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Pressure Measurement in the Post-Combustion Section of a Hybrid Rocket Motor

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PRESSURE MEASUREMENT IN THE POST-COMBUSTION SECTION OF A HYBRID ROCKET MOTOR

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Abstract

A pressure measurement system for the aft combustion chamber of a hybrid rocket motor has been designed. The pressure transducer is exposed to the hot combustion gases through a small port in the aft combustion spacer. This port is back-pressured through the transducer's helium bleed. Sealing integrity of the transducer mounting was carefully maintained to avoid leak paths which would allow hot, oxygen rich gases to contact the transducer or the motor housing. The measurement system's frequency response was determined, and the notch frequency due to the spacer hole and the volume under the transducer hole was observed. This notch occurs in the range of interest for the measurement system and must be included in any frequency analysis. Otherwise, the measurement system has a generally flat frequency response in the domain of interest.

Introduction

The hybrid rocket consists of a stationary solid fuel layer which is brought into contact with an oxidant. The oxidant may be liquid or gaseous oxygen or air which is flowed over the solid fuel. Combustion takes place along the surface of the fuel, and thrust is generated by the exiting, energetic combustion gases.

The hybrid rocket is often cylindrical, with the fuel surrounding the oxidant flow. This configuration offers an interesting platform for studying coupled acoustic/combustion phenomena. The broadband excitation provided by the combustion process is guaranteed to excite the fundamental acoustic modes of the cylinder. Since the acoustic waves introduce density changes in the burning combustion gases, the chemical process is altered. The process is further complicated by the turbulent fluid flow through the cylinder, caused by the nozzle and by the discontinuous area changes at the combustion chambers.

Given the complex interactions, oscillations and instabilities will exist in the operating regime of any hybrid motor. These oscillations will potentially excite the rocket's support structure and be translated to the vehicle to which the rocket is attached. These resonances can then excite modes of other components or cause unacceptable damage or wear.

Further, the processes can exhibit unsteady or nonlinear behavior, depending on the flow regime. Due to the high temperatures and uncertain composition of the gases, simple calculations of acoustic resonances are not likely to yield meaningful results [1, 2] as the speed of sound and fluid density are unknown. Further, the termination impedances are uncertain, due to the flow through the tube and the combustion process.

The nonlinear behavior may exhibit chaotic properties, as chaos has been observed in a number of acoustically driven combustion processes. [3, 4, 5] This behavior would manifest in both the pressure data and the plume flicker data [1, 2], and may depend on the flow regime.

One dimensional modeling can be used to study this process. [3, 6] Simulations can yield estimates of critical parameters which can be monitored for either design or control purposes. However, simulations must be verified using experimental data, since simplifying assumptions must be made to reach a workable model.

Several years ago, UALR developed and built a labscale hybrid rocket motor. [7] This motor is composed of an oxygen injector head connected to the main body of the motor (see Figure 1). A precombustion chamber is formed by a graphite spacer. The oxidant contacts the flame front at the fuel. Combustion propagates along the fuel to the aft combustion chamber, which is also formed by a graphite spacer. The hot combustion gases exit the motor through a graphite nozzle. Currently, there is a pressure measurement in the injector head.

In order to verify modeling efforts and to study the process between the injector head and the aft combus-

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tion chamber, a pressure measurement in the aft combustion chamber of the hybrid rocket motor is required. This measurement can be used to complement the pressure data in the injector head and can be correlated with the plume flicker data. There will be a smaller time delay between the aft pressure measurement due to its closer proximity to the plume, and the majority of the combustion process will occur between the injector head pressure measurement and the aft pressure measurement.

Design

There are several critical factors which must be accommodated when inserting a pressure probe in the aft combustion chamber of a hybrid rocket motor. Plume measurements have shown that temperatures after the aft combustion chamber are above 3000 °C. Further, there is uncombined oxygen in this section, which, at these temperature, could begin to burn the steel housing or the pressure transducer.

A PCB Piezotronics Model 123A Gas Bleed Pressure Transducer with sensitivity 1.165 pC/psi. This transducer can withstand 5000 psi pressure spikes and has a linear range up to 3000 psi. Its frequency response is 25 kHz. When connected to a helium bleed source and with water-cooling at 50 psi, the transducer can withstand up to 5000 °C for short durations.

Even with the transducer's ability to withstand the operating temperature, the transducer must still be maintained well below 3000 °C so that its dual sensitivity to temperature does not create an unacceptable offset.

The spacer in the aft combustion chamber had a hole drilled in it to transfer the chamber pressure to the transducer (see Figure 2). A measurement ring was designed and press fit on the motor housing above the aft combustion chamber (see Figure 3). This ring was necessary as the thickness of the motor housing was not sufficient to accommodate the length of the pressure transducer.

Alignment of the spacer hole with the corresponding hole in the housing and measurement ring is a problem due to vibration during the combustion process. Rather than introducing a fixture, a small grove was machined around the circumference of the spacer (see Figure 2). This groove allows the pressure to equalize around the entire circumference of the ring, regardless of the location of the hole.

The size of the hole had to be kept as small as possible. Hot combustion gases flowing through the interior of the motor contact either the burning fuel or the high temperature materials of the spacers or nozzle. These gases are introduced to the reactive metals of the housing and measurement ring through this hole. It is important that convective flow be reduced or eliminated. Without convection through the spacer, the only heat transfer path is through conduction through the gases or through the spacer. These gases are back-pressured through the helium bleed. In the absence of convection, the only means for high temperature, uncombined oxygen to reach the metal housing or transducer is through diffusion, an extremely slow process.

This configuration for transmitting pressure will act as a notch filter and will potentially exhibit modal behavior at higher frequencies. [8] As the size of the hole is reduced, the acoustic filter frequency is also reduced. This leads to a trade-off. The hole must be as small as possible to prevent damaging the transducer and upsetting the measurement; however, it must be as large as possible to avoid attenuating the measurement at important frequencies.

The stagnant volume introduced by both the gap between the end of the transducer and the rocket housing and by the groove in the spacer also influence the measurement frequency. The larger the volume, the lower the frequency of the notch. These must be maintained as small as possible.

Experimental

In order to confirm the frequency response of the measurement system, a series of experiments were run. The rocket motor housing was excited with an acoustic pressure wave containing many frequency components. The pressure at the inlet to the spacer was measured with a Bruel and Kjaer Sound Level Meter, model 2236.

Both the PCB pressure transducer and the B&K sound level meter were sampled with a DSP Technologies Siglab data acquisition system. A system identification algorithm was run, with the B&K signal as the input and the PCB signal as the output. The resulting transfer function represented the dynamic response between the measureand pressure, Pm, and the measured pressure, Po.

In order to achieve good resolution over the various frequency bands of interest, different sampling rates and different frequency components in the test signal were used. In order to demonstrate repeatability, the system identification was run on three separate data sets for each sampling frequency.

Difficulties arose in achieving acceptable signal to noise ratio between the acoustic wave and the pressure transducer. Given that the PCB transducer was designed to measure up to 3000 psi and that speakers generate signals below 100 psi, the output from the PCB transducer was on the order of millivolts. In the very low frequency range (below 50 Hz), it was impossible to generate a signal above the noise floor without resorting to specialized sub-woofers. Therefore, no valid data was obtained in that region.

Results and Discussion

The low frequency response (see Figure 4) demonstrates both the general flatness of the frequency response over the majority of the band between 65 and 140 Hz. At about 77 Hz, the notch frequency caused by the measurement system occurs. This notch is severe and must be considered in evaluating any frequency response data gathered with this measurement system. The spike at 120 Hz is a harmonic of the 60 Hz line noise. For the larger signals which occur during rocket firing, this signal becomes negligible and can be ignored.

In the mid-range frequency band (135 Hz to 380 Hz), overall flatness occurs with minor bumps around 175 Hz and 275 Hz (see Figure 5). This should have minimal impact on the measurement system. There is also a general positive trend in this frequency band.

In the high frequency band (375 Hz to 1500 Hz), the measurement system begins to become unreliable. Another notch occurs near 550 Hz and a strong resonance occurs around 1390 Hz. Although data above 500 Hz may be used to determine qualitative effects, it cannot be used to determine absolute values of frequency peaks in that range.

Conclusions

A pressure measurement system to gather data in the aft combustion chamber of a hybrid rocket motor has been designed and built. The frequency response for this system has been determined. Although the overall system exhibits linear frequency response up to 550 Hz, there are notches due to the pressure release mechanism. These notches occupy a small region in the frequency band of interest. However, they must be considered in evaluating any frequency data generated with this measurement system.

The overall goals for this system have been met. Improvements can be made with little redesign. The notch filter effect of the spacer hole size and volume can be alleviated by increasing the hole size and reducing the volume.

Acknowledgments

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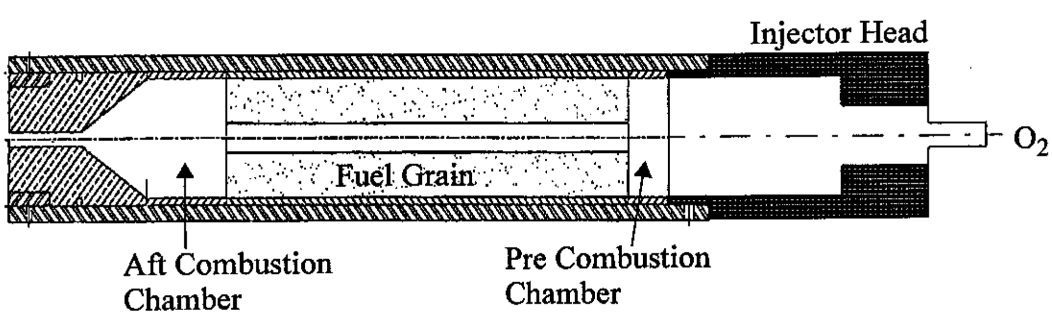

FIGURE 1: Schematic of original hybrid rocket motor configuration

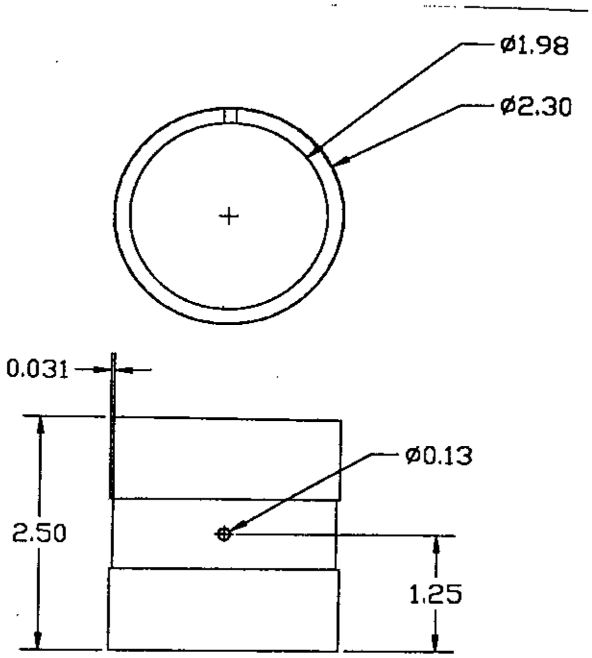

FIGURE 2: Spacer with hole and groove for pressure release.

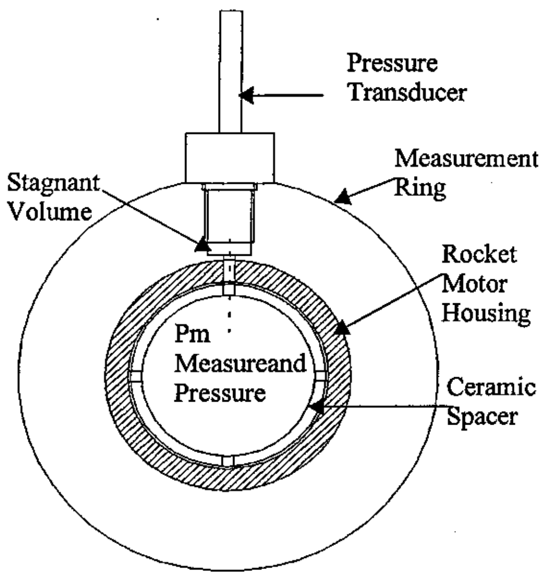

FIGURE 3: Cross-section of aft section showing pressure transducer and transmission path

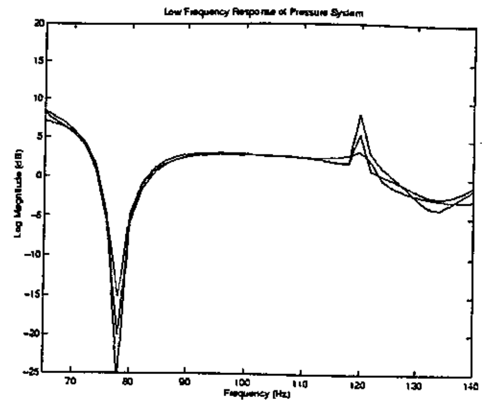

FIGURE 4: Low frequency response of pressure system, including notch filter effect.

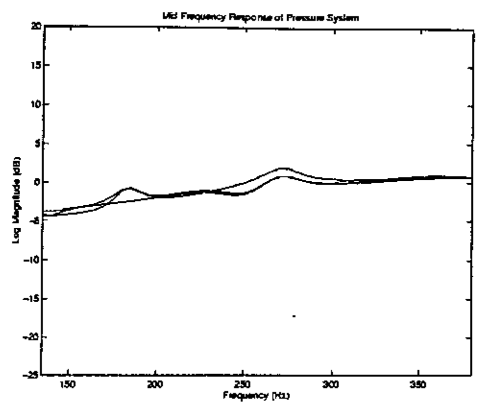

FIGURE 5: Mid-range frequency response of pressure system.

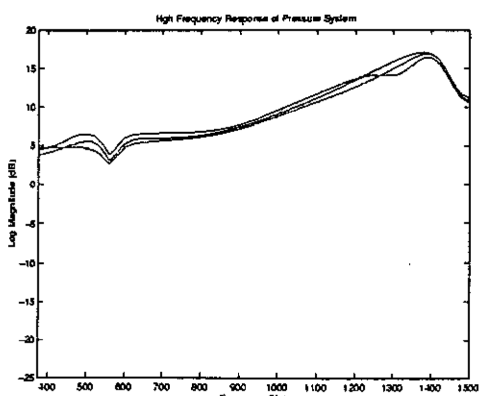

FIGURE 6: High frequency response of pressure system.