High-Temperature and Hostile Environment Sensing Through Stress-Wave Propagation

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ABSTRACT

Current pressure and temperature sensing technologies are limited by the maximum operating temperature of the sensing materials (e.g. piezoelectric or strain gauge) and associated electronics. An application where this limitation is experienced is making hot-section pressure measurements in turbine engines – this is currently done using standoff tubes that permit piezoelectric-based sensors to be mounted in cooler, remote locations where they can operate reliably. These standoff tubes are prone to condensation and clogging and also limit the frequency range over which valid measurements can be made. Additionally, there are many locations where it would be beneficial to make measurements but it is not practical due to limited access and serviceability at these locations. Vibration monitoring of turbine engine main bearings is an example of such a limitation. A new sensing technology based on stress-wave propagation through fine wires enables many of these previously impractical measurements to be made reliably and accurately.

Etegent Technologies has developed two methods for extracting measurements (e.g. strain, force, acceleration, temperature, pressure) from stress-wave propagation characteristics: the “passive” waveguide sensor, and the “active” waveguide sensor.

PASSIVE WAVEGUIDE SENSOR

The passive waveguide transfers dynamic strain energy from a sensing location (the location where the vibration of interest must be determined) to a remote measurement location where the stress waves are measured to generate an electrical signal proportional to the vibration at the sensing location. This sensor is a mechanical device constructed of materials that can be robust to corrosion, temperature and mechanical damage. It is much more rugged than typical piezoelectric sensors, which can be easily damaged by shock, temperature extremes, etc. The transducer element (which generates the electrical signal) can be placed in any convenient location; this permits close monitoring of components that were previously inaccessible due to a hostile environment or difficult/expensive access for sensor replacement. These waveguides can be a small number of millimeters in diameter (individual wire diameter is dependent on the desired application bandwidth), over a meter in length and constructed in curved/bendable configurations for installation on practical systems.

Figure 1 shows a notional installation of a waveguide sensor for monitoring a gearbox bearing. While the sensing end of the waveguide could be attached to the exterior component housing, it could easily be positioned intimately near a component of interest via, for instance, a small drilled installation hole. The measurement end can be located in a convenient, non-hostile location.

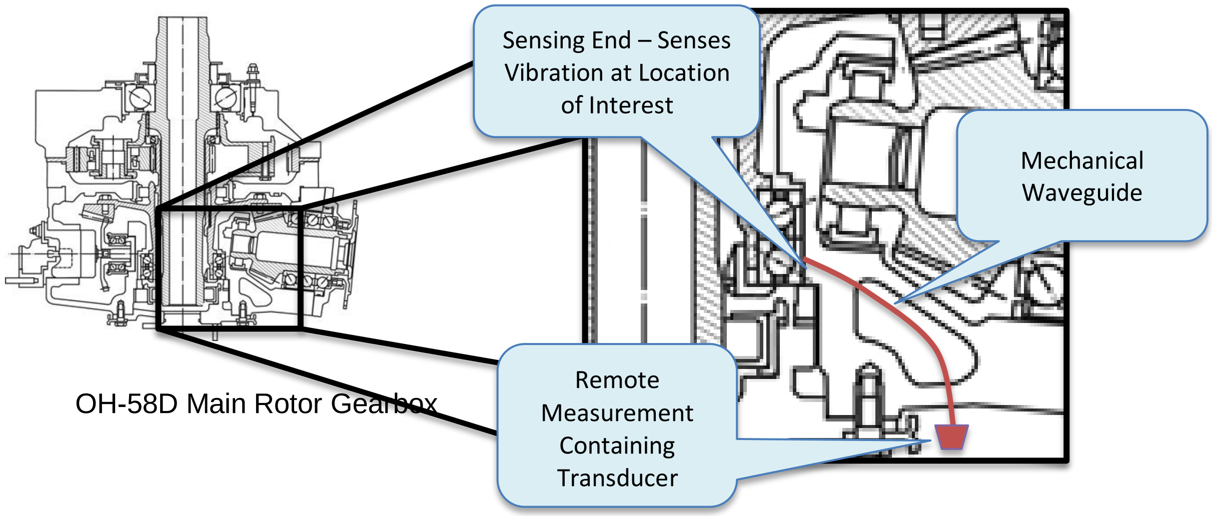

Figure 1. Notional installation of waveguide for monitoring of critical bearing in gearbox.

An additional advantage of this sensing method is that the vibration transfer path along the waveguide is very simple, uniform and stable. This is a useful feature for gear and bearing monitoring methods which employ deconvolution techniques. It also means that for enveloping/demodulation algorithms there is less likelihood of the bearing or gear energy landing in a frequency region of poor energy transmission, so signal to noise is improved.

RESONANT WAVEGUIDE REFLECTIONS

One of the key issues limiting performance of mechanical waveguides is signal reflection caused by abrupt changes in acoustic impedance at the waveguide ends. The frequency domain manifestation of this phenomenon is periodic, lightly damped resonances in the frequency response of the waveguide which distort the transmitted signal. This is essentially identical to an organ pipe, which resonates at one fundamental frequency and many harmonics. To make accurate broadband measurements with a waveguide these resonant reflections must be eliminated.

The authors have developed three innovative, patent pending, approaches to solve this problem. One approach is to alter the shape of the end of the waveguide transmission wire – a tapered wire end breaks up the stress-wave reflections and reduces their amplitude. Another approach is to extend the transmission wires past the transducer element and treat these portions of the waveguide wires with a damping material which absorbs the stress-wave energy which has passed the sensor. The third approach is to use multiple wires (a small bundle of fine wires) which extend past the senor and terminate at different lengths. The reflections from these wires of different lengths are incoherent and therefore destructively interfere, drastically attenuating resonant effects. Any combination of these techniques can be used together to optimally attenuate resonant characteristics.

Figure 2 shows the time-domain response to a single impulse of a "standard" waveguide (top) and also the time-domain response of a "reflection-free" waveguide (bottom) developed by Etegent. The reflections in the standard waveguide would clearly corrupt vibration signals utilized for system monitoring. Figure 3 shows the corresponding input-output frequency response of a standard waveguide and the “reflection-free” waveguide developed by Etegent. The standard waveguide (red trace) shows sharp peaks at the reflection-frequencies of the waveguide, while the reflection-free waveguide clearly has a much flatter response.

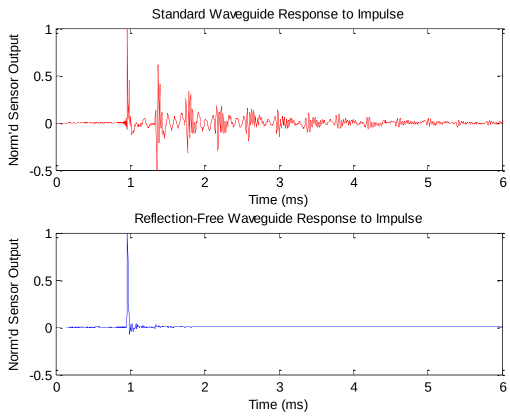

Figure 2. Waveguide Reflection Attenuation, Time Domain

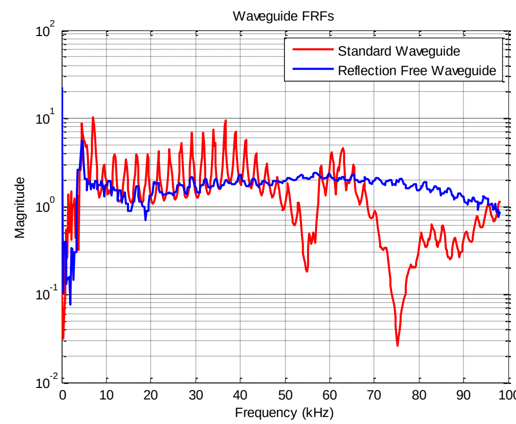

Figure 3. Waveguide Reflection Attenuation, Frequency Domain

Note that if one were trying to monitor a component with a standard waveguide, the measured amplitude of the vibration signal can change significantly if the operating speed of the component changes to cause a vibration frequency to align with a waveguide resonant frequency. That is, on the red trace in Figure **3**, the measured vibration amplitude just below 20 kHz would be about 4x higher than just above 20 kHz, and this is only due to the resonant reflection characteristics of the waveguide. Appropriate thresholds for condition monitoring indicators would be strongly dependent on component operating speed, and sensitive to small fluctuations in speed.

EXAMPLE MEASUREMENTS - ACCELERATION

Comparative measurements were made between a prototype waveguide and a high-frequency accelerometer sensing on the bearing block of a bearing test rig. Spectrums of the raw vibration signals measured with the accelerometer and remotely at the end of the meter-long waveguide are shown in Figure 4. Multiple harmonics of the ball-pass fault frequency are clearly evident in data from the accelerometer and also in the data acquired with the waveguide with a transducer element one-meter distance from the bearing block. This and other tests validated the utility of the waveguide for making high-fidelity measurements of fault signatures close to the fault, even in extremely hostile environments, thus reducing transmission path effects and masking vibration.

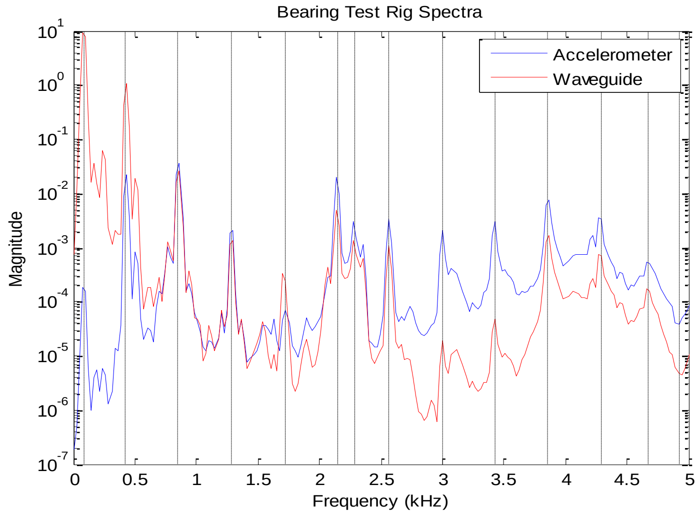

Figure 4. Bearing fault spectra measured with a high frequency accelerometer and remotely with a one-meter length wave guide. The 84 Hz shaft speed and multiple harmonics of the 440 Hz outer race defect (ball pass) frequency are readily apparent in the data measured with both the accelerometer and the one-meter long waveguide. The vertical, dashed, black lines highlight these frequencies and demonstrate that both the waveguide and the accelerometer are transmitting this information.

EXAMPLE MEASUREMENTS - DYNAMIC PRESSURE

The waveguide can be used to measure more than acceleration; for example, dynamic pressure measurements can be made by placing the sensing end directly in contact with fluid. Dynamic pressure measurement testing was done by the authors using a 3hp multi-stage water pump. Figure 5 shows the pressure spectra from the waveguide immersed in water for three cases: normal flow (blue trace), pump off (black trace), and choking the outlet flow (red trace). Note that choking the outlet flow would be expected to induce cavitation, causing very high frequency fluid pressure fluctuations. The Bandwidth of these measurements is 100 kHz. Figure 6 shows the same three cases with the waveguide sensing end mounted on the pump housing. Clearly, additional high-frequency information is available when making direct pressure measurements.

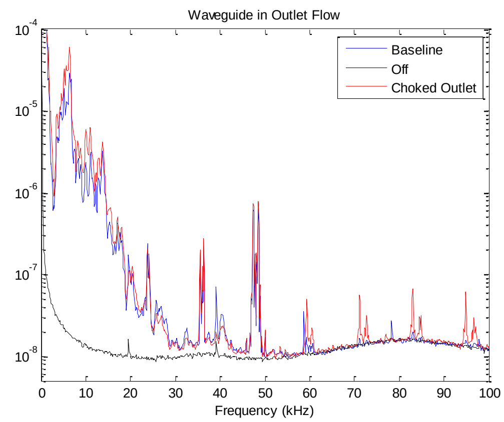

Figure 5. Spectrum of pressure measured by waveguide in contact with fluid at pump outlet.

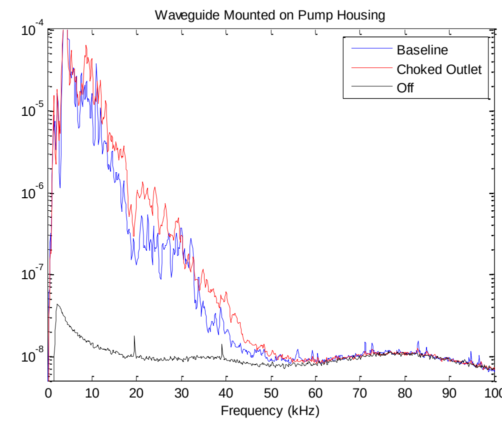

Figure 6. Spectrum of pressure measured by waveguide mounted on exterior of pump housing

ACTIVE WAVEGUIDE BASED SENSORS

Etegent has also demonstrated the feasibility of extending the passive waveguide concept to an active waveguide sensor technology. These active waveguide sensors help to eliminate one of the major drawbacks to passive sensors - the inability to measure static (DC) values. This new sensing technology uses ultrasonic stress waves transmitted through a waveguide to interrogate a sensing end to infer physical quantities such as pressure, temperature, strain or vibration. This approach separates the measurement end from the sensing end which is exposed to the hostile environment. This enables a sensor design which can be employed to reliably and economically measure static and dynamic pressure in the harshest sections of a turbine engine (such as the combustor) without the additional complications of pressure tubes or external cooling.

The pressure sensor utilizes ultrasonic phase detection to measure very small strains in a waveguide sensing wire caused by deflection of a pressure-sensing diaphragm. Other pressure-sensing design configurations are possible as well as sensor configurations to measure temperature, vibration and strain. This method applies established methods utilized in optical-based sensor designs such as interferometry and Bragg filters without the fragility usually associated with optical components. This suite of sensors is field deployable without the complications associated with precise tuning of complex optical components during manufacturing, installation and maintenance.

Active waveguide-based sensors enable the sensor to be constructed from a single, homogeneous material; this eliminates the differential thermal strain which is a major design and reliability problem for traditional piezoelectric or optical approaches. This reduces manufacturing complexity, extends life and improves reliability. The sensor can be constructed of the same material as, for instance, a turbine engine combustor, enabling pressure and temperature measurements to be made in the combustor which could not be previously made.

A proof of concept sensor has been built and tested at room temperature. The demonstration sensor is shown in Figure 7 and an example phase vs. pressure curve for the demonstration sensor is shown in Figure 8.

Figure 7: Demonstration pressure sensor

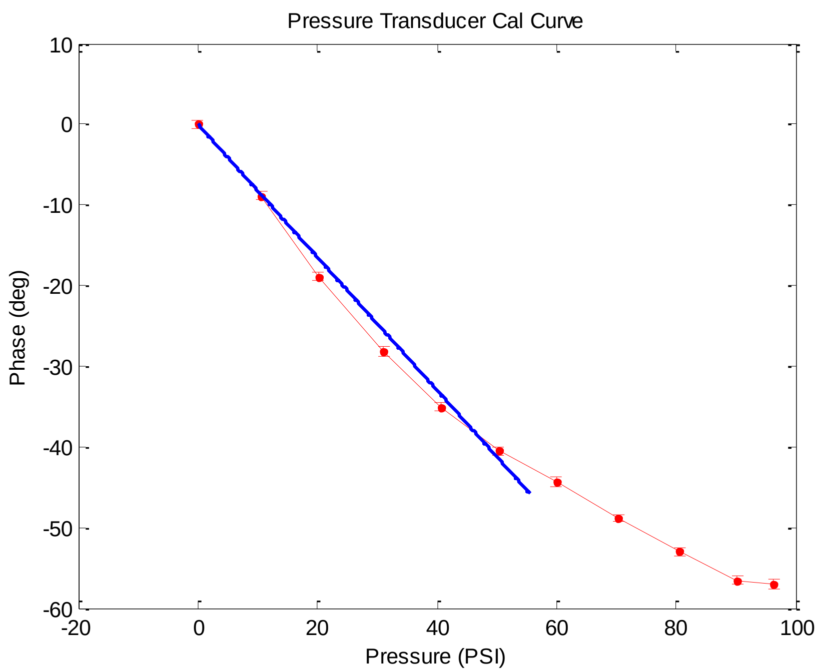

Figure 8: Phase vs. Pressure for demonstration sensor with error bars (1 sigma)

TEMPERATURE COMPENSATION AND MEASUREMENT

Large changes in temperature are a major issue for any sensor which must operate in the hot section of a turbine engine Temperature fluctuations have multiple effects on the sensor's performance:

- Thermal expansion/strain can cause a bias error in the measured quantity
- High temperatures alter the thermal properties of the sensing element (i.e. modulus) causing a calibration error
- Temperature and strain related aging and creep can cause a bias error in the measured quantity

The long term effects of aging and creep are significant issues. By suitable material selection these can be minimized. In addition, any long term changes in geometry due to creep can be calibrated out by re-zeroing the sensor.

The active waveguide sensor technology is ideally suited to both compensating temperature related pressure sensor bias and calibration errors, and also to making collocated temperature measurements. Multiple sensing elements can be multiplexed on a single waveguide sensor to simultaneously measure pressure, temperature compensation information and also medium temperature for process control and monitoring.

EXTENDING MEASUREMENT TO MULTIPLE SENSORS

This same measurement system can be extended to include multiple sensors on a “waveguide” network. The different sensor channels can be separated by time division multiplexing or frequency division multiplexing. Multiplexing enables simpler temperature compensation, simpler system design, less complexity, and lower cost.

TIME DIVISION MUTIPLEXING AND PULSE ECHO MEASUREMENTS

The waveguide system supports separating outputs from different sensors by spacing them in different time slices. A pulse is sent down the waveguide fiber and the sensor output is returned by each of the sensors. This is continued for each of the sensors. In order to use time division multiplexing, a specially designed pulse is sent down the waveguide fiber and each of the sensors return the output in their time-slice. The time slice is determined by the length of waveguide fiber between the different sensors along with the velocity in the medium.

SUMMARY

A new sensing technology, active and passive waveguide-based sensors, has been presented that can measures vibration, temperature compensated pressure, temperature and other parameters. Multiple sensors of different sensing modes can be multiplexed on a singe waveguide. A prototype active waveguide pressure sensor has been constructed which measures static and dynamic pressure. Passive waveguides have been constructed and demonstrated for measurement of vibration and dynamic pressure. Approaches to improve temperature stability and the ability to make co-located temperature measurements are also discussed.

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