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Enhanced Static-Dynamic Pressure Transducer for the Detection of Acoustic Level Flow Instabilities in Gas Turbine Engines

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ABSTRACT

The push to advance the performance and longevity of gas turbine engines requires better characterization of flow instabilities within the compressor and most importantly the combustor. Detecting the earliest onset of these flow instabilities can help engineers either manipulate the flow to re-stabilize it or make informed design changes to the engine. The pressures within gas turbine engines are typically composed of an undesired, low-level oscillatory pressure of less than 1kPa to several kPa superimposed on top of a large, relatively constant pressure of several thousand kPa [1-7]. The high-pressure transducers used to measure the pressures within these environments are often unable to resolve these low-level oscillatory pressures that characterize the flow instabilities because the signal output for such pressures is often the same level as the noise within the sensor-data acquisition system. This paper presents an engine test ready, high temperature, combined static and dynamic pressure transducer that uses static pressure compensation in order to measure these low-level dynamic pressures with an excellent signal to noise ratio and, at the same time, captures the overall static pressure within a gas turbine [8-10].

Test bench experiments demonstrate the static-dynamic transducer's unique ability to capture both large static or quasi-static pressures of 1,380kPa or greater and simultaneously measure the acoustic-level dynamic pressures superimposed on top of these pressures. The static-dynamic transducer achieves this advanced sensitivity through the use of a low-pass acoustic filter that passes the large static pressure to the reference port of a high sensitivity dynamic pressure sensor within the transducer such that the overall static pressures cancel out and the sensor measures all acoustic-level dynamic pressures. These bench tests additionally demonstrate the transducer's ability to operate reliably when exposed to the harsh, high temperature environment (up to 500°C) within a gas turbine [8-10].

INTRODUCTION

Gas turbines are a low capital cost, efficient solution to meet power generation and propulsion needs. They can be implemented in combined-cycle power plants, which achieve efficiencies of ~60 percent [4]. Such high efficiencies lead to lower emissions of CO_2 and NO_x. With the push to further advance efficiencies and reduce emissions, gas turbines operate below the stoichiometric air/fuel ratio. In addition, gas turbines are being operated with new biofuels and synthetic gas derived from coal. Fuel lean air-fuel mixtures and changes in the type of gas used in turbines have increased combustion instability issues. Tim Lieuwen and Keith McManus explain in their article "That Elusive Hum" that these instabilities are manifested through unsteady pressures, heat releases and flow rates [3]. The underlying driving factors of these flow instabilities are not understood and modeling turbulent combustion has yet to be fully developed. Therefore, engineers typically rely on experimental test results in order to make informed design decisions. Engineers have further examined reducing such instabilities by using combustion active feedback control systems. However, these systems must operate extremely fast to capture flow instabilities, analyze the instabilities and then adjust the reactive mixture or other parameter of the system to re-stabilize the flow. Therefore, the earlier flow instabilities are detected the more time there is for the active control system to stabilize it [2-4].

Historically, dynamic pressure transducers have been used to map the flow within turbines. Unfortunately, the high-pressure, high temperature transducers typically used in gas turbines struggle to accurately capture the earliest onset of the acoustic-level pressures that characterize the flow instabilities because the signal to noise ratio is poor for such low pressures in the high temperature, noisy gas turbine environment. In other words, the sensitivity of the high-pressure transducers is low, giving rise to a poor signal to noise ratio. While thermal noise within the transducer is typically low, gas turbines have many rotating components that generate significant electrical noise. Further, most transducers are unable to be flush mounted to the flow within the turbine due to temperature limitations. Consequently, the frequency response of many turbine transducers is limited by the recess tubes or semi-infinite tubes used in mounting.

The static-dynamic transducer was developed with two independent sensors to enable gas turbine engineers to accurately measure the high static pressure within their turbine and simultaneously capture any acoustic-level dynamic pressures superimposed on top of the large static pressure that characterize these flow instabilities. The static-dynamic transducer was designed to operate at temperatures up to 500°C so that engineers could mount the pressure transducer flush to the flow and achieve a high bandwidth frequency response without attenuation or phase shift. The dynamic sensor within the transducer uses a mechanical low-pass filter to provide static pressure compensation. This mechanical filter uses viscous dissipation to dampen out all low-level dynamic pressures within the high-pressure environment, passing just the large static pressure to the backside of the dynamic sensor's diaphragm, effectively canceling out the impact of the large static pressure upon the sensor. Thereby, the dynamic sensor accurately detects the earliest onset of acoustic-level oscillatory pressures [8-10].

This paper presents the industry ready design and packaging of the static-dynamic transducer. It further discusses the experimental testing, compensation and dynamic pressure characterization of the transducer.

PRESSURE SENSING ELEMENTS AND PACKAGING

The static-dynamic transducer uses two independent silicon-on-insulator (SOI) piezoresistive pressure sensors that are fabricated on a single chip. SOI piezoresistive sensors perform well in the harsh, high temperature environments such as those within gas turbine engines [11, 12].

The static sensor on the chip has a small diaphragm, which makes it ideal for sensing high pressures of 1,380kPa and greater, as displayed in right section of the structure of Figure 1. The dynamic sensor, on the other hand, has a larger diaphragm which enables it to deflect more under low pressures in the range of 103kPa, as illustrated in the left section of Figure 1 [13, 14]. As pressure is applied, the diaphragms deflect, inducing a strain in the piezoresistors, which generates a voltage change. The voltage change directly correlates with the pressure in the environment.

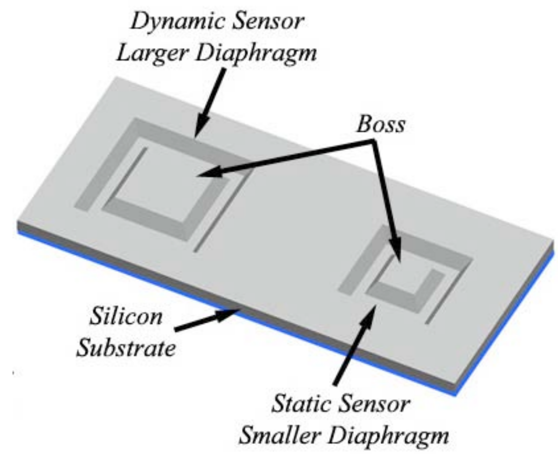

Figure 1: Static and dynamic sensors on a single structure.

The piezoresistors are encapsulated in a high temperature glass that has a structural "stop" in it. The structural "stop" micromachined into the glass allows the diaphragms to deflect to a maximum value well within the elastic region of the silicon. In the event the sensors are exposed to a large overpressure the diaphragms will not fracture but instead deflect until they come in contact with the "stop," which then prevents any further deflection. Figure 2 illustrates the static and dynamic sensors on a single chip with the encapsulating glass and "stops" [15].

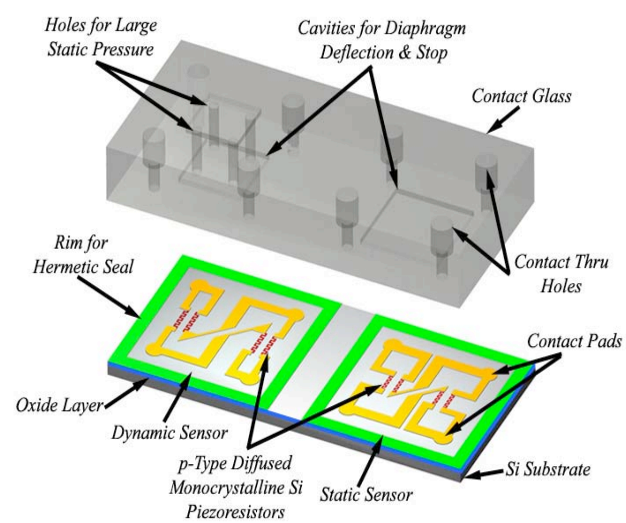

Figure 2: Leadless schematic with contact glass

To ensure that the low-pressure dynamic sensors do not fail during unforeseen rapid overpressures, the low-pressure dynamic sensors are tested to large overpressures, typically up to 6,895kPa. Stop depths were determined using empirical data and Timoshenko's equation for the deflection of a square plate with clamped edges:

$$w = \alpha \frac{q a^4}{E h^3}$$

q is the pressure on the diaphragm, a is the width of the square, E is Young's modulus (160GPa for silicon), and h is the thickness of the diaphragm [16]. The dimensions of a piezoresistive silicon pressure sensor are typically 1000 X 1000 micron square with a thickness of 20microns depending on the desired pressure range [17]. The numerical factor, α, was estimated from experimental results. Stop depth is determined for every pressure range and typically designed such that the sensor stops at approximately three times the rated pressure. For a 103kPa sensor, the depth of the "stop" was set such that the sensor is prevented from deflecting further at approximately 310kPa. The results below in Figure 3 illustrate that the sensor is operating properly by stopping at ~275kPa and withstanding an overpressure of 4,135kPa (3X the rated pressure of the static sensor).

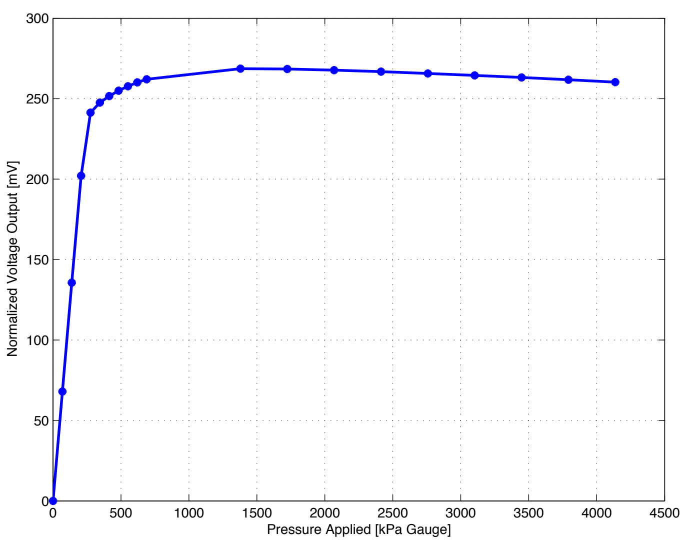

Figure 3: Overpressure test of "stopped" dynamic sensor.

Once the 4,135kPa is reached the pressure is removed to determine if there is any change in the zero pressure reading. The change from the initial zero reading to the return zero reading was 0.03% of the full-scale output of the sensor, which is marginal [15].

The static and dynamic sensors on a single chip are assembled using a leadless packaging method in order to ruggedize the sensors for high temperature and/or corrosive environments [18-20]. The key feature of the leadless packaging technique is that the electrical interconnects between the sensor chip and the transducer body are made with a high temperature metal/glass material that is encapsulated rather than the typical gold ball bonded technique. The sensor chip is assembled into a screw housing. Figure 4 shows the static and dynamic sensors assembled into the screw housing with a replaceable low-pass mechanical filter module.

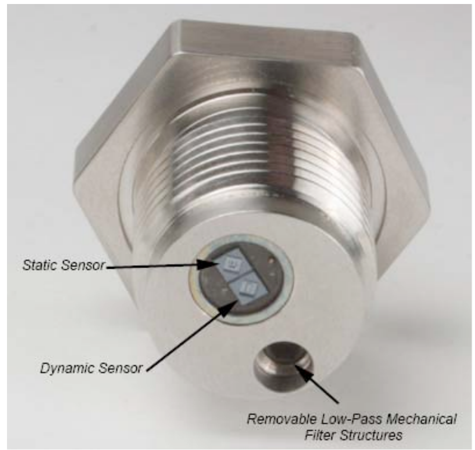

Figure 4: Static and dynamic sensors mounted into screw housing with replaceable low-pass mechanical filter module.

One of the features of this design is that the patented low-pass mechanical filter structures are built into a removable and replaceable module [5, 6]. In the event these filter structures clog with soot or debris, users can remove and clean and/or replace the filter module using a hex key. Figure 5 is a schematic of the filter module.

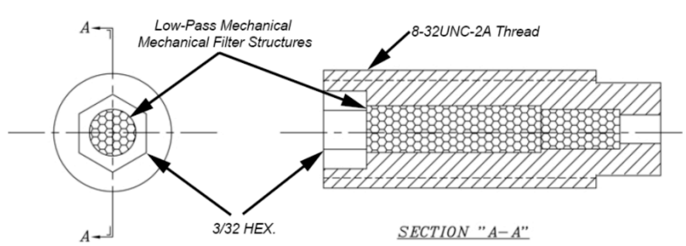

Figure 5: Removable filter module [5, 6].

The screw housing with the filter module, containing the low-pass mechanical filtering structures is then assembled into a fully high temperature package that can withstand 500°C at its frontend, and approximately 350°C at the backend, where the cable attaches to the unit [20].

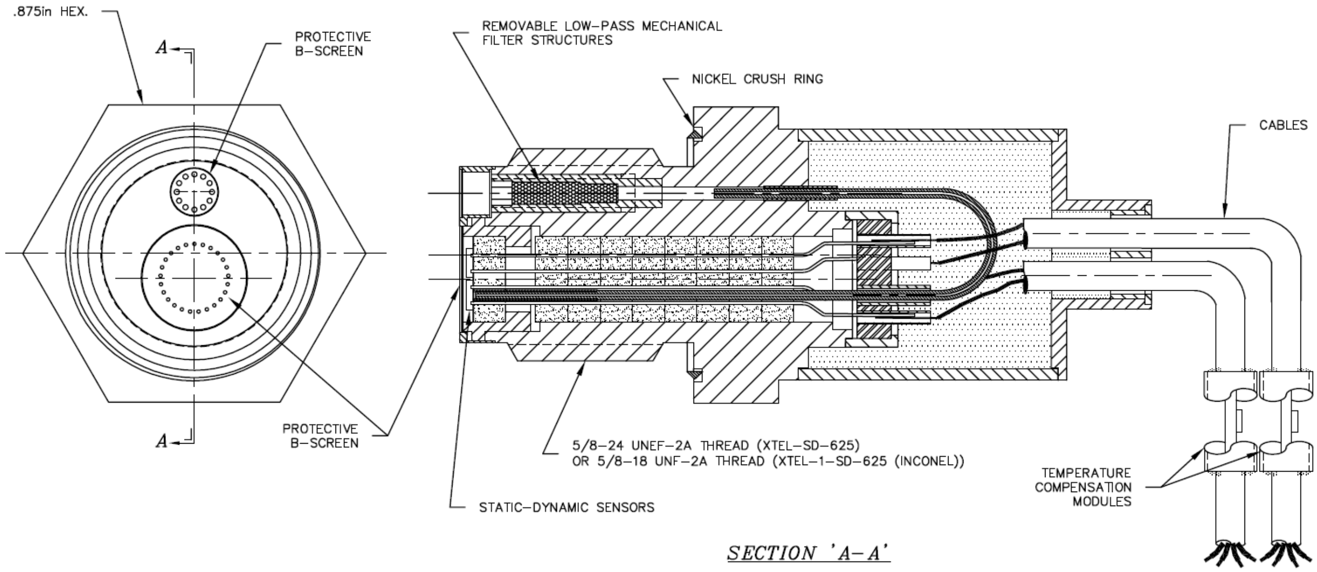

Figure 6: Static-dynamic transducer assembly

Figure 6 is a cross sectional view of a fully assembled, industry ready static-dynamic transducer designed for high temperature operation. All components, from the low-pass mechanical filtering structures to the cable connections, are designed for high temperatures and high vibration environments [18-20]. A photograph of a fully assembled static-dynamic transducer can be found in Figure 7, below.

Figure 7: Photograph of fully assembled static-dynamic transducer (screen over removable filter module not shown).

The static-dynamic transducer has a tip diameter of 0.545inches (13.84mm) and two thread types, 5/8-24 UNEF-2A and 5/8-18 UNF-2A. This size is relatively large in comparison to the typically probe size desired for gas turbine instrumentation. Smaller package sizes are currently being explored that can fit a dual sensor chip and mechanical low pass filter to achieve static pressure compensation.

TRANSDUCER PERFORMANCE CHARACTERISTICS

The static-dynamic transducer is evaluated under constant pressure conditions to determine the sensitivity of both the static and dynamic sensors. Such static pressure calibration is done at multiple temperature points to fully characterize the thermal sensitivity and zero shifts. With this data, a passive resistor based compensation scheme is implemented for both sensors to correct for thermal sensitivity and zero shifts. Such passive thermal compensation reduces the thermal sensitivity and zero shifts to within ±2.7% of the full scale output per 100°C up to 449°C [21].

The low-pass mechanical filter, which provides static pressure compensation to the dynamic sensor, is characterized using a dynamic pressure generator. The dynamic pressure generator has a high speed motor that spins a rotating valve thereby creating a low-level dynamic pressure that oscillates at frequencies of ~10Hz up to ~2kHz. The dynamic pressure generator is swept from 10Hz to 2kHz with the static-dynamic transducer exposed to the oscillating flow. A low-pressure reference transducer, (XCQ-062-103kPa Differential), is also mounted flush to the flow. The performance of the low-pass mechanical filter and dynamic sensor within the static-dynamic transducer is then evaluated by comparing the output of the reference sensor to that of the dynamic sensor. To examine the performance at all frequencies, a transfer function is computed comparing the reference and dynamic sensor output. Figure 8 displays the resulting experimental transfer function [22].

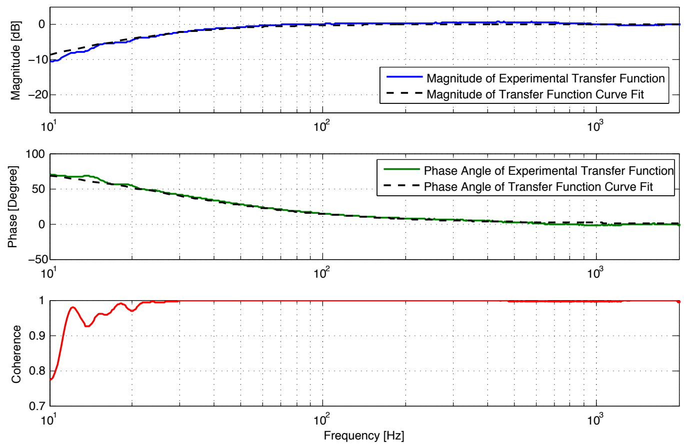

Figure 8: Dynamic sensor of static-dynamic transducer experimental spectral response.

As expected, Figure 8 exhibits roll-off at low frequencies with a -6dB point at approximately 15Hz. This roll-off is the result of the low-pass mechanical filtering structures passing the slowly oscillating and static pressures to the backside of the dynamic sensor's diaphragm, which leads to them canceling each other. Due to the intricacies of the low-pass mechanical filter, there is some variability between filters with the -6dB point falling between 10 and 20Hz.

Since the dynamic pressure generator is limited to a range of 10Hz to 2kHz, a transfer function curve fit was applied to the results so that the performance of the transducer could be extrapolated beyond this limited frequency range. The equation of the transfer function, *G,* curve fit, which is shown in Figure 8, is displayed below:

$$G(j\omega) = \frac{0.0064 * j\omega}{0.0064 * j\omega + 1}$$

where j is a complex number and ω is the angular frequency in radians per second [22]. This transfer function curve fit can be used to better understand the performance of the dynamic sensor outside the experimentally tested range. The results displayed in Figure 8 indicate that the dynamic sensor and low-pass mechanical filter within the static-dynamic transducer are performing as desired, making it possible for low-level pressure instabilities superimposed on top of static pressures to be measured far more accurately.

CONCLUSION

The static-dynamic pressure transducer is a solution to the problem of measuring high frequency acoustic-level pressure instabilities that may exist on top of the high pressures within the combustors and compressors of gas turbines. With the enhanced sensitivity of the dynamic sensor within the static-dynamic transducer, engineers will be able to detect flow instabilities earlier which will advance active control systems and enable more informed design decisions. The test bench experimental results demonstrate the static-dynamic transducers ability to operate at temperatures as high as 500°C and capture low-level dynamic pressures. With these high temperature capabilities, the static-dynamic transducer can replace the commonly used semi-infinite tubes and provide a better frequency response along with measurement of the large static pressure and, most importantly, an enhanced sensitivity for acoustic level dynamic pressures riding on top of the static pressure to enable engineers to reduce gas turbine flow instabilities and advance efficiencies. Future work will involve evaluating the transducer's performance on a gas turbine by comparing it to the commonly used semi-infinite tube pressure probes. Additional work will be done to advance the temperature capabilities of the sensor so that it can be used in numerous locations on an engine.

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