BROADBAND WAVEGUIDE SENSORS FOR USE IN HIGH-TEMPERATURE, CORROSIVE, AND OTHER HARSH OR DIFFICULT-TO-ACCESS ENVIRONMENTS

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Abstract: Monitoring difficult-to-access components such as turbine engine main bearings or gears which are deeply buried in large transmissions is challenging due to the fact that vibration sensors generally must be mounted on the external case. The long transfer path through multiple component joints tends to attenuate the vibration signal of interest, and masking vibration from other sources further obscures these low-amplitude signals. A new waveguide-based sensing technology which carries the vibration stress waves to the desired sensor location permits high-fidelity vibration measurements of components that would otherwise be inaccessible. This sensor separates the mechanical sensing element from the electronics; the sensing element can be made of stainless steel, Inconel, or similar materials, which permits measurements in environments which are much too harsh for PZT or strain gauges. The sensing electronics can be conveniently located in a more benign location which is easily accessed for service. Waveguides have been used for harsh-environment sensing for years, such as probes which separate ultrasonic transducers from hot surfaces when doing non-destructive testing; however, many drawbacks have prevented their use as broadband vibration sensors. Methods for addressing these issues have been developed by the authors, enabling a new sensing technology for monitoring mechanical components in harsh and difficult-to-access environments.

Key words: Aerospace; bearings; diagnostics; gears; health management; sensors; turbine engine

Introduction: Vibration monitoring has been used for many years to infer machinery health. Because damaged gears and bearings emit a well-understood and predictable family of frequencies based on the component geometry and shaft speed, it is possible to identify the faulty component from the vibration signature. Due to noisy environments and difficulty in mounting accelerometers near a gas turbine engine’s main bearings, vibration monitoring of main bearings has proven difficult. With case-mounted accelerometers, vibration-masking noise can completely overwhelm any discernible vibration signature from main bearings. Mounting accelerometers inside the engine is generally not an accepted solution, partially because of the harsh environment, but primarily because a sensor failure would require a costly engine teardown. Assuming that good vibration data is available, it can be used to reliably identify and isolate faulty components.

Waveguide Sensor Background: Ultrasonic waveguides have been used for non-destructive (NDT) testing and process measurement in hot or harsh environments for many years [1]. One of the simplest examples of this is using a metal rod to isolate an ultrasonic transducer from a hot object for NDT or acoustic emission testing [2]. The metal rod is simply a conduit to transmit ultrasonic stress waves from the hot surface to the piezoelectric ultrasonic transducer; Figure 1 illustrates this concept.

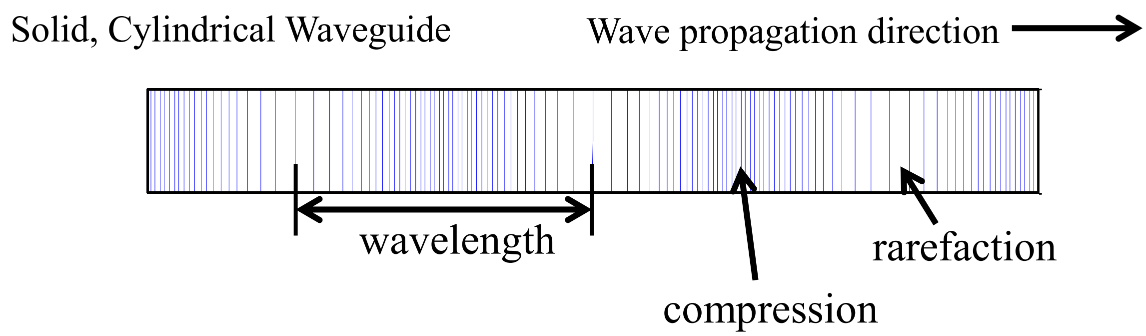

Figure 1: Stress-Wave Propagation Through a Cylindrical Waveguide

Waveguides can be used to construct a number of different sensor types. They can be broken up into two fundamental classifications, active and passive. Passive waveguides simply transmit the vibration signal of interest from the sensing location to a benign measurement location; they are not able to measure static quantities. Active waveguide sensors actively interrogate the sensing head, enabling sensors to measure static quantities (e.g. static pressure and strain), but require interrogation electronics.

Both waveguide technologies can be implemented to measure a variety of different physical quantities. To date, Etegent has demonstrated the feasibility of using passive waveguides to measure vibration and dynamic pressure. Active waveguide sensor prototypes have been demonstrated measuring pressure, strain and temperature. This paper deals with the passive waveguide vibration sensor.

Broadband Waveguide Vibration Sensor: Mechanical waveguides can be designed to transmit stress wave energy over long distances with minimal attenuation or change [3]. Stress waves are generated by any dynamic force (e.g. pressure, vibration) and are transmitted from the sensing end of the waveguide to the measurement end.

A number of design considerations must be respected in a practical application; for example, the diameter and the number of wires and wire termination method are important practical considerations for successfully implementing a broadband waveguide. Of primary importance is designing the passive waveguide to avoid resonant reflections, which will distort the transmitted signal. The top trace in Figure 2 shows the response of a poorly designed waveguide to a pulse input – there are significant "echoes" in the response. The bottom trace in Figure 2 shows the corresponding response of a correctly designed waveguide, with no distorting echoes apparent in the pulse response

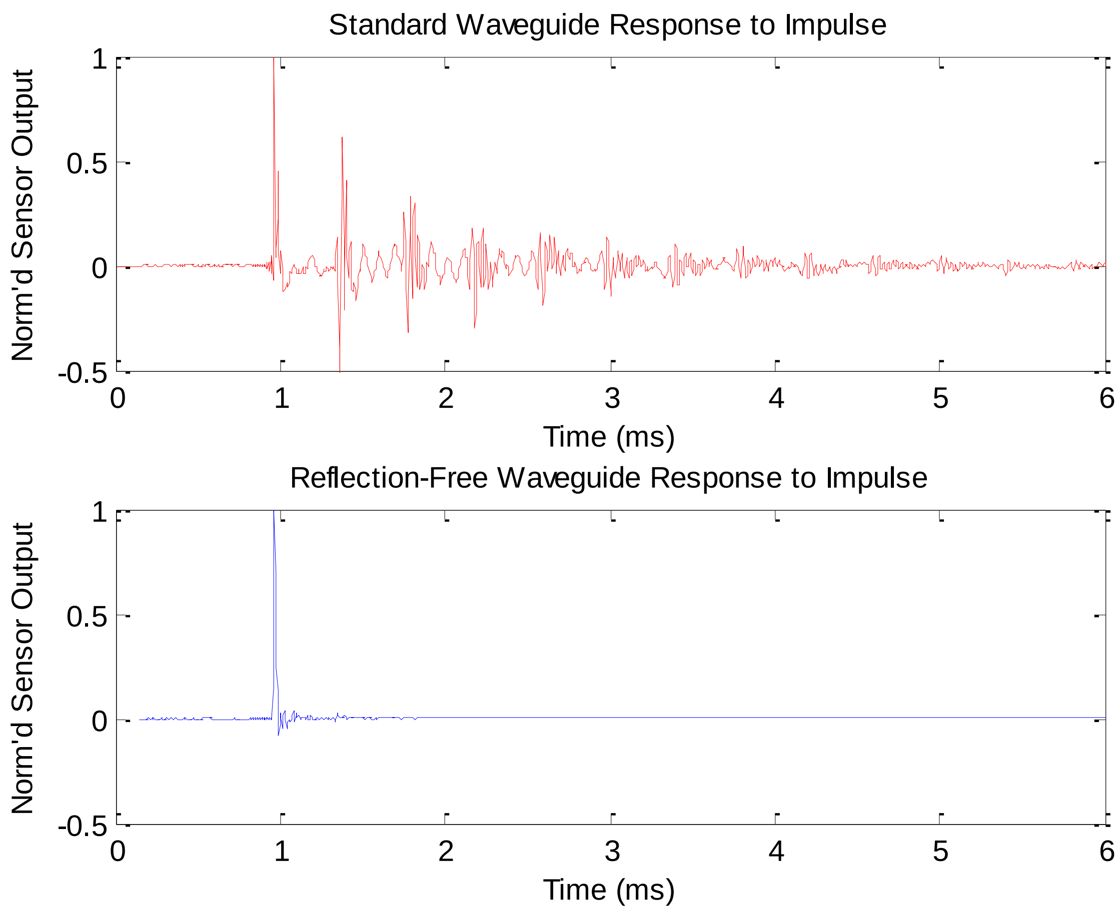

Figure 2: Design of Passive Waveguide to Eliminates Reflections (Bottom), Enabling True Broadband Response, Compared to Uncompensated Waveguide (Top)

Etegent has applied for a patent* on the reflection elimination technique; this has been accomplished in three ways. The first is in extending the wires past the sensing end and terminating these in differing lengths. This produces reflections which are incoherent and add destructively; see Figure 3. The second approach is to tailor the shape of the end of the wire: rather than a flat end, a taper can be used to make the reflected strain energy dispersive (Figure 4). The third method is to extend the wires past the sensing end and cover them in a viscoelastic damping material to absorb reflected strain energy before it reaches the sensing element.

* Application Serial No. 13/071,159

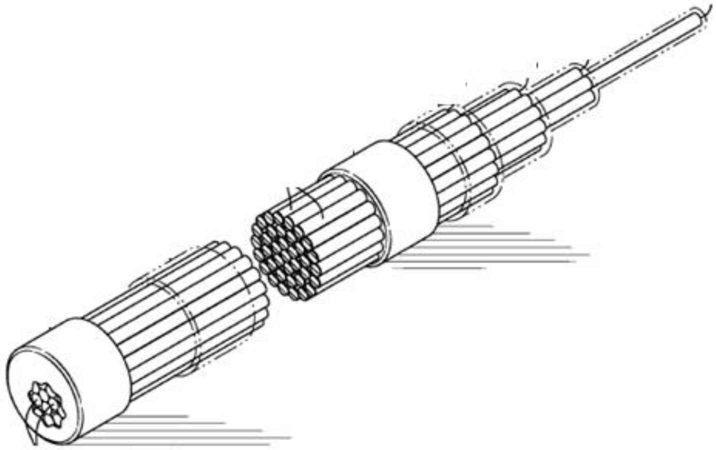

Figure 3: Waveguide Vibration Sensor Reflection Elimination Through Incoherent Reflection

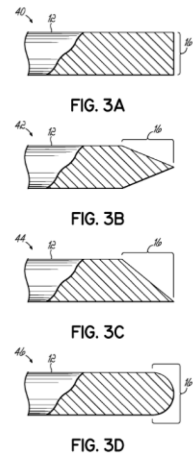

Figure 4: End Termination

Since these mechanical waveguides can be made of any material that readily transmits vibration energy, materials can be selected which permit operation to very high temperatures and/or in very corrosive environments. For example, tungsten wires could be used in applications that require operation to $4000^{O}F$

Figure 5 shows an early waveguide prototype mounted on a Chinook T55 engine. This was done as part of transfer path measurement testing performed for the Army to improve their Health and Usage Monitoring Systems (HUMS). These frequency response functions (FRFs) were measured by mounting a high-frequency reaction-mass piezoelectric shaker to the engine at various locations and recording input with a high-frequency load cell, and measuring vibration response alternately with high-frequency accelerometers and a waveguide sensor. Figure 6 shows the waveguide and high-frequency accelerometer FRFs. While the responses are somewhat different due to minor transfer path differences, the two sensors are clearly providing data which is suitable for most bearing monitoring applications. Note that the FRFs are only shown above 2 kHz; this is because the reaction-mass shaker does not provide much energy below this frequency.

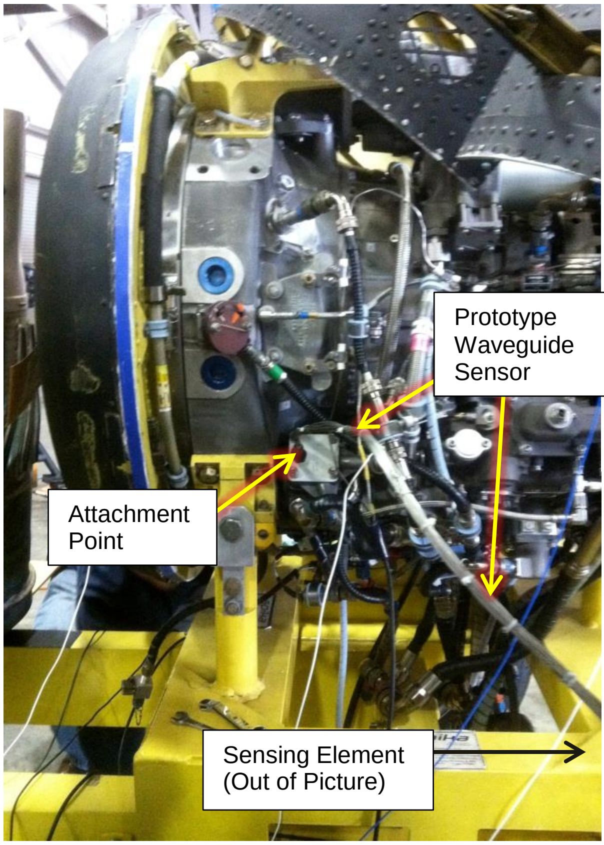

Figure 5: Waveguide Sensor Mounted on Chinook T55 Engine

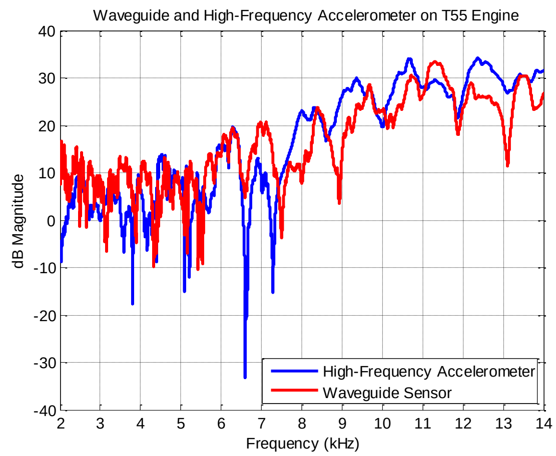

Figure 6: Comparison of Waveguide and High-Frequency Accelerometer on Chinook T55 Engine

Not only do passive waveguides 'channel' the desired vibration signal out of a harsh or inaccessible environment and bypass masking vibration noise; they also provide a stable, easily characterized vibration transfer path. Figure 7 illustrates the challenges inherent in monitoring the main bearings in a turbine engine with case mounted accelerometers. A dynamic fault force is generated by a main bearing defect. The fault force is a function of the defect type and severity, and also the operating conditions of the engine. This excitation force causes vibration response that travels through a complex path, across multiple component interfaces, to a case mounted accelerometer. Not only is the amplitude of the fault vibration signature attenuated highly through the transfer path, but the transfer path characteristics can vary with engine operating conditions. This means that vibration condition indicators (which are weakly measured to begin with) can change substantially with engine operating conditions without any change in defect severity. On top of this, there are many sources of high amplitude masking vibration which can overwhelm the weakly-transmitted bearing fault vibration, and this masking vibration can also vary strongly with engine operating condition, corrupting the defect indicators in an unstable and variable manner.

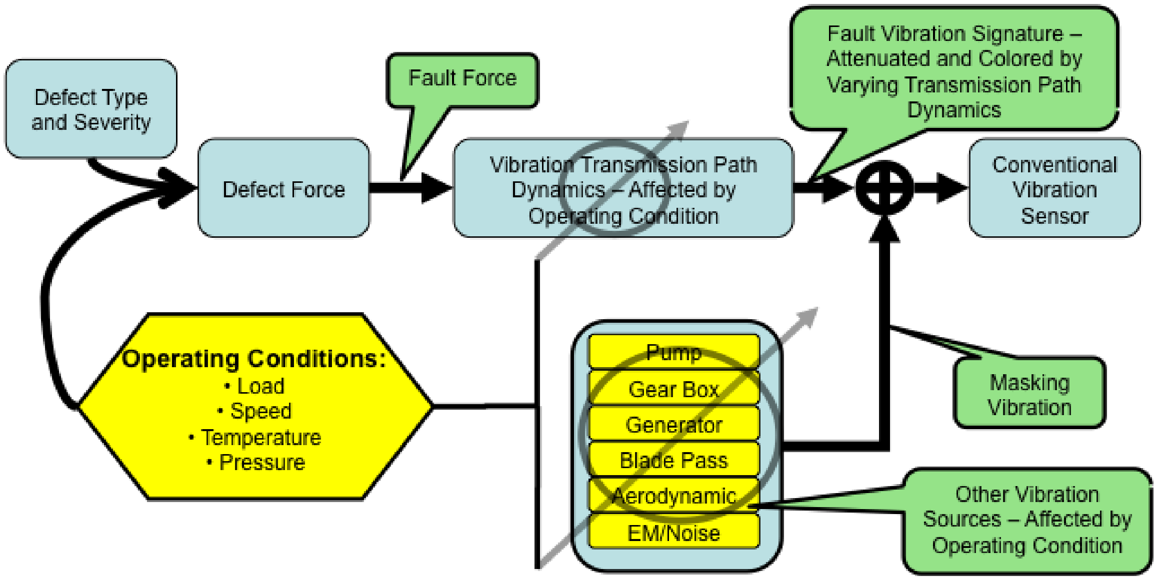

Figure 7: Schematic Showing Operating-Condition Sources for Change in Vibration Transfer Path which Affect Measured Vibration Amplitude

In a recent paper from Honeywell, these issues are summarized:

> On the test rig, the accelerometers are mounted close to the bearing of interest so that bearing vibrations are transmitted directly to the sensor. No other interfering signal sources drown out the signal of interest. In an engine though, the bearings are inside the engine casing. The measured vibration signals of interest are highly attenuated because they travel from the faulted bearing through the engine structure to a sensor mounted externally on the engine casing. (The sensors are mounted externally to avoid the hot operating environment and to preserve casing integrity.) The engine environment has a variety of other interfering signals such as the noise made by the combustor, the air passing through the various stages of the engine, and even from bearings and gears that will drown out the signal of interest. [4]

When these challenges are considered, the difficulties historically experienced when transitioning vibration monitoring technology from the lab to operating systems are easily understood.

A waveguide vibration sensor can substantially mitigate these challenges. As illustrated in Figure 8, a waveguide sensor attached near a main engine bearing transmits the vibration fault signature directly to the measurement element without attenuation, through a stable, unchanging transmission path (the waveguide) and bypasses much of the masking vibration. The waveguide can be multiple meters in length enabling the measurement element and electronics to be located in a benign environment. The proposed waveguide sensors have the potential to provide vibration fault signature measurements which have unprecedented clarity, stability and efficacy for detecting and isolating component faults.

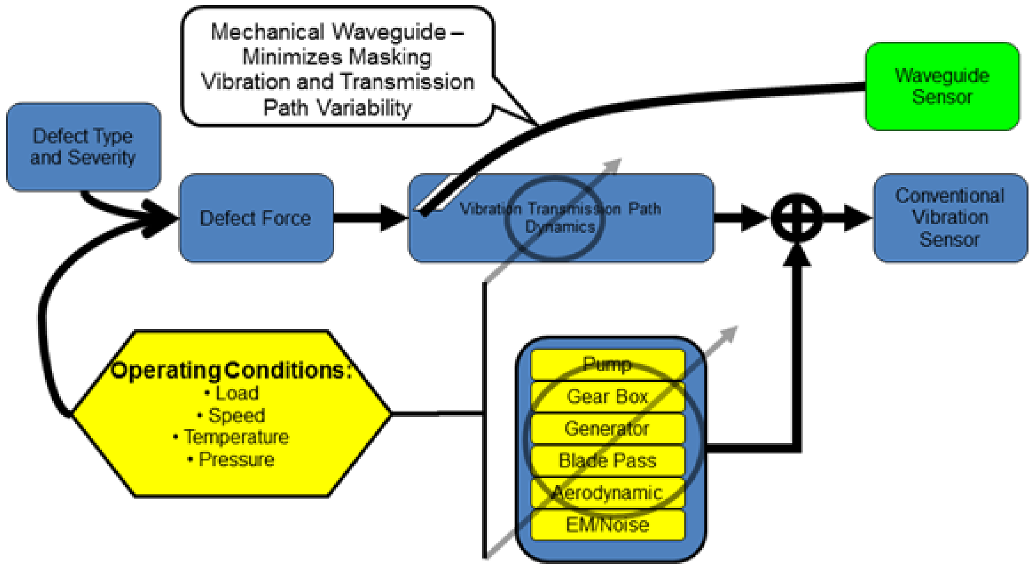

Figure 8: Schematic Showing Operating-Condition Sources for Change in Vibration Transfer Path which Affect Measured Vibration Amplitude

A further advantage of the waveguide vibration sensor is the *simplicity* of the transfer path. When using high-frequency content for vibration monitoring (e.g. for enveloping or demodulation techniques), the frequency region to be used must be carefully chosen. Consider the vibration transfer path measured on an Army Chinook gearbox shown in Figure 9 (left trace): the dynamic range of this transfer path is over three orders of magnitude in this frequency range (5 – 40 kHz). If an enveloping/demodulation technique is to be used, it should probably be done over the 10 – 15 kHz region. Consider the waveguide transfer path shown in Figure 9 (right trace, shown on the same scale for clarity): the dynamic range of this transfer path is less than an order of magnitude. An enveloping/demodulation algorithm would be much less sensitive to the chosen frequency band; in fact, waveguide FRFs have been measured by the authors up to 100 kHz, and the frequency response is quite flat.

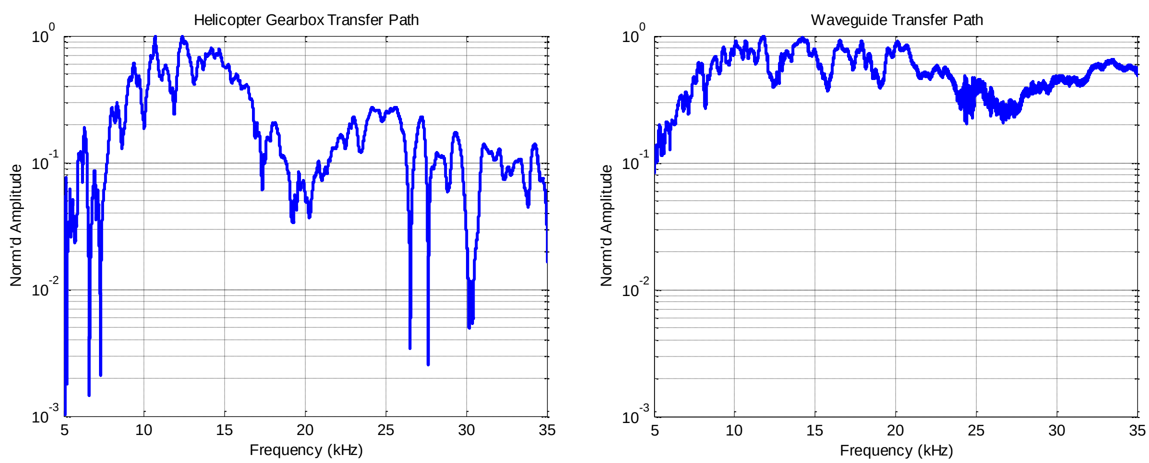

Figure 9: Helicopter Gearbox Transfer Path (Left Trace) Has Large Dynamic Range and Substantially Alters the Vibration Signal; Waveguide Sensor Transfer Path (Right Trace) Has Narrow Dynamic Range and Does Not Significantly Alter the Vibration Signal.

Conclusion: Measuring high-quality vibration data for monitoring turbine engine main bearings and gears in large transmissions is difficult due to the inability to mount sensors near the components of interest. While high-temperature accelerometers or MEMS devices may survive in some of these locations, a sensor failure would mean a costly tear-down. Waveguide vibration sensors permit high-fidelity measurements of these components without the maintenance concerns: the waveguide itself is essentially a simple metal rod, and the piezoelectric sensing element can be located in any convenient, benign location. The waveguide provides a flat, stable vibration transfer path which effectively eliminates problems associated with signal attenuation due to the transfer path dynamics – this simplifies many of the challenges associated with high-frequency health monitoring.

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References:

[1] L. C. Lynnworth, Ultrasonic Measurements for Process Control: Theory, Technoques, Applications, Academic Press, 1989.

[2] I. Neill, I. Oppenheim and D. Greve, "A Wire-Guided Transducer for Acoustic Emission Sensing," in Proc. SPIE 6529, 652913, 2007.

[3] D. Zakharov, S. Pichkov and V. Shemyakin, "Acoustic Emission Signal Attenuation in the Waveguides Used in Underwater AE Testing," in ECNDT 2010 - Acoustic Emission, Moscow, Russia, 2010.

[4] O. Uluyol, K. Kim and C. Hickenbottom, "A Systematic Approach to Bearing Health Monitoring," Phoenix, May 11-13, 2010.