Pressure, Plume Flicker, and Acoustic Data Correlation in Labscale Hybrid Rockets

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ABSTRACT

The development of the hybrid rocket motor has been plagued by combustion instabilities. These are usually monitored as fluctuations in chamber pressure and are on the order of tens of Hz in frequency. Previous work using our labscale hybrid system has also indicated instabilities at these frequencies. These have been attributed to fuel chuffing or other phenomena. Additional studies, in areas such as IR and other spectral monitoring, have indicated that these oscillations are also present in the plume as light emission flicker. However, they were not investigated in the previous work.

This paper presents a study of these specific phenomena and attempts to correlate plume flicker, acoustic data, and higher speed chamber pressure monitoring. It was found that the plume flicker frequencies match those found using high speed pressure transducers, although these light intensity fluctuations demonstrate greater amplitude. Acoustic data could not be correlated, as it appears as a form of white noise. The authors feel that flicker data offers an inexpensive but sensitive alternative to high-speed pressure transducer use.

Keywords: hybrid rocket, exhaust plume, plume diagnostics, combustion diagnostics, engine health monitoring, optical emissions, acoustic emissions

Introduction

The premise for this paper was to explore combustion instabilities associated with hybrid rockets. Although the existence of these combustion instabilities is well known, they have not been well explored.[1] In this study, measurement of pressure oscillations was targeted as the best way to investigate instabilities; plume flicker data and acoustic data were recorded to examine possible correlations with the pressure oscillations.

The hybrid rocket facility at the University of Arkansas at Little Rock (UALR) consists of a labscale hybrid rocket motor, video monitor, data acquisition system, and computer control system. The facility was originally built for plume diagnostic and combustion studies. Recently, emphasis has been added to focus on physical parameters of the rocket motor.

The rocket has two main parts, a head assembly and the chamber body. Constructed of 303 stainless steel, the head assembly contains a portion of the precombustion chamber. The head also contains the igniter inlet and the pressure transducer ports, as well as inlets for the gaseous oxygen, nitrogen, and propane. The chamber body, manufactured from schedule 80, 304, stainless steel pipe, houses the rest of the precombustion chamber, the fuel grain, the postcombustion chamber and the nozzle. The hydroxyl-terminated polybutadiene (HTPB) fuel grain is 10 inches long and 2 inches in diameter (254×51 mm). Gaseous oxygen is used as the oxidizer. Additional information on the construction and operation of the facility can be found in previous papers.[2-4]

Experimental

The goal of the project was to reveal information relating to the combustion instabilities in hybrid rockets. The paper focuses on three measurements: pressure, plume flicker and acoustic output. All data for this paper originated from twelve rocket firings using HTPB as

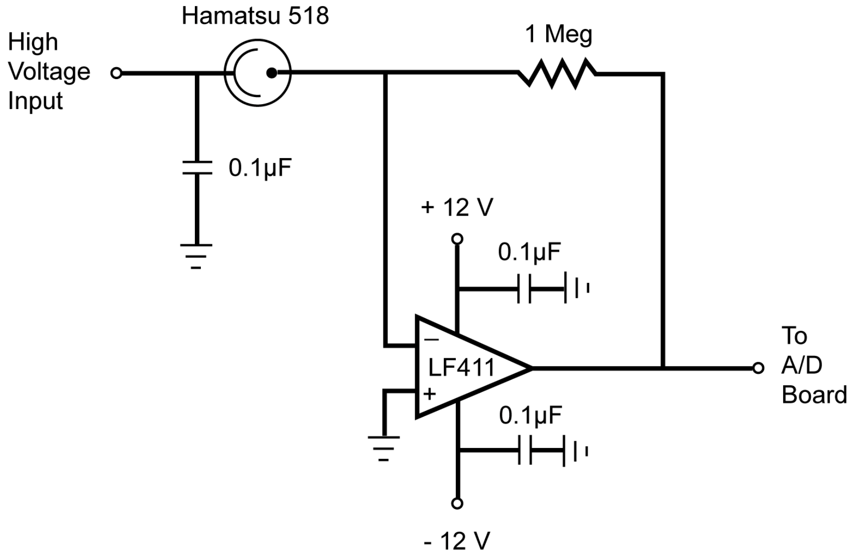

Figure 1. Schematic of phototube detector circuit.

the fuel. The oxidizer flow was varied from 0.04 to 0.14 pounds-mass/second (18 to 64 g/s).

Pressure and plume flicker data were taken using a Computer Boards CIO-DAS-1600 12-bit data acquisition board in a 486DX-33 MHz computer. Data was sampled at 50 kHz. The rocket was equipped with two pressure transducers, both located in the pre-combustion chamber. A piezoresistive transducer manufactured by Keller PSI (series 21) capable of measuring up to 1000 psia (6890 kPa) at 1 kHz was used by the control system and sampled at 25 Hz. It was used for routine monitoring of the pressure during a firing and as a safety shutdown.[2] The second was a Kistler Model 7063A piezoelectric pressure transducer designed for use in an internal combustion engine.[5] A Kistler Model 5010 Dual Mode Amplifier, operated in charge mode, powered it. To ensure precise measurements, it was water-cooled and manufactured with an extra thermal shield to minimize errors due to hot combustion gases. Safety shutdown for the rocket occurs at 580 psi (3996 kPa), however the Kistler transducer was allowed to record to 1000 psi (6890 kPa). The charge amplifier, set at 1v/100 psi (689 kPa), was fed into the A/D board. The piezoelectric pressure transducer has minimal damping and therefore was modeled as an under-damped, spring-mass system.[5] To maintain errors associated with the damping factor to less than 5%, the output of the pressure transducer is considered acceptable to 20% of the natural frequency, in this case to 6 kHz. A filter in the amplifier limited the bandwidth of the data to 6.8 kHz (–3 db @ 6.8 kHz). Linearity is specified to ±0.5% of full-scale output, in our case ±18 psi (124 kPa). Both transducers were calibrated using a dead weight pressure tester and tested to within 4% of each other.

The plume flicker sensor was built in our laboratory. A Hamamatsu 518 side-on type phototube was used for the sensing element.[6] The current output from the phototube was converted into voltage by the use of an LF411 op-amp. The circuit produced 1-volt output for every 1 µA produced by the phototube. This output was fed into the A/D board. Figure 1 is a schematic of the phototube circuit. The Hamamatsu literature states that vacuum phototubes can provide frequency response to 100 MHz, so our system was limited by the bandwidth of the op-amp (approximately 4 MHz). In laboratory testing and modeling, the transducer showed acceptable response from DC to 100 kHz. The phototube has an optical response from 185 to 850 nm. Testing the transducer with neutral density filters (metal film type, flat response) and various light sources proved that it had a linear response (±6% transmission from 15 to 98% transmission). The entire plume was viewed by the phototube. The phototube was

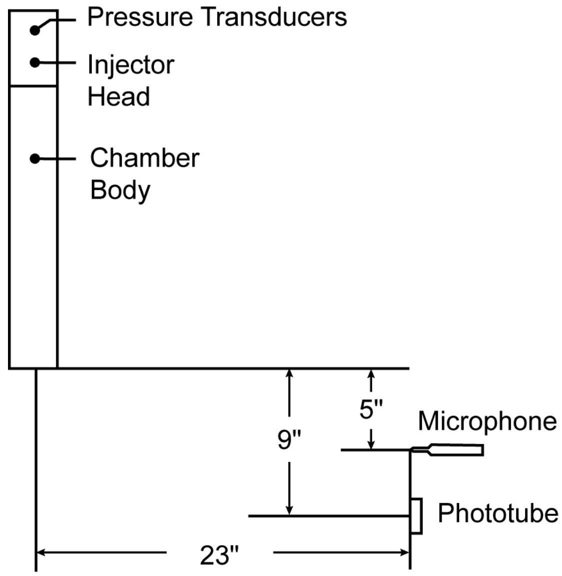

Figure 2. Top view of transducer positions.

located in the horizontal plane of the test stand, 23 inches (580 mm) from the plume and 9 inches (230 mm) from the end of the motor casing as shown in Figure 2. An iris was used to control the amount of light allowed to strike the phototube and was set to 0.094 inches (2.4 mm).

The acoustic output was sampled at 44.1 kHz by a 16-bit multimedia audio card manufactured by Turtle Beach Systems, Inc., in a 486DX2-50 MHz computer. A Bruel & Kjaer 4135 condenser microphone in conjunction with a 2801 power supply was used to record the acoustical output of the rocket. The manufacturer's calibration provided with the microphone stated acceptable response to 100 kHz. Output of the microphone was 3.39 mV/Pa. The microphone was located in the plane of the horizontal test stand, 23 inches (580 mm) from the plume centerline and 5 inches (127 mm) beyond the end of the motor as shown in Figure 2.

Results and Discussion

Fast Fourier Transforms (FFTs) of the microphone data were done using Hypersignal® for Windows. Acoustically, the rocket produces a wide band frequency spectrum within the bandwidth of our system and appears as white noise. While various frequencies appear to be emphasized at any one instant, overall no individual frequencies stand out and certainly none

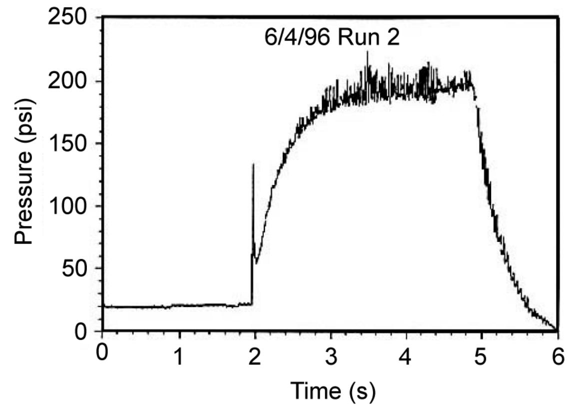

Figure 3. Typical pressure data (data averaged for display purposes).

correlate with the pressure data. The sound pressure level for our firings ranged from 146 to 168 dB (in reference to 2×10^{-5} Pa for 0 db).

Time and frequency domain analysis of the pressure and plume flicker data provided similar results. Figures 3, 4, and 5 are time plots of the data. The data sets were analyzed using in-house software and results are listed in Table 1. The amplitudes listed in Table 1 are maximum amplitude values expressed as a percentage of the mean value for a given data set. The frequencies are approximate center frequencies. Fast Fourier Transforms were completed on 0.16-second intervals of the data; no windowing was used. Representative FFT spectra are shown in Figures 6 and 7. The 30 Hz oscillation could be identified as the chuffing of the fuel: this oscillation is visible in the time base data for the pressure and flicker. Approximation of parameters using a 1/4-wave tube revealed an acoustic frequency of about 500 Hz. It is be-

Table 1. Pressure and Flicker Oscillations.

Frequency (Hz)	Pressure (% of DC value)	Flicker (% of DC value)
30	6	100
450	4*	40
900	2*	20
1,800	1*	10

* Magnitude less than specified transducer linearity.

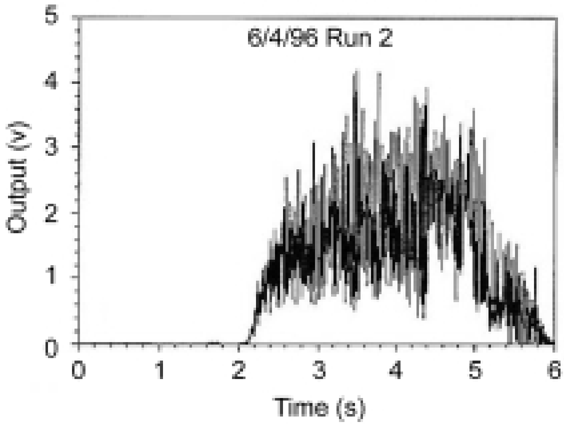

Figure 4. Typical plume flicker data (data averaged for display purposes).

lieved that the 450 Hz frequency is the fundamental longitudinal mode and the 900 and 1800 Hz frequencies are harmonics of the fundamental mode.

The Kistler pressure transducer provided the facility with new information. At ignition, there is often a short initial high-pressure spike, which the piezoresistive transducer cannot detect. The Kistler equipment, however, allowed gaining a better understanding of the start up transients. The spike is believed to be caused by slight imbalances in the propane/oxygen mixture used to ignite the fuel. The indication is that the propane pressure is too high. This phenomena has been noted in this and previous studies as an audible "popping" during ignition. During the

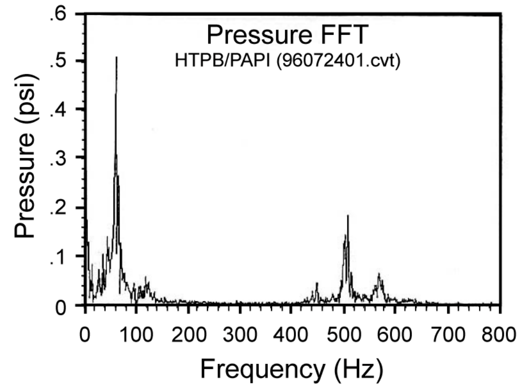

Figure 6. Frequency spectrum resulting from FFT analysis of pressure data.

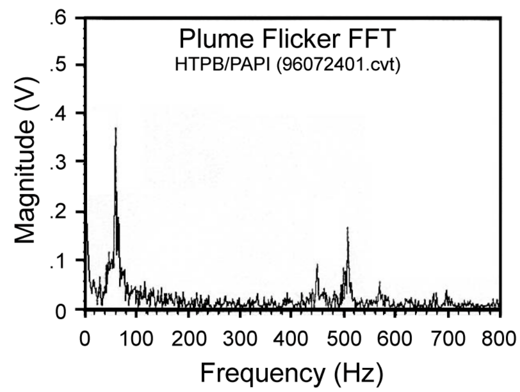

Figure 7. Frequency spectrum resulting from FFT analysis of plume optical flicker.

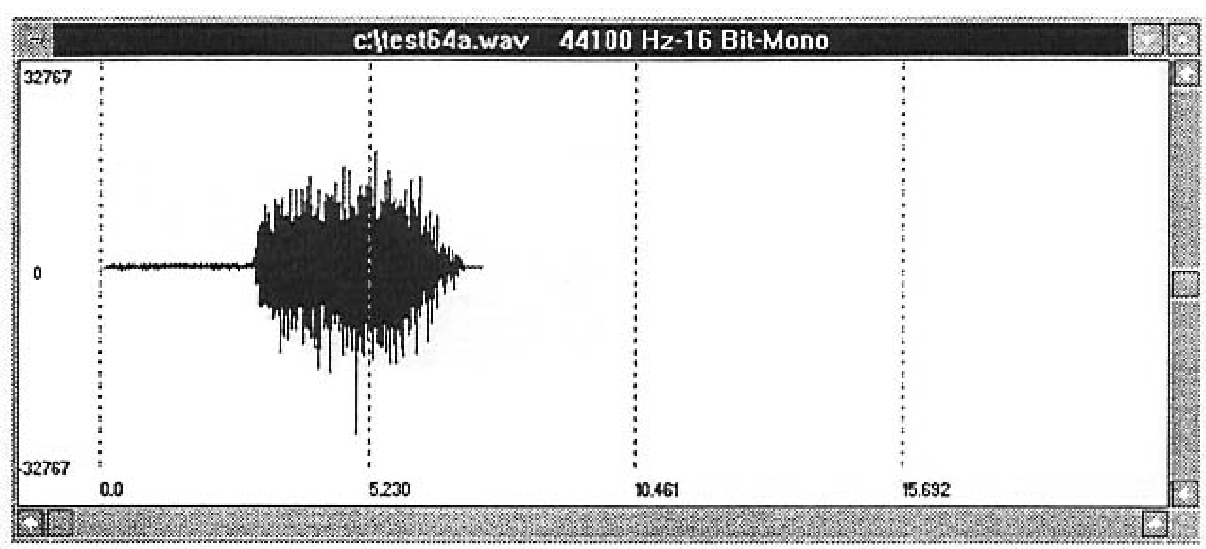

Figure 5. Typical microphone data.

steady-state portion of the firing, slight oscillations were observed at 450, 900, and 1800 Hz. However, the magnitudes of the majority of the oscillations were lower than that of the specified linearity for the transducer, therefore, the exact magnitude is uncertain. In routine firings, the Keller transducer will continue to be used but will have its sampling rate increased in an attempt to capture the 450 Hz pressure oscillations.

Previous work on plume flicker with a different transducer exhibited frequencies at 430 Hz, therefore, there is confidence that the oscillations in the plume flicker are repeatable. The plume flicker and pressure oscillations were detected at the same points in time. The initial spike of the plume flicker data was detected 0.2 seconds after the initial pressure spike. This can be explained by considering two points. First, that the propane flame/plume is a gaseous selective radiator and that the motor may not have an actual plume at this point in time. Second, that the actual rocket plume resulting from the HTPB fuel is a particle-laden plume, with a large blackbody emission, giving significant optical radiation for monitoring plume flicker.[4] If there is, in fact, any plume resulting from the propane ignition, it will exhibit a very weak optical emission spectrum. In any case, this shows that the use of plume flicker data provides a good indicator of the pressure oscillations in a hybrid rocket motor. Flicker monitoring should also be applicable in solid propellant systems and other particle-laden plumes.

Conclusions

It was possible to detect and correlate pressure and plume flicker oscillations in our labscale hybrid motor. By using this method, future investigators may find a non-invasive alternative to the use of expensive pressure transducers for certain combustion monitoring activities. The acoustic output did not prove to be useful in this study, since it consisted of white noise. The study in this area will continue with the addition of a thrust sensor to the system. Further plume data will be taken, correlating pressure in addition to the parameters monitored here, and also focusing on particular regions of the plume.

Acknowledgments

The authors would like to thank William St. Cyr and personnel at the NASA Stennis Space Center for the loan of the Kistler equipment and to NASA Grant NCCW-55 for support of this work. Thanks also to Richard Cadille of Kistler Instrument Corp. (Amherst, NY) for providing the filter to accurately obtain pressure data. Reagan Cole was instrumental in helping to develop the flicker transducer. Paul McLeod and Doug Wilson were also of great help in the analysis of the data and Armand Tomany with all fabrication needs. The W-Plot software written by Bill Hood was very useful for data analysis. This paper was originally presented at the 1996 AIAA Joint Propulsion Conference and Exhibit, Lake Buena Vista, Florida (July 1996), AIAA paper number 96-2834.

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