Abstract: Mechanical waveguides have been demonstrated for monitoring turbine engine main shaft bearings. As case-mounted accelerometers are so distant from the bearings, low-level vibration signatures are typically overwhelmed by noise and other vibration sources. Mechanical waveguides are rugged metallic wires which can be mounted inside the engine near the bearing and routed to the case where the piezoelectric element can be placed in a cool, serviceable location. This provides superior bearing defect vibration signal-to-noise to case-mounted accelerometers while maintaining serviceability. To date, the waveguide vibration sensor has been demonstrated on two engines with thrust bearings with seeded defects: a T63 (military version of the Allison/Rolls-Royce 250-C18) and a Rolls-Royce 501-KB5+ (the industrial version of the military T56). While the waveguide vibration sensor has been demonstrated for monitoring turbine engine main shaft bearings, it is a useful tool for vibration monitoring any mechanical component in a harsh or difficult-to-access environment.

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. This has been demonstrated on many test rigs over the years. Test rigs provide an excellent opportunity for health-monitoring algorithm exploration as they do not have much additional vibration or noise and sensors can be placed very close to the components of interest.

Due to noisy environments and difficulty in mounting accelerometers near a gas turbine engine’s main shaft bearings, vibration monitoring of main shaft bearings has proven difficult. With case-mounted accelerometers, vibration-masking noise can completely overwhelm any discernible vibration signature from main shaft bearings. Choosing where to mount accelerometers is often driven by convenience (e.g. accessibility, surface temperature), and the best place to monitor a given bearing may not be intuitive – expensive testing may be required to select the best sensor location [1, 2]. 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. Good vibration data can be used to reliably identify and isolate faulty components; the purpose of the waveguide is to provide good data when traditional accelerometers cannot.

**Waveguide Sensor Background:** Ultrasonic waveguides have been used for non-destructive testing (NDT) and process measurement in hot or harsh environments for many years [3]. 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 [4]. 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 Slender Waveguide](image)

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. Passive waveguides have been demonstrated for vibration and dynamic pressure measurement. Active waveguide sensor prototypes have been demonstrated for pressure, strain and temperature measurement. This paper deals with the passive waveguide vibration sensor and its utility for turbine engine main shaft bearing health monitoring.

**Broadband Waveguide Vibration Sensor:** Mechanical waveguides can be designed to transmit stress wave energy over long distances with minimal attenuation or change [5]. 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 and make broadband measurement impossible. 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. Etegent has addressed this issue, permitting use of waveguides for broadband vibration measurement.

![Image](attachment:image.png)

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

**T63 Seeded Defect Test:** The T63 turboshaft engine (Rolls Royce/Allison 250-C18) is a small engine which powers a large number of military and civilian rotorcraft and fixed-wing aircraft. The version tested here has a length of 23.2 inches, a diameter of 19 inches, a dry weight of about 180 lbs., and produces about 317 shaft horsepower (max takeoff).

The T63 engine was run on a water-brake dynamometer at the Air Force Research Laboratory (AFRL) with seeded defects in the thrust bearing – one set of tests with an inner race defect and one set with an outer race defect. Additionally, data was recorded with a new, undamaged bearing. Only the inner-race defect and undamaged cases are presented here. The waveguide was mounted to the compressor rear diffuser, which mounts the bearing; this is easily accessible from the outside of the engine. Figure 3 shows one of the AFRL’s T63 engines.
The test bearing for this engine is located between the compressor section and the gearbox, as shown in Figure 4. The test bearing is the #2 location angular contact thrust ball bearing on the high-speed spool. The high speed turbine powers the compressor, whereas the low speed turbine powers an output shaft via a reduction gearbox.

The waveguide was mounted to the compressor rear diffuser along with a high temperature accelerometer for reference. Figure 5 shows the sensor mounting to the engine.
While this bearing is far more accessible than those found in large engines, the test still demonstrates the ability to use a waveguide to transmit vibration to a distant, cool and accessible location for the measurement electronics.

**Inner Race Defect:** The engine was assembled with a seeded inner race defect in the thrust bearing on the high-speed spool. Spalling was initialized on the inner race by indenting the surface with a Rockwell C tester and running the bearing under high load in a test rig. Figure 6 shows the indents and the resulting spall.

The equation for computation of the inner race defect frequency (ball-pass frequency – inner, or BPFI) is given by:
$$BPFI = \frac{nf}{2} \left( 1 + \frac{d}{D} \cos \theta \right)$$

where $n$ is the number of rolling elements, $f$ is the shaft rotation frequency, $d$ is the rolling element diameter, $D$ is the pitch diameter, and $\theta$ is the contact angle [6]. At 50,500 RPM, this yields an expected inner race defect frequency of 6280 Hz.

Data was recorded in sixty-second captures sampled at 196,608 Hz; the power spectral densities (PSD) of the waveguide and high-temperature accelerometer were compared. Figure 7 shows the results with the engine at 50,500 RPM: the blue trace is the PSD of the high-temperature accelerometer; the green trace is the PSD of the waveguide.

With inner race defects, sidebands are often present in the spectrum, as the defect frequency is modulated by the shaft speed. Because the defect frequency is modulated by the engine shaft speed, sidebands appear at multiples of the shaft speed. Plotting the PSD in the order domain simplifies sideband identification. Additionally it shows which peaks are integer multiples of engine order; these can then be attributed to blade-pass, etc. The defect frequency and its harmonics as well as significant engine orders are marked.

Figure 7: T63 Engine, Inner Race Defect, PSD, Order Domain
No-Defect Case: The engine was also assembled and run with a good bearing. Figure 8 shows the recorded data with a good bearing.

![Figure 8: T63 Engine, No Defect, PSD, Order Domain](image)

Note that there is a peak very near or where the expected outer-race defect frequency would be. Small peaks at inner or outer race defect frequency are sometimes seen with healthy bearings. This could be due to small imperfections in the bearing. No harmonics of this peak are visible, nor is the inner-race defect frequency or its harmonics.

T63 Seeded Defect Test Conclusions: This test demonstrates that it is possible to measure bearing defect frequencies intimately close to the bearing, using a waveguide to transmit the vibration to a more benign and convenient location for the sensing element.

Rolls-Royce 501-KB5+ Seeded Defect Test: While the T63 provided an excellent opportunity to demonstrate the waveguide as a vibration sensor in a turbine engine environment, the bearing is close to the case and accessible with traditional accelerometers. To demonstrate the waveguide on a larger engine, the waveguide was mounted in the air diffuser of a Rolls Royce 501-KB5+ industrial turbine engine near the #2 thrust bearing. The 501-KB5+ is the industrial version of the T56, which powers the Hercules C130. The 501-KB5+ is a much larger engine than the T63 – this engine is about 146.1 inches in length, 27 inches in diameter, has a dry weight of about 1940 lbs. and produces about 4100 - 4500 shaft horsepower. This provided an opportunity to demonstrate the waveguide on an engine where the bearing is more distant from the case and more difficult to monitor with traditional case-mounted accelerometers. Figure 9 shows a cutaway T56 engine photographed at the Rolls Royce museum in Indianapolis.
For this test, a power-generation turbine was used. The test was performed at OnPower, a gen-set company located in Lebanon, Ohio. The generator was not connected to the grid; instead, the power generated was dissipated with large resistor banks. For 60 Hz power, the engine is run at 14,400 RPM (240 Hz).

The thrust bearing is mounted at the end of the compressor stages at the air diffuser. Figure 10 shows the test engine without the turbine section – the bearing is located inside the air diffuser.
**Instrumentation:** The engine was instrumented with thirteen sensors:

1) Waveguide – sensing head mounted inside the air diffuser

2) Internal Accel, Upper – PCB 357B11 mounted just above the waveguide sensing head in the diffuser

3) Internal Accel, Lower – PCB 357B11 mounted just below the waveguide sensing head in the diffuser

4) Case Tangent – PCB 357B06 mounted on the case joint near the front of the engine, on the right side if facing the front of the engine, sensitivity tangent to the case circumference

5) Case Radial – PCB 357B06 mounted as above, with the sensitivity toward the engine center

6) Front Inlet, Radial – PCB 357B06 mounted to the top of the front of the engine, with sensitivity toward the center of the engine

7) Air Diffuser, Axial – PCB 357B11 mounted to the join between the case and the air diffuser, on the left side of the engine if facing the front, sensitivity along the direction of the shaft axis

8) Air Diffuser, Radial – PCB 357B06 mounted same as sensor 7, except with sensitivity towards the engine center

9) Toadstool – the already-installed velocity sensor mounted on top of the engine’s rear section

10) Microphone – GRAS 40AE mounted to a support under the engine

11) Tachometer – 40 pulses per rev, normally a 25 – 40 Volt signal, divided by 10 to accommodate the 10 Volt limit of high-speed DAC

12) Thermocouple – mounted in the air diffuser near the waveguide, accelerometers, and seeded defect bearing. The temperatures were not recorded by the high-speed DAC, but were instead manually recorded in test notes.

13) GasTOPS Oil Debris Monitoring (ODM) – data recorded by the AFRL on their system.

The waveguide was routed into the air diffuser through an oil vent passage. Additionally, two high-temperature accelerometers and a thermocouple were mounted near the waveguide for reference. Note that for reasons of accessibility for maintenance, accelerometers are not typically mounted permanently inside turbine engines. Figure 11 shows the waveguide, accelerometers and thermocouple mounted inside the air diffuser.
Figure 11: Waveguide, High-Temperature Accelerometers, and Thermocouple Mounted Inside Air Diffuser

Figure 12 shows the ‘Case’ accelerometer mounting location as well as the waveguide sensing end and the feedthrough.

Figure 12: Location of Case Accelerometers, Waveguide Electronics, and Feedthrough into Air Diffuser

Figure 13 shows the location of the air diffuser accelerometers.
Figure 13: Location of Air Diffuser Accelerometers

Figure 14 shows the location of the front inlet accelerometer.

Figure 14: Location of Front Inlet Accelerometer

Figure 15 shows the microphone location.
Figure 15: Microphone Location

Figure 16 shows the ‘toadstool,’ which is a traditional velocity sensor.

Figure 16: 'Toadstool' (Velocity Sensor)

*Seeded Defect:* The outer race of the thrust bearing had a 0.020” notch cut across the race using the EDM process. Figure 17 shows the notch.
Defect Frequency: The defect frequency was calculated using the BPFO equation presented above. This bearing has 14 balls, a ball diameter of 0.65625 inches and a pitch diameter of 3.35 inches. With a shaft speed of 240 Hz and zero thrust angle, the BPFO is 1351 Hz. The frequency increases with thrust angle (which increases with load) – at a 25° thrust angle, BPFO is 1382 Hz.

Results: A full discussion of the results includes the thermocouple, the installed velocity sensor (the “toadstool”), each of the accelerometers, waveguide, and defect detectability metrics. Thermocouple—Temperatures were periodically checked; due to the oil lubrication of this bearing, the recorded temperatures were about 200°F during the test.

Toadstool—Figure 18 shows the toadstool power spectral density – engine orders are dominant.
Figure 19 shows the toadstool PSD zoomed to the region of the bearing defect frequency. While 5th and 6th engine orders are clearly visible along with minor peaks at 1170, 1206, and 1230 Hz, these are all lower than the expected defect frequency; the region where the defect actually lies is empty.

Figure 19: Toadstool Zoomed to Include Defect Frequency Region

Defect Frequency—The following two figures show the defect frequency region for each of the accelerometers and waveguide. For these plots, the engine was generating 2 MW, and the defect frequency was found to be 1384.5 Hz. While not shown here, the defect frequency was positively identified from varying load data – the other peaks in this window remained constant, while the defect frequency increased with load, as the contact angle increased. The toadstool and microphone are not shown here, as the defect frequency was not visible. The defect frequency region was defined as the defect frequency ±1.5%, as this is common for any RMS or RSS energy detection method. The figures show power spectral densities, which were computed using a flattop window, 50% overlap, and a blocksize which includes 10⅔ seconds of data. A flattop window was used for the best amplitude estimate, and the blocksize was chosen for frequency resolution of sub 0.1 Hz. These were normalized by the defect frequency amplitude for each sensor. This facilitates signal-to-noise comparison between the sensors. Figure 20 shows the waveguide along with one of the internal accelerometers (both were similar), the case tangent accelerometer, and the case radial accelerometer. While the waveguide provided the best signal-to-noise ratio (SNR), the case radial sensor provided surprisingly good results.
Figure 20: Defect Frequency Region, Normalized by Defect Frequency Amplitude, Showing the Waveguide, Internal, Case Tangent, and Case Radial Accelerometers
Figure 21 (plotted similarly to Figure 20) compares the waveguide to the inlet accelerometer and the two air diffuser accelerometers. Comparing these sensors, the waveguide again provides the best SNR, though the inlet accelerometer provided better results than expected.

Figure 21: Defect Frequency Region, Normalized by Defect Frequency Amplitude, Showing the Waveguide, Inlet, Air Diffuser Axial, and Air Diffuser Radial Accelerometers

Detectability and Separability Metrics—Four metrics for estimating defect detectability and separability are presented.

The first metric for comparing defect detectability is the signal to noise ratio (SNR). This is the defect frequency amplitude divided by the local noise floor amplitude. The local noise floor amplitude was computed as the median in the defect frequency window, which is ±1.5% the defect frequency. This metric provides a measure of defect detectability and rates the sensors as to confidence in identifying a defect vs. flagging a false alarm. A score of 21 indicates that the defect frequency was 21 times higher than the local noise floor amplitude for that sensor. Figure 22 shows the metric.
The second metric compares the defect peak amplitude to the highest amplitude peak in the defect window. As the waveguide is mounted very close to the bearing, the defect amplitude was the highest peak in the window. While the defect frequency is evident in the other sensors, it is often dwarfed by larger peaks in the window. This metric provides a measure of separability between the defect frequency and other peaks. The metric is computed by dividing the defect frequency by the largest peak amplitude in the window which is not the defect frequency; this is also normalized by the waveguide and shown in Figure 23.
The third metric provides a measure of the number of confusers which appear in the defect frequency band. A ‘confuser’ is a peak in the defect frequency window which is not the defect frequency; a health-monitoring algorithm may mistake it for a defect. The peaks are counted above two thresholds: since the signals are normalized by the defect frequency, the thresholds are 0.5 and 0.2. N/A means that the noise floor was within the threshold. The results are shown in Table 1.

Table 1: Number of Confusers Metric (Lowest Score is Best)

<table>
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<tr>
<th>Sensor</th>
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<tr>
<td>Waveguide</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Internal Accel</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Case Tangent</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Case Radial</td>
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<td>6</td>
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<tr>
<td>Front Inlet, Radial</td>
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<td>5</td>
</tr>
<tr>
<td>Air Diffuser, Axial</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Air Diffuser, Radial</td>
<td>6</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The fourth metric provides a measure of defect detectability by comparing the total energy in the defect frequency band with the defect to the total energy in the band without the defect. Since there was not time or budget to assemble the engine with a waveguide both with and without a defective bearing, the defect-free data was simulated by subtracting the defect frequency from the data. While the good bearing testing in the T63 demonstrated that this is not always the case, it provides a baseline for comparison. This metric is a common algorithm for bearing defect detection: the energy in a band defined as some small percentage of the defect frequency (to account for change in defect frequency due to thrust angle, ball slip, etc.) is summed, and an increase in energy in this band indicates a defect. As mentioned above, the band used for this case is ±1.5% the defect frequency. The results are shown in Figure 24; both as a percentage increase in energy over the simulated no-defect case, and normalized by the waveguide.
**Conclusions:** The waveguide provides a reliable means of transmitting vibration energy from one location to another. Since the waveguide can be made of any material which transmits vibration energy, aerospace alloys can permit operation in common aerospace environments, enabling high-fidelity vibration measurement of main shaft bearings and better defect detection. The T63 test demonstrated the feasibility of the waveguide for making vibration measurements in a turbine engine environment. It also provided an opportunity to understand defect frequency identification on a real engine with considerable harmonic content and further development of defect detection capability and understanding.

In the case of the Rolls 501-KB5+ engine test reported here, the velocity sensor (toadstool) was unable to detect the defect frequency, though this was expected, as its function is primarily to detect imbalance and not subtle bearing defect signatures. The accelerometers mounted internally did not detect the defect as well as two of the case-mounted accelerometers, though this was likely due to the fact that their sensitivity direction was not optimal for this defect. In this frequency range, the waveguide is sensitive to both axial and transverse vibration, so the defect frequency was strongly measured. Two of the accelerometers mounted near the front of the engine showed better detectability than the two sensors mounted on the air diffuser, and while unexpected, this demonstrates that intuition alone is insufficient for selecting locations for monitoring accelerometers. While the case-mounted radial-direction accelerometer was able to detect the defect reasonably well, it is unknown if this particular sensor location would work well for a similar defect in another orientation, other defects or even other engines of the same type, as the vibration measured at that sensor is highly dependent on the vibration transfer path dynamics at that frequency. Additionally, a larger engine would likely demonstrate even less defect detectability with case-mounted accelerometers.

Ideally, this test will be repeated with tri-axial accelerometers installed inside the engine with the waveguide – this would confirm the suspicion that the defect detectability was more strongly directionally dependent than initially thought. It would also be desirable to repeat the test with

![Figure 24: Total Energy Metric (Highest Score is Best)](image-url)

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Score</th>
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</thead>
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</tr>
<tr>
<td>Air Diffuser, Axial</td>
<td>5</td>
</tr>
<tr>
<td>Front Inlet, Radial</td>
<td>20</td>
</tr>
<tr>
<td>Case Radial</td>
<td>15</td>
</tr>
<tr>
<td>Case Tangent</td>
<td>10</td>
</tr>
<tr>
<td>Internal Accel</td>
<td>5</td>
</tr>
<tr>
<td>Waveguide</td>
<td>45</td>
</tr>
</tbody>
</table>

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*Figure 24: Total Energy Metric (Highest Score is Best)*
waveguides mounted at each main shaft bearing, to determine if one waveguide mounted near the main shaft can detect defects in other bearings, or if a waveguide is required at each bearing.

References:


