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Dynamic ICP® Pressure Sensors

For Detection of Combustion Instability and High Intensity in Rocket Motor Research

Dynamic ICP® Pressure Sensors for Detection of Combustion Instability and High Intensity Acoustics in Rocket Motor Research

Abstract

Rocket motor combustion instability is caused by pressure fluctuations and acoustic resonances in the combustion chamber, which may reduce engine performance, induce structural vibration, and possibly lead to catastrophic failure by a break-down of the thermal insulating boundary layer of the nozzle or other engine component. It is difficult to model in three dimensions during rocket motor design, even with modern computing power, and can be hard to eliminate. Dynamic quartz piezoelectric pressure sensors are available to assist design engineers in studying combustion instability problems. Piezoelectric ICP® (Integrated Circuit Piezoelectric) pressure sensors are rugged, hermetically sealed, and structured with acceleration-compensated quartz sensing elements that detect rapid pressure transients, pulsations, turbulence, noise, and spikes. Quartz piezoelectric pressure sensors monitor dynamic pressure while subjected to high static background pressure. ICP® output features on-board electronics to provide conditioned output signal and ease of use. Many physical configurations are available with various Aerospace Standard fitting sizes. This paper will discuss their effectiveness in helping a design engineer to study rocket motor combustion instabilities, and assist in proper sensor selection.

Introduction

Combustion instability is a combination of internal combustion and flow processes with natural acoustic resonances. Unstable combustion occurs when pressure pulses are in phase with oscillations in heat release and resultant gas expansion.[1] The acoustic modes are primarily a function of combustor geometry. Liquid rocket motors are also affected by injector patterns, while solid motors may be affected by something passing through the motors, such as un-burned propellant or a sudden increase in burning surface area due to propellant voids in the fuel.[2] Every passage or chamber has some acoustic resonance, the most common example being a large church organ. The very nature of the music is created by the various tubes being excited into resonance by air flow.

Combustion instability can lead to unsteady thrust resulting in structural vibrations, an uncomfortable ride for astronauts or payload, difficulty with guidance systems, and in extreme cases, erosion of the chamber wall, resulting in catastrophic motor failure. Amplitudes of damaging combustion instability can range from a few hundred psi for small solid rocket motors to the low thousands of psi for large liquid motors. Most damaging frequencies occur in the low Hz to low kHz band.

Analysis Tools

Lacking perfect computation models, design engineers have resolved problems of combustion instability with experimental analysis. Prior to the availability of solid state quartz piezoelectric sensors, test facilities relied on strain gage technology. The limits of this technology were primarily temperature, resolution and lack of high frequency response. The temperature problem was often solved by use of a standoff tube that moved the sensor a distance away where the operating temperature could be maintained. However, the standoff tube itself was an acoustic resonator, and therefore was not very useful for the kilo-hertz bandwidth required to study instabilities, as shown in Figure 1.

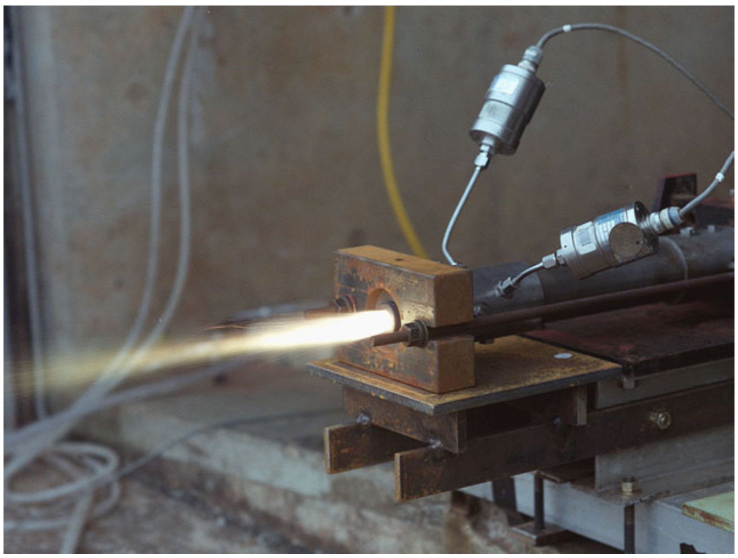


Figure 1
Hybrid rocket motor test, showing strain gage pressure sensors installed via long stand off tube in the motor's combustion chamber
(NASA Marshall Space Flight Center Collection, 1997-06-10)

Strain gage technology requires the ability to operate at or near full scale output, yet it is desired by test engineers to measure tiny pressure pulses of only a few percent of full scale. These devices would typically have at most 20 to 30 mili-Volts output at full scale. The chance for noise encountered across long cable runs compounded the problem, since test cells are often large outdoor structures, with control rooms and signal conditioning electronics located far from the sensor, therefore making small changes in pressure hard to detect.

Quartz piezoelectric sensors for rocket motor combustion instability testing were used as early as 1966. ICP® pressure sensors, structured with naturally piezoelectric, stable quartz sensing elements, are well-suited to measure rapidly-changing pressure fluctuations over a wide amplitude and frequency range.

The sensors are AC coupled and designed to operate in very high static pressures. For example, a sensor rated for 1000 psi dynamic pressure, has a maximum pressure rating of 5000 psi and a broadband resolution of 0.020 psi. Solid-state construction, hermetically-sealed housings, and laser-welded construction provide undistorted high frequency response and durability, even in adverse environmental conditions such as rocket motor combustion.

The maximum operating temperature quartz rocket motor sensors, with ICP® output is 250 °F. However, rocket motors with long burn times can exceed this temperature in tens of mili-seconds. Helium-bleed and Water-cooled Series 122, 123 and 124 sensor, (example Figure 2) were designed expressly for measurement of combustion instability in rocket motor combustors.

Figure 2
Series 123B Helium-Bleed, Water-Cooled
Rocket Motor Sensor

The helium bleed concept originated from work performed at the Guggenheim Laboratories of Princeton University[3] in 1965. It involves a blanket of cool Helium gas flow around the body and diaphragm of the quartz transducer. This enveloping gas cools the transducer, insulates it against the hot combustion gases, fills the passage in front of the sensor, and greatly improves the frequency response of the connecting passage by a factor of three. To avoid backflow of hot gasses into the passage, the Helium pressure is maintained at two times the expected static combustion pressure.

Water cooling, with an open internal passage surrounding the sensing element, allows for maximum thermal stability and extends sensor operating temperature. Combined with a coating of ceramic on the outer adapter for ablative purposes, the sensor may be used in long burning tests and high soak temperatures after motor shutdown.

Water cooling tests, with a thermocouple inserted into the water cooled housing (Figure 3) show that the a cooling flow rate of 0.059 gal/min kept the location of the thermocouple at 337 °F, while the entire structure was soaking in a thermal chamber at 1000 °F. Further testing showed increased flow rates to have a diminishing effect past 0.18 gal/min (approx 50 psi), with a reduced temperature of 192 °F. This is fine for charge output style sensor, but if better signal to noise ratios are desired, ICP® technology should be used. This means that the charge amplifier is built in to the sensor. These devices are typical limited to 250 °F, so additional thermocouples were installed in this area of the water cooled housing, (Figure 4) showing electronic temperatures as low as 100 °F, more than adequate for ICP® technology. Figures 5 and 6 show plots of the thermocouple output versus flow rate for the sensor and electronic locations respectively.

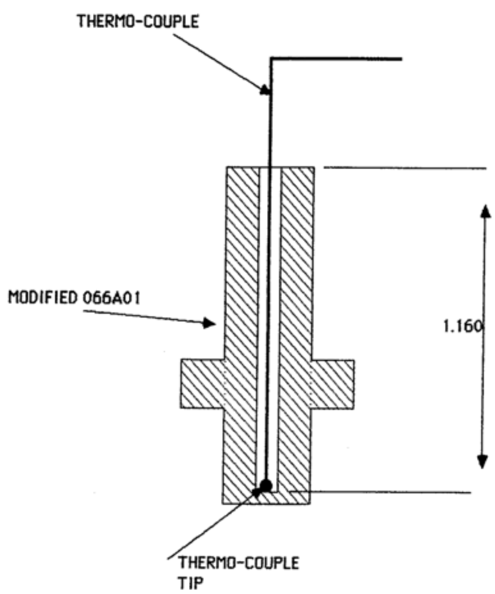


Figure 3
Thermocouple Location Simulating Sensor Location

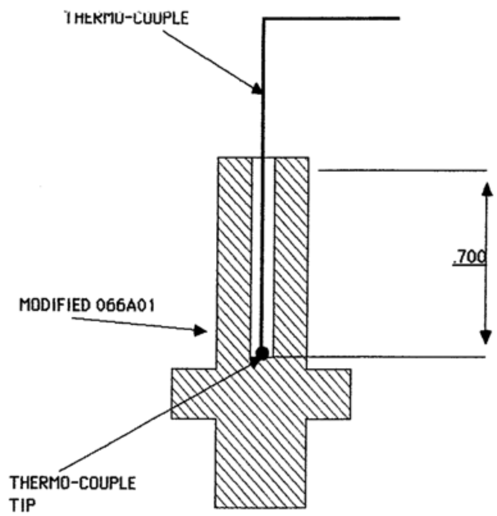


Figure 4
Thermocouple Location Simulating Electronics

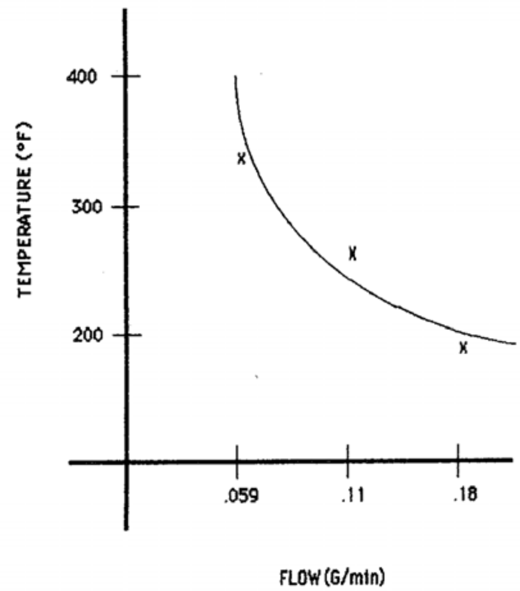


Figure 5

Temperature of Sensor Location Vs. Flow Rate in 1000 °F Oven

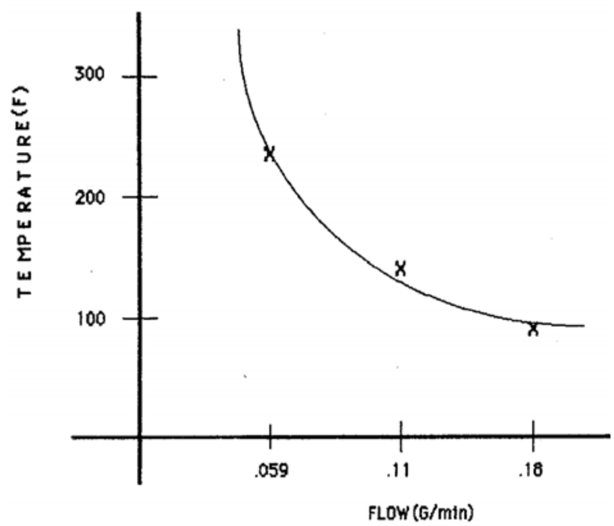


Figure 6

Temperature of Electronics Location Vs. Flow Rate in 1000 °F Oven

Gas Passage Resonances

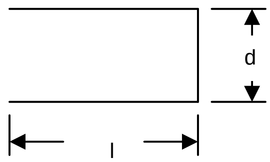
One challenge often faced with combustion instability measurement is how to successfully mount the sensor in the combustion chamber. In order to facilitate water cooling, the pressure sensor diaphragm must be located in a recessed manner. This allows coolant to flow completely around the sensing element. However, long passage lengths that lead up to the diaphragm can suffer from their own resonant frequencies. The resonance of a simplistic example for a passage of constant diameter and closed on one end (the sensor diaphragm) may be calculated by knowing that the wavelength of the passage is equal to four times the length.

For example, let us say we have an installation with a 1.0 inch passage length and 0.10 inch diameter as depicted below. The formula to calculate passage resonance is:

$f_n = c/(4L)$ where c = speed of sound in the gas and L = effective length of the passage

The effective passage length is the sum of the linear length of the passage plus forty percent of the diameter.

$L = l + 0.4d$



Using the speed of sound in air at STP, c = 1085 ft/sec, or 13,021 inch/sec, the resonant frequency in the example above is 12.5 kHz. When Helium, a gas with less density leading to a faster speed of sound, is used for the calculation, the result is 36.7 kHz.

Modern Installations

Quartz piezoelectric pressure sensors are ideal for rocket motor testing to verify instabilities during motor firings. One such example was a hybrid engine comprised of solid fuel and liquid oxidizer. Testing performed on the rocket motor used a Series 124A water cooled sensor mounted in the combustion chamber. Figure 7 shows the sensor installed in the motor's combustion chamber in front of the nozzle exit.

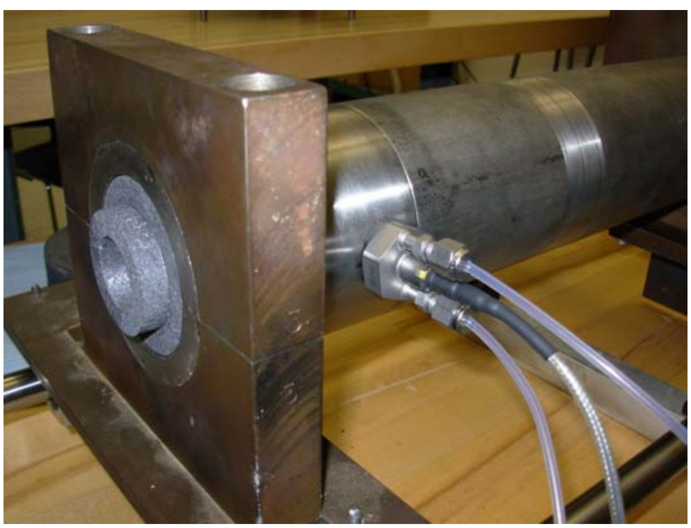


Figure 7
Model 124A24 ICP® Rocket Motor Sensor installed in Meteor Hybrid Rocket Motor Combustion

Example Data

An example set of data is presented in Figure 8 for the hybrid motor shows how the combustion instability may appear for a solid or hybrid rocket motor. Solid motor technology shows a gradual increase in chamber pressure as the surface area of the propellant increases due to expanding chamber volume. The oscillation, evident at approximately six seconds, is most common in solid motors and is caused by voids or bits of un-burned propellant breaking off into the gas flow.

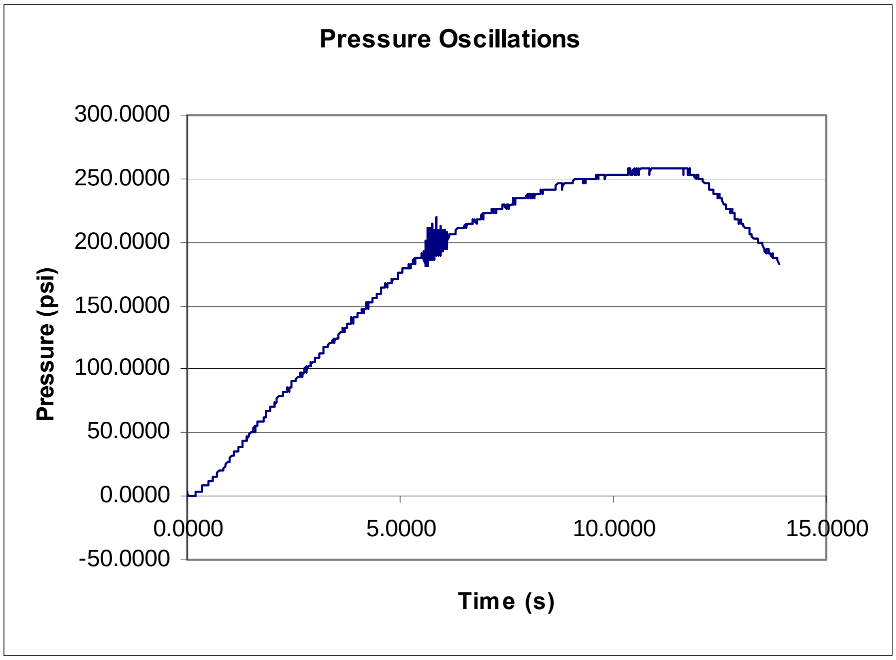


Figure 8

Dynamic Pressure Test Data

Cryogenic Sensors

Liquid rocket motors must carry condensed fuels in a cryogenic state. A popular fuel mix is Hydrogen and Oxygen. The rocket motor is fed by cryogenic turbo pumps, and their job is to pump the fuel from the tank and pressurize it. Cryogenic pressure sensors are ideal for evaluation of frequency oscillations of fuel and oxidizer turbo pumps, which can cause cyclic variations in thrust, and can damage payloads or the rocket. They are also useful for studying liquid rocket injector performance. Quartz piezoelectric pressure sensors were first used to successfully measure uneven fuel flow in liquid rocket engines that caused a “pogo” effect, which is a vibratory motion in multistage rockets caused by uneven fuel burning.

Figure 9

Cryogenic Pressure Sensor

These sensors are a special version of high-resolution, ICP® quartz sensors and are designed for cryogenic environments using special cryogenic microelectronics. Each sensor is qualification tested in liquid Nitrogen. Series 102A10 sensors provide a variety of ranges and sensitivities that measure dynamic pressures from 0.01 to 5000 psi starting at any static level from full vacuum to 15,000 psi. The ICP® cryogenic sensor uses an internal high-pass filter to eliminate the static pressure component of the signal, allowing measurement of low-pressure fluid born noise, oscillations, and surges under high static loading.

Summary

Combustion instability due to acoustics in the chamber or fuel supply issues is a common design problem that is not easy to model. Water-cooled, Helium-bleed, and cryogenic ICP® pressure sensors detect rapid pressure transients, pulsations, turbulence, noise, and spikes. The pressure sensors monitor dynamic pressure while subjected to high static background pressure. ICP® output features on-board electronics to provide conditioned output signal and ease of use. All of these tools assist in finding very small dynamic pressure instabilities, allowing the test engineer to find the source and correct the design problem. Water-cooling and Helium-bleed injection allows the ICP® output pressure sensor to operate at extremely high temperatures in rocket motor combustion environments.

References

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