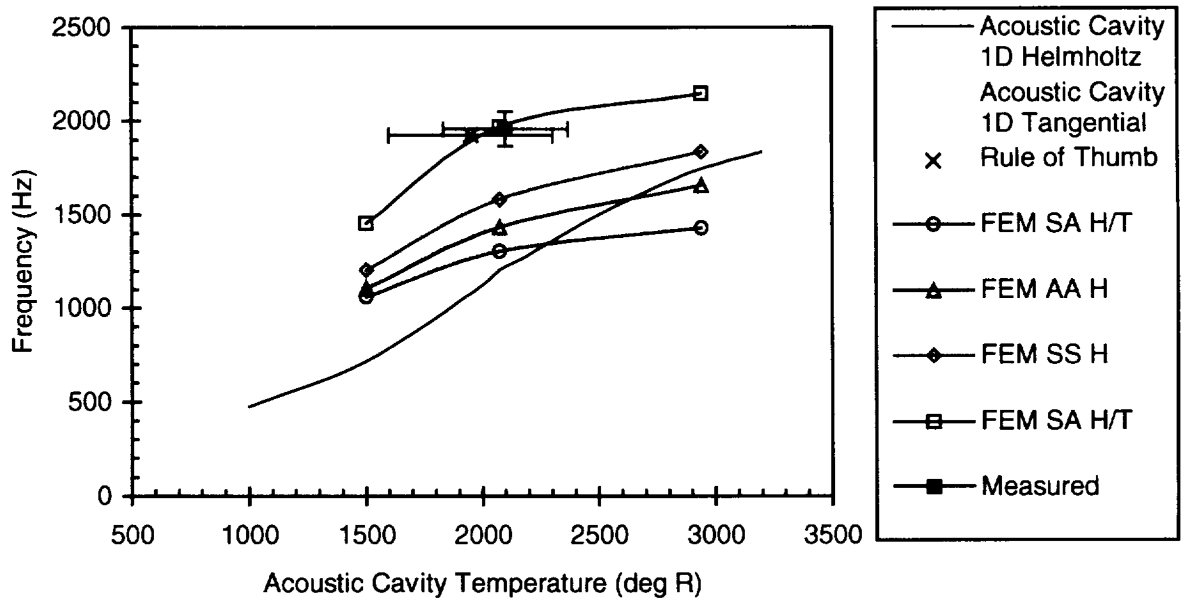

Figure 9. Estimated vs Measured Frequencies

Conclusions

A three dimensional modal analysis was performed using finite fluid elements. The analysis shows four distinct modes of the Fastrac chamber plus cavities near the frequency of the chamber first tangential mode. The mode shapes illustrate the complexity of fluid oscillations in a three dimensional chamber and acoustic cavity. In addition, a first tangential forcing function was applied to the chamber with three different acoustic cavity fluid temperatures. It was observed that the acoustic cavity fluid temperature has a significant effect on the response of the chamber to first tangential mode oscillations.

References

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