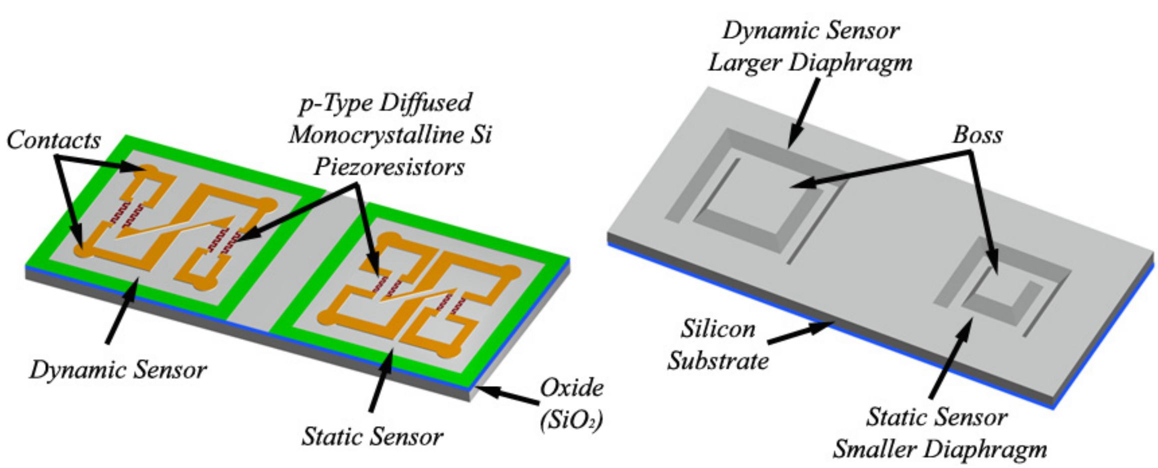
STATIC-DYNAMIC TRANSDUCER APPLICATION NOTE

STATIC-DYNAMIC TRANSDUCER
XTEL-4-SD-625/XTEL-5-SD-625

1) <u>Background:</u> Gas turbines can exhibit low-level flow instabilities within their compressor or combustion chamber. Historically, it has been challenging to measure such flow instabilities because they are typically dynamic pressures that are a fraction of a psi to possibly $10\,psi$ superimposed on top of a high static pressure of $200\,psi$ or greater in the turbine. Pressure transducers designed to measure such large static pressures of $200\,psi$ or greater are unable to accurately capture such low-level flow instabilities because the signal generated from these low pressures are similar in magnitude to the noise level within the system.

To help gas turbine manufacturers detect and then solve such flow instabilities, Kulite Semiconductor Products Inc. has developed a piezoresistive sensor, which combines on a single chip a differential low-pressure high frequency dynamic sensor together with a high-pressure static sensor. The composite sensor is shown in Figure 1. One may note that the sensing diaphragm of the dynamic sensor is much larger than that of the static sensor and is a differential transducer instead of absolute. To fashion such a sensor from a single slice of silicon one requires the same thickness but different dimensions obtaining, therefore, different sensitivities. The Kulite static-dynamic transducer, shown in Figure 2 with the innovative patented [1,2] low-pass mechanical filtering structures to insure that the dynamic gauge pressure sensor will capture all high frequency pressure oscillations on the order of $10\,psi$ or less that may exist within the high-pressure environment of $200\,psi$ and greater within the turbine engine. While this dynamic transducer measures the low-pressure oscillatory signals that may exist, a second, high-pressure static sensor within the static-dynamic transducer measures the large pressures in the engine of $200\,psi$ and greater. In this way, a single transducer is capable of measuring high static or quasi-static pressures, while simultaneously measuring low-pressure dynamic signals with a high signal to noise ratio.



(a) (b)

Figure 1: Front (a) and back (b) of static-dynamic silicon-on-insulator sensing elements.

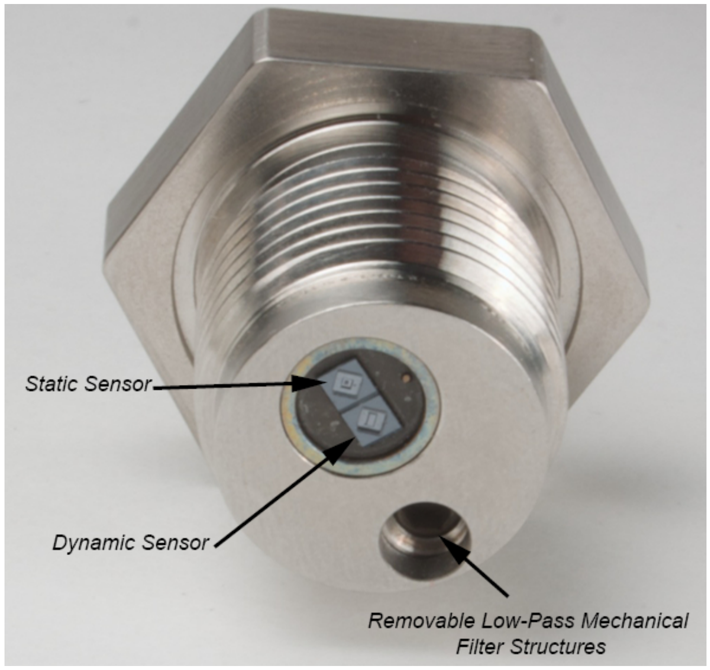


Figure 2: Photograph of static-dynamic sensors fabricated on a single structure.

2.) Installation and Operation: The static-dynamic transducer screws into a machined port on a gas turbine engine. The front of the transducer is capable of operation at temperatures up to 400°C (750°F). The backend of the unit and cable should be kept below temperatures of 274°C (525°F).

There are two versions of the static-dynamic transducer: XTEL-4-SD-625 and XTEL-5-SD-625. Both transducers feature a 5/8-18 UNF-2A thread along with a high temperature crush ring. Both series of transducers feature a Inconel 625 construction for material thermal matching thereby reducing the likelihood of the transducer seizing on the turbine. The XTEL-4-SD-625 is a standard 4-wire output transducer. The XTEL-5-SD-625 is a 5-wire output transducer with 2 voltage supply wires, 2 wires for the differential output from the Wheatsone bridge and a 5th wire that captures the temperature of the bridge. This 5-wire constructions enables advanced post-process temperature correction should the user record the output from the bridge that corresponds with pressure and the 5th wire output that corresponds with temperature.

In both versions of the static-dynamic transducer, the dynamic sensor and static sensor have individual cables. Both sensors require a voltage excitation of 10 VDC. There are two individual millivolt outputs, one that is for the large static pressure within the engine of $200 + psi$ and the second is for the acoustic-level oscillatory pressures from the dynamic only sensor. The innovative low-pass mechanical filter structures within the static-dynamic transducer are permanently built into the transducer. An outline draing that captures the mechanical features of both lines of transducers is shown in Figure 3 below. There is a threaded port with a 2-56 thread that enables static pressure calibration for the dynamic sensor specifically.

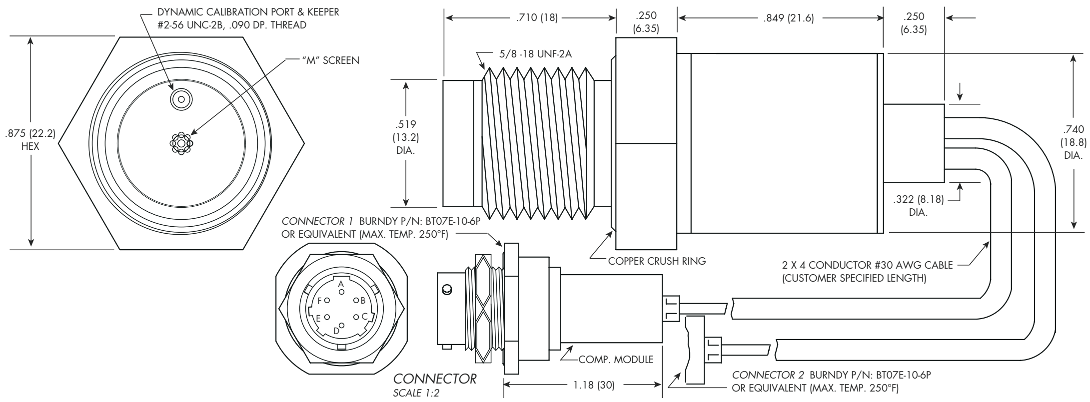


Figure 3: Static-dynamic transducer outline.

3.) Low-Pass Mechanical Filter Structures & Static-Dynamic Transducer Bandwidth: The key advancement of the static-dynamic transducer is its unique ability to detect low-level dynamic pressure signals within a high pressure environment through the use of a mechanical filter. The static-dynamic transducer uses various mechanical structures to filter out high frequency dynamic pressure perturbations that may be superimposed on large static pressures. These large static pressures are then routed to the backside of the highly sensitive differential pressure sensor via a reference tube. In this way, the front of the differential sensor is exposed to the static plus the dynamic pressure, while the back is exposed only the static pressure. The sensor responds therefore to the difference of these two pressures which is the dynamic signal alone. Because the dynamic sensor responds only to the small dynamic signals that it was designed to detect, a substantially higher signal-to-noise ratio is achieved when compared to conventional measurement approaches.

To measure the larger static pressure a second sensor with a lower sensitivity is also included in the transducer. By combining the signals of the dynamic and static sensors, continuous improved-accuracy pressure measurements are achieved in high-pressure environments. Thus, the static-dynamic transducer uses a pressure transducer designed to measure low-pressures of less than $10\,psi$ to capture these low-level pressure oscillations rather than attempting to determine these pressure perturbations from a measurement made by a high pressure transducer, designed to measure large pressures of $200\,psi$ and greater.

Figure 4 below illustrates a typical situation where the static-dynamic transducer would be used. The actual pressure signal (shown in blue) is $2\,psi$ peak-to-peak AC pressure which is superimposed on top of a $200\,psi$ DC pressure. The static sensor (shown in red) can measure the DC portion of the signal, but its sensitivity is too low to effectively resolve the much smaller AC pressure. The dynamic sensor (shown in green), on the other hand, captures the AC pressure well because of its higher sensitivity. It filters out the DC pressure as is intended.

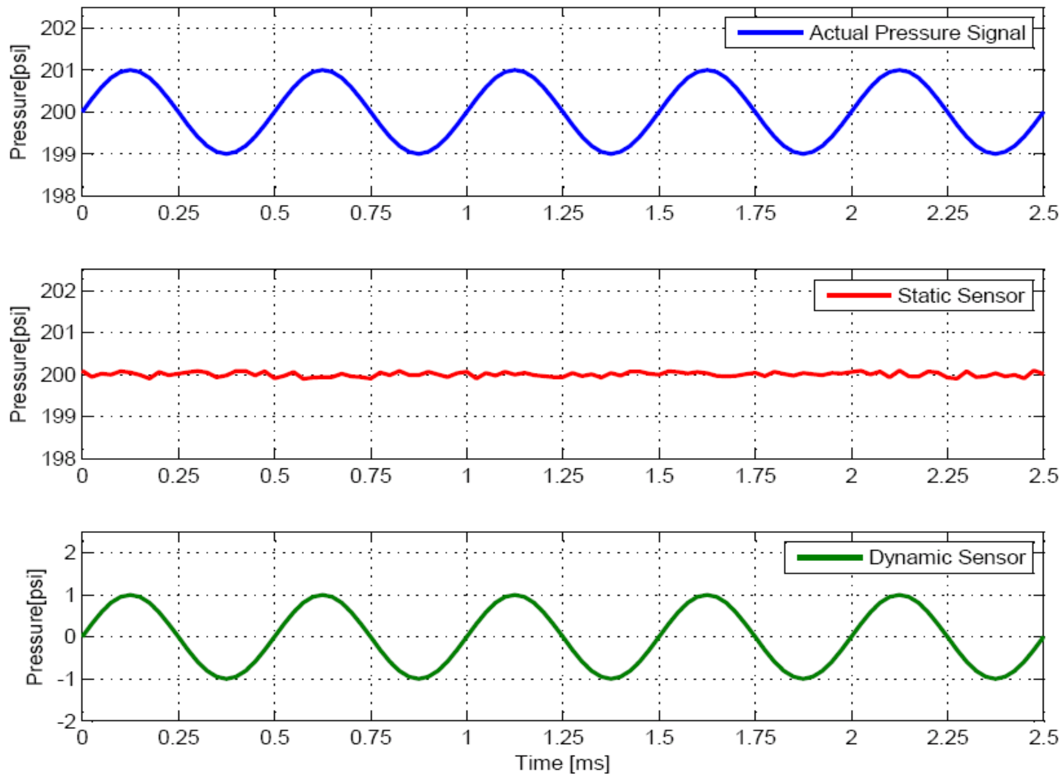


Figure 4: Outputs of the static-dynamic transducer for a typical pressure signal.

To characterize the frequency response of the static-dynamic transducer, a dynamic pressure source was swept from $10\ Hz\ to\ 2\ kHz$ and a transfer function was computed. Figure 5 is a Bode plot of the dynamic transducer's performance.

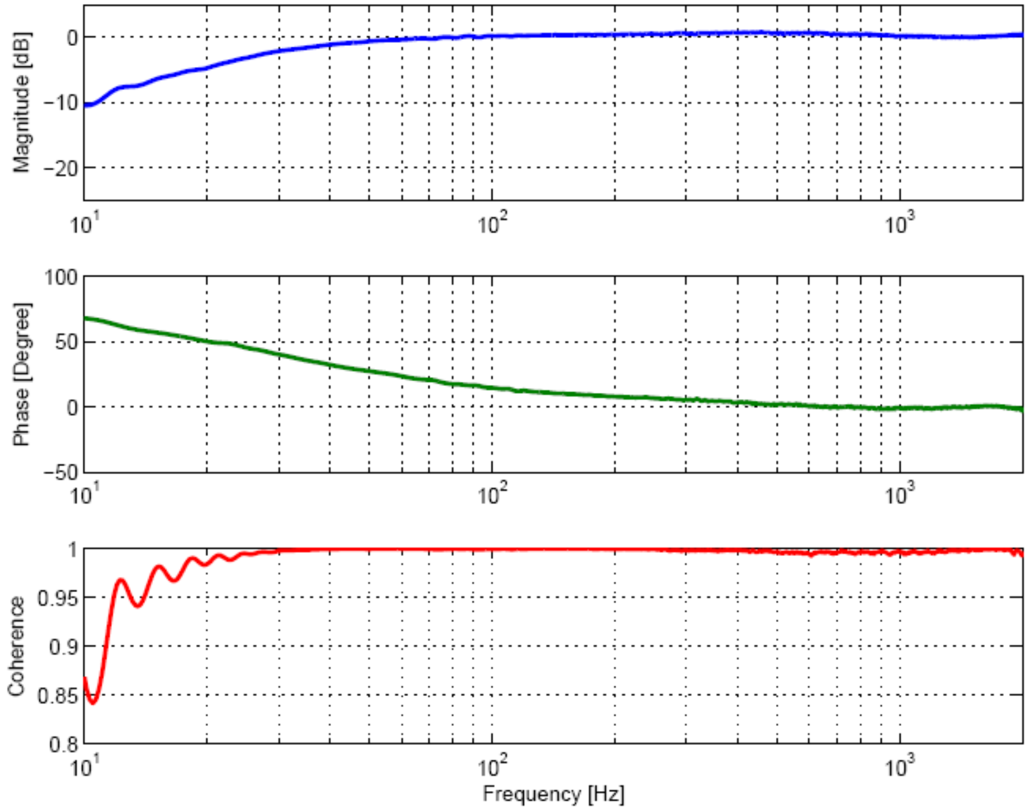


Figure 5: Dynamic sensor's spectral response.

The typical low-frequency cutoff frequency (-3 dB) of the dynamic transducer is $15\ \pm 10\ Hz$. (This cutoff frequency can be adjusted if desired). The flat bandwidth of the dynamic sensor extends to greater than $6.5\ kHz\ (\pm 2\ dB)$. The static sensor of the static-dynamic transducer likewise has a bandwidth of $DC\ to\ 6.5\ kHz\ (\pm 2dB)$. It is important to note that the static sensor accurately measures the overall static and quasi-static pressures within the environment.

4.) Data Acquisition & Processing: It is highly recommended that the user combine the static-dynamic transducer with a KSC-2 signal conditioning system in order to apply amplification along with antialiasing electrical filters. Effectively conditioned data can then be captured from the static-dynamic transducer through a standard voltage based data acquisition system. At the start of an experiment, before pressure has been applied to the transducer, a zero reading should be taken and recorded as a reference point. After taking this zero reading on both the static and dynamic sensors, the desired test can be completed. It is important for users to limit their cable length to $10\ ft$ or less for the unamplified signal from the static-dynamic pressure transducer as the cable length can result in an unwanted low-pass electrical filter due to the combined cable capacitance and the bridge resistance of the transducer.

The data from the static and dynamic sensors can be processed in real-time using the data acquisition software or post-processed using MATLAB or Python. The data should first be converted to pressure using the equations below:

$$P_{static} = \frac{(V_{static} - V_{static\,zero})}{Sensitivity_{static}}$$

$$P_{dynamic} = \frac{(V_{dynamic} - V_{dynamic\,zero})}{Sensitivity_{dynamic}}$$

In equation above, V_{static} and $V_{dynamic}$, are the static and dynamic voltages recorded with time by the data acquisition system in units of volts. Please note if any amplification is used this must be included in the equations above (gain not shown in equations). Similarly, $V_{static\,zero}$ and $V_{dynamic\,zero}$ are the zero readings of the respective sensors at atmospheric pressure. The sensitivities of the sensors are in units of Volts per psi. Applying the formula above converts the voltage output from the dynamic and static sensors into pressure.

The pressure data from the static sensor can provide engine manufacturers with the overall performance of their turbine. The static sensor will also capture any rapid changes in the large static pressure within the turbine. The dynamic sensor will measure any acoustic level pressure oscillations within the high-pressure environment above approximately $15\ Hz\ (Typ.)$. An example of a typical dataset captured by the dynamic sensor can be viewed in Figure 6 below.*

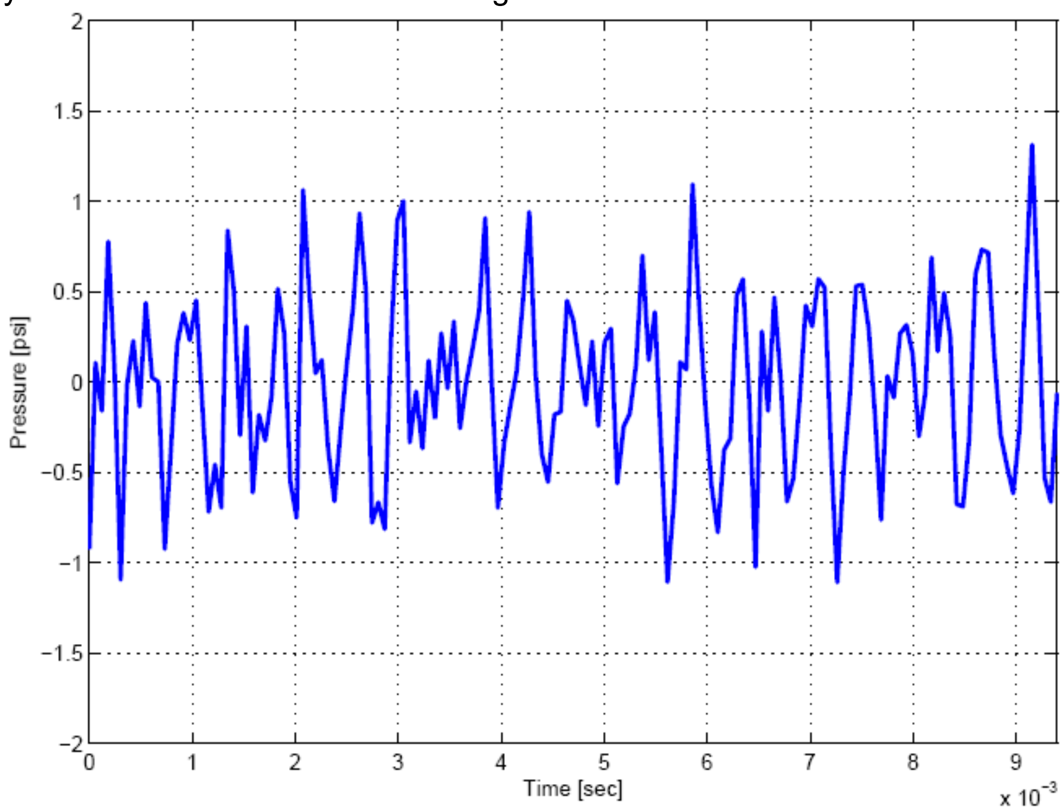


Figure 6: Sample pressure vs. time data captured by the dynamic sensor of the static-dynamic transducer. * Typical dataset.

In order to better understand the periodic signals within the example dynamic data presented above, this time-based data can be transferred into the frequency domain via the discrete Fourier transform. In the frequency domain, the sample data shown above provides well defined peaks at the major frequency components of the pressure signal. A plot of the Fourier transform of the sample dynamic sensor's data is displayed in Figure 7 below.

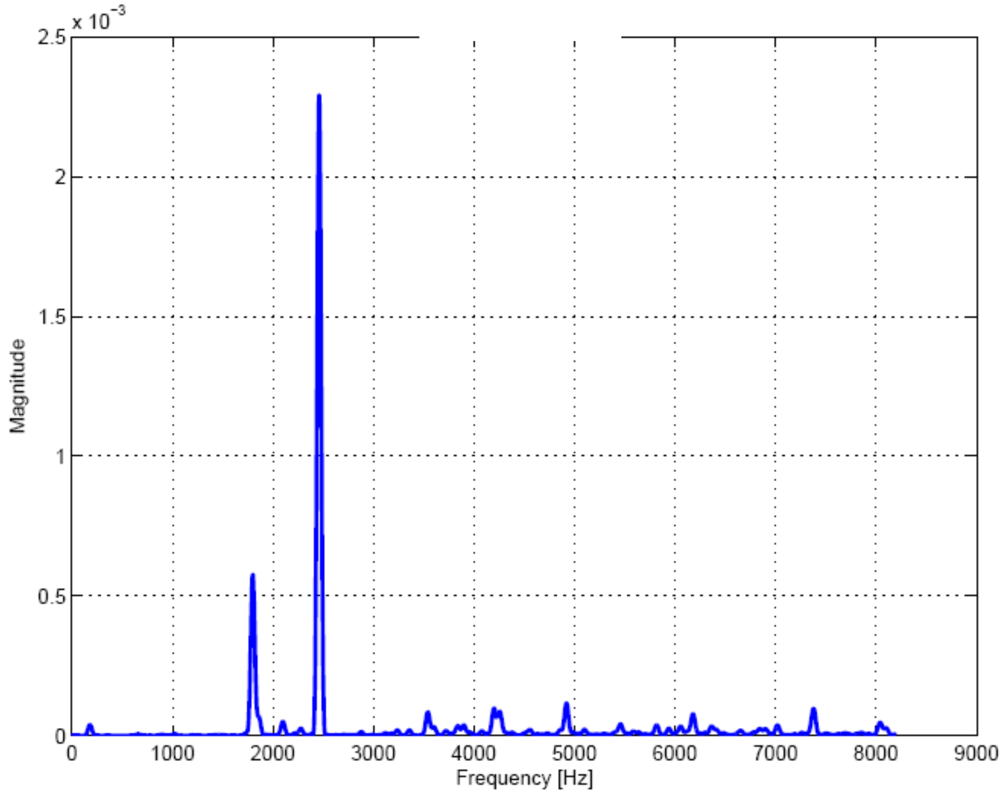


Figure 7: Fourier transform of sample dynamic sensor pressure measurement within a gas turbine. *Results are typical.

In gas turbines, the dynamic sensor of the static-dynamic transducer will often capture complex dynamic pressure signals. The Fourier transform is a powerful tool for analyzing the dynamic data in order to identify major frequency components of the signal, which will be apparent through the well-defined peaks in the frequency domain, as illustrated in Figure 7 above.

5.) Performance: Please refer to the data sheets for the specifications for the XTEL-4-SD-625 and the XTEL-5-SD-625 series of pressure transducers at www.kulite.com

6.) References:

[1] Kurtz, Anthony D. "Pressure transducer for measuring low dynamic pressures in the presence of high static pressures." U.S. Patent 7,107,853, 18 September 2006.

[2] Kurtz, Anthony D., Shang, Tonghuo, and Kochman, Boaz. "Low pass filter semiconductor structures for use in transducers for measuring low dynamic pressures in the presence of high static pressures." U.S. Patent 7,188,528, 13 March 2007.