Sensing Challenges for Mechanical Aerospace Prognostic Health Monitoring

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***Abstract*— No Prognostic Health Monitoring (PHM) algorithm can turn poor sensor data into an accurate Remaining Useful Life (RUL) prediction, and measuring high-fidelity vibration data in noisy aerospace mechanical systems can be very challenging. Generally, for sensor selection and placement, temperature, masking vibration, electromagnetic interference, and vibration transfer path dynamics must all be considered. Additionally, although aerospace systems are built to exacting tolerances, variability between systems due to manufacturing differences, overhaul, and even variability between vibration sensors must be considered when setting up condition indicators. Many of these factors have been explored through high-frequency transfer-path testing of US Army helicopter gearboxes, resulting in a better understanding of the factors which influence the measured inputs into a PHM system and improved techniques for more reliable condition-based monitoring.**

Keywords-sensors; bearings; gears; health management; HUMS; PHM; RUL

I. Introduction

Vibration monitoring of aerospace components is challenging: sensors must tolerate high temperatures and high vibration; flight-certified sensors must be used instead of high-frequency laboratory sensors; limited numbers of sensors must monitor multiple components, sometimes from a much greater distance than would otherwise be desired; also, since aerospace platforms are very reliable and very expensive, condition indicator thresholds often must be set without any testing or known faulty-component vibration data. The purpose of this paper is to highlight some of the challenges encountered when setting up or attempting to improve a vibration-based aerospace health monitoring system.

II. Sensor Selection and Placement

When selecting sensors for machinery health monitoring, the desired bandwidth must be carefully considered. Historically, the shock-pulse method used an envelope band around the sensor's mounted resonance [1]. Although this can work well due to the added amplification of the resonant response, there are a few caveats. First, the sensor's mounted resonance must be known; while a nominal resonant frequency is published for most available accelerometers, this is usually a theoretical calculation of the sensor in a free-free condition. Even if the modeled resonance is quite accurate, the *mounted* resonance can be significantly different due to the dynamics of the structure and mounting conditions. Consider an antinode on a structure which is unresponsive at a given frequency – an accelerometer with a free-free resonance at this frequency mounted at the antinode will not measure any response. This can be seen in Figure 1, which shows the Frequency Response Functions (FRFs) of two accelerometers mounted to a helicopter gearbox (blue and red traces) with an advertised resonant frequency of 43 kHz, along with the theoretical free-free response of the accelerometer (dashed black trace). The mounted resonances of the accelerometers are very different from the free-free resonance.

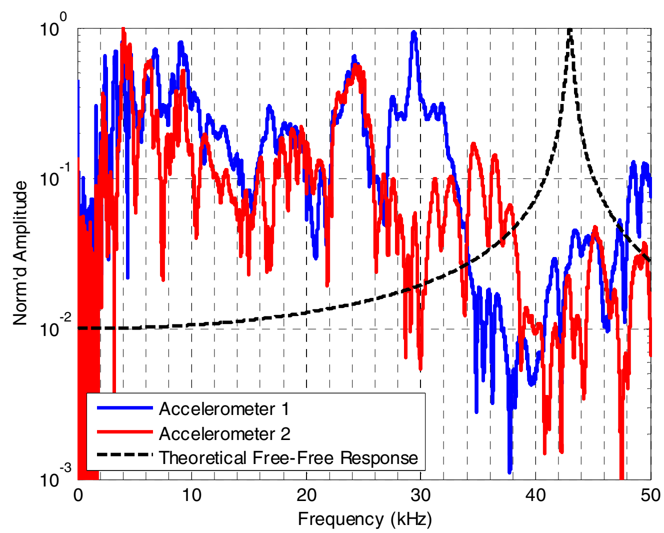

Figure 1. Mounted accelerometer resonance dependent on structure and mounting conditions

Additionally, a sensor's output is much less repeatable when used near its mounted resonance. An example of this is shown in Figure 2 – ten FRFs were recorded without disturbing the test setup and the autospectra are all plotted together. The sensor's advertised bandwidth is up to 20 kHz – note that the response above that frequency is much less consistent between tests, in some regions by as much as an order of magnitude. At the resonance (near 30 kHz) the difference is about a factor of 3, which may or may not prove to be a problem for consistent health monitoring; however, for a fleet of aircraft, the response difference at the resonance between sensors across the fleet through different operating conditions could be significant, and should be considered. The response amplitude differences make selecting condition indicator thresholds for good detectability without false alarms difficult. The input power spectra (not shown) are very consistent test-to-test, so the variability is due to the accelerometer.

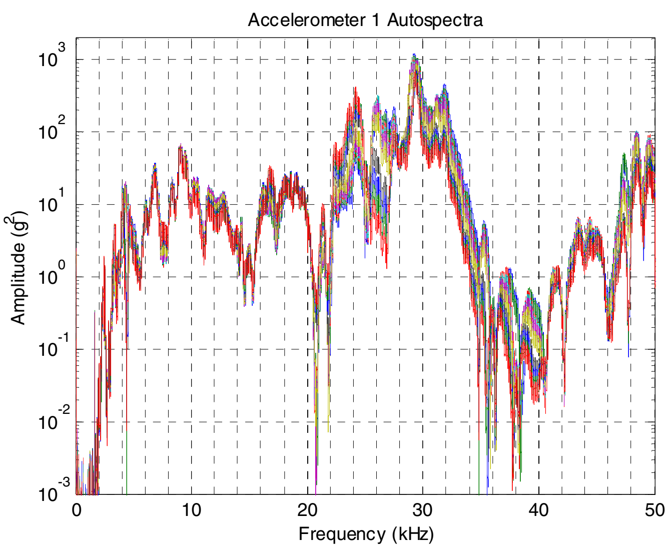

Figure 2. Repeatability of an individual accelerometer near its mounted resonance

When selecting a sensor, sensitivity must be specified as well, and aerospace engines and drivetrains tend to be very noisy, so sensitivity generally has to be quite low to avoid overloads. Overloading a sensor is not always obvious: if sampling at low frequency, one expects the anti-aliasing filters to remove any content above the desired bandwidth, and this is quickly forgotten. However, saturation at high frequency can and does occur, and this affects the filtered low-frequency response as well [2].

Other environmental effects must also be considered, with temperature being one of the most obvious. High-temperature accelerometers can be used, but they have significant tradeoffs. Cost is the biggest; sensitivity, bandwidth, longevity, repeatability, and other tradeoffs are also usually encountered [3]. For example, PCB offers accelerometers for aerospace applications; the model with the highest frequency range with a 550F temperature limit has only 9 kHz bandwidth (Model 357B81), and if a 900F range is required, the maximum bandwidth drops to 4 kHz (Model 357C71) [4]. These factors limit where sensors can be mounted and what can be monitored. Due to the impracticality of mounting accelerometers close to turbine engine main bearings, they are probably the most difficult mechanical aerospace components to monitor.

Signal attenuation is a concern – placing a sensor 'far' from the gear or bearing of interest means that the desired signal will be much more difficult to measure than if it is 'near.' This is a real problem, as a limited number of sensors can be placed on an engine or gearbox, and there will often have to be components which are 'far' from the sensor. If the vibration response from the component is small relative to all the masking vibration (e.g. gears, pumps, aerodynamic noise, or any vibration source which is not the component of interest), the defect frequencies may not be measurable until the defect has become very serious, or they may not be measurable at all.

While not part of the mechanical transfer path, electromagnetic interference (EMI) can also be a concern in aerospace systems. Placing a sensor or cabling too close to a generator or other source of EMI can introduce considerable unwanted noise into the measured response.

III. TRANSFER PATH DYNAMICS

The measured response at the monitoring accelerometer is highly dependent on the transfer path. The measured acceleration due to the bearing defect is the defect force convolved with the transfer path dynamics; both effects contribute significantly to the selection of frequency bands for PHM. For example if the one of the harmonics of the defect frequency lines up with a zero in the transfer function, it will be very difficult to detect a fault using that band.

This can easily be demonstrated with a numerical model. Consider a bearing defect with a fundamental frequency of 1 kHz; the power spectrum of this defect with its harmonics (and some added noise) is shown at the top of Figure 3. A synthetic transfer path is shown at the bottom of Figure 3. The response (i.e. the input force convolved with the transfer path) is shown in Figure 4. Because of the FRF peak at 20 kHz, there is a large measured response signal, and the green band shown in Figure 4 would be an ideal region for enveloping. However, due to the zero in the transfer path at 30 kHz, there is very little response there, and trying to envelope in the red region shown in Figure 4 would not provide any information.

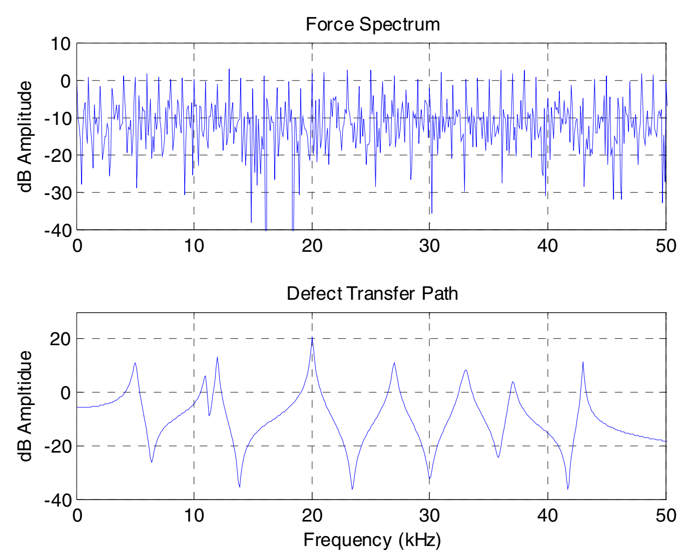

Figure 3. Synthetic force input spectrum (top) and FRF (bottom)

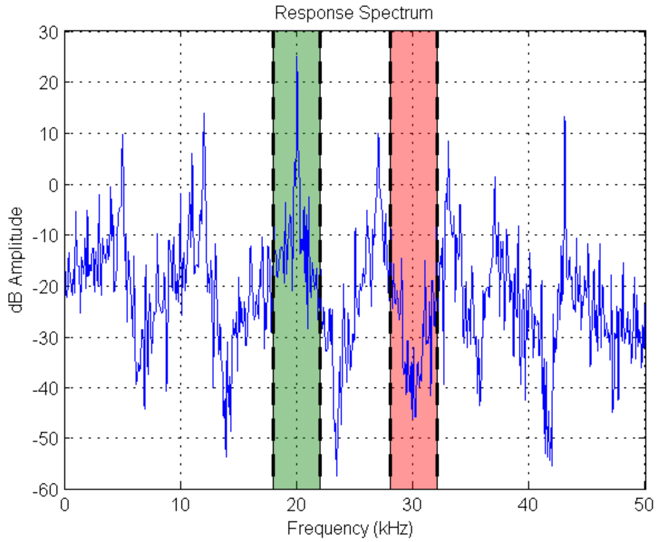

Figure 4. Synthetic response spectrum. Green region would provide information for health monitoring, while red region would not.

Even healthy bearings may exhibit some low-level amplitude of their defect frequencies; setting up an "alarm," or condition indicators requires some knowledge of how the amplitude of the defect frequencies changes with defect severity. For a simple, single-speed machine, it is usually possible to make some baseline vibration measurements when it is new or the bearings are known to be in good condition and then simply monitor for increased vibration amplitude, particularly at the known defect frequencies. However, any change in operating conditions such as speed, load, temperature, etc. can also cause a change in the measured acceleration amplitudes – it is very difficult to distinguish these changes from actual changes in the bearing condition. For this reason, setting up condition indicators is generally a non-trivial task. Ideally one should have a large matrix of data: known good bearing data from multiple machines as well as known faulted bearing data and all of this across all relevant operating conditions [5].

This testing, particularly acquiring the known faulted bearing data, can be very costly. For example, the ideal test plan for gathering this data for the Blackhawk helicopter would require running each of its seven gearboxes on a test rig with seeded defects of each type (outer race, inner race, and rolling element) in each bearing and doing this over a range of operating conditions. Clearly, this would be a monumental task for just one model of helicopter, and the US Army uses several. Due to differences between aircraft of the same model (due to design or manufacturing differences or even changes made during overhaul), it is best to repeat this test on multiple samples, such as a new unit, one through half of its service life, and an overhauled unit, and if there are significant design changes, then representative samples of these should be tested as well.

An alternative is to measure the vibration transfer paths, from the bearing defect to the monitoring accelerometer [6]. This provides clear information about which frequency bands will readily transmit energy and which bands will not. This does not provide a complete picture, however, as the frequency content of the defect force is unknown. That is, one might choose an enveloping band in a high-frequency region of strong structural response, but a typical defect in the bearing of interest may not excite the structure in that high frequency range. Still, knowledge of the transfer path dynamics is definitely superior to simply guessing at the frequency bands chosen for demodulation.

Measuring the transfer path is only slightly easier than running seeded-defect tests, however. Exciting at the defect locations is extremely difficult, and this must be done with the gearbox in its assembled condition; if it is disassembled for access, the system dynamics will be considerably different. The excitation device must be installed at each bearing defect location, which means disassembling each gearbox at least once. Additionally, the measurements must be made throughout the frequency range available for monitoring.

A device for making bearing defect transfer path measurements is shown in Figure 5. This is a reaction-mass shaker with sensor made using 5x5x2 mm piezoelectric chips from Physikinstrumente both for transducer and sensor. The miniature shaker is placed on the bearing race and the bearing is assembled into the gearbox, permitting transfer path measurements in a fully-assembled condition. If sensor placement is to be established, a tool like this can be used to evaluate sensor locations.

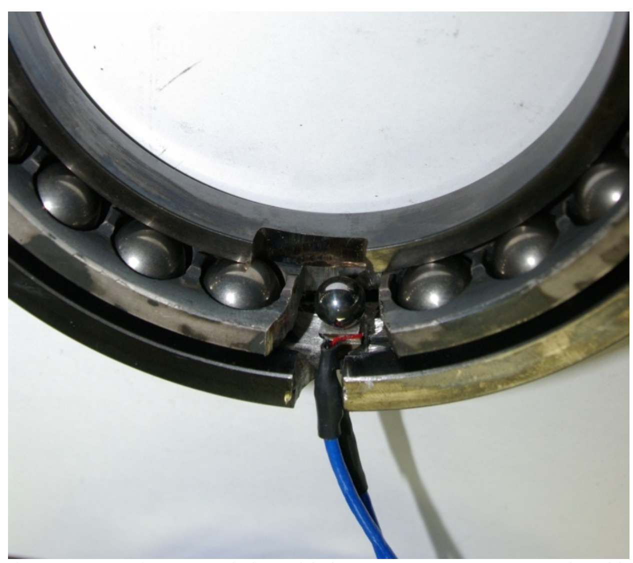
Figure 5. Reaction-mass shaker with force-measurement sensor placed in bearing for defect transfer path measurement.

Many bearings are near the surface of the gearbox, and it was found that these FRFs are similar enough to the true transfer path FRFs to identify frequency regions which readily transmit bearing defect vibration. These measurements are simple and easy to make; they can be done directly on a helicopter in the hangar without any major disassembly. The validity of the surface-made measurements was demonstrated in the lab using an Apache intermediate gearbox. The bearing excitation device shown above was used to measure the 'true' transfer path, which was compared to measurements made externally on the gearbox near the bearing defect locations. The bearing defect locations are assumed to be on the bearing race in the load direction; a defect on a rolling element has a continuously changing transfer path, but it would share this transfer path once per revolution. An example of the internal and external FRFs is shown in Figure 6. Note that while the FRFs are not identical, they share the same trends and both provide the required information: which frequency regions may be good for monitoring (good energy transmissibility) and which should be avoided (poor energy transmissibility). Also note that the noise and poor coherence (a measure of FRF quality) at low frequency (under 3 kHz for the external measurement and under 8 kHz for the internal measurement) is due to the low force amplitude in that region inherent in reaction-mass shakers.

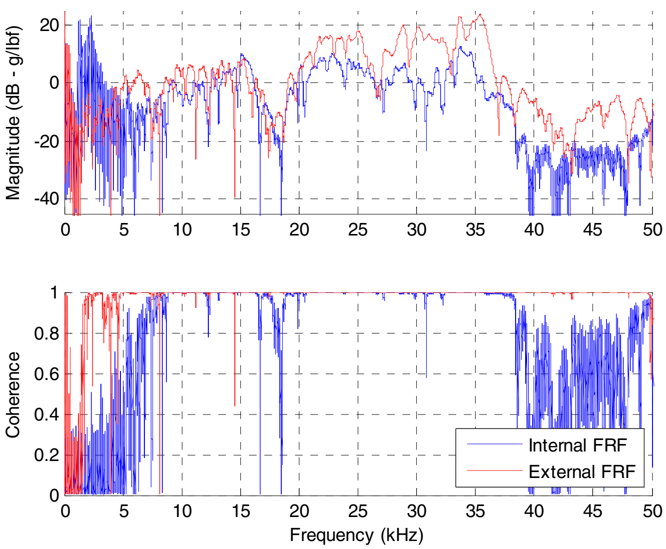

Figure 6. Internal and external FRFs measured on Apache IGB

When setting up condition indicators for monitoring a fleet, one must consider the fact that many factors can affect the amplitude of the transfer path dynamics between serial numbers, and this affects the measured response amplitude. Consider the Blackhawk helicopter: they have been built since the 1970s, and even minor design changes to a transmission case can yield substantially different transfer path dynamics (especially at high frequency). Additionally, differences in sensor sensitivity, sensor placement and orientation, and even changes made during an overhaul can yield considerably different response amplitude between helicopters. Again, response at higher frequency is generally more greatly affected. Figure 7 shows FRFs recorded on three different Blackhawk intermediate gearboxes. While some frequency regions are very similar, some are quite different. Clearly, the condition indicator thresholds must be high enough that the gearboxes with larger-amplitude FRFs do not cause false alarms, and low enough that gearboxes with lower-amplitude FRFs do not risk missed detection – depending on the vibration amplitude from a faulty component, it may not be possible to set a threshold that gives an acceptable false alarm/missed detection rate. Note that at least ten years separates the oldest with the newest of these helicopters, and one of the gearboxes had been overhauled.

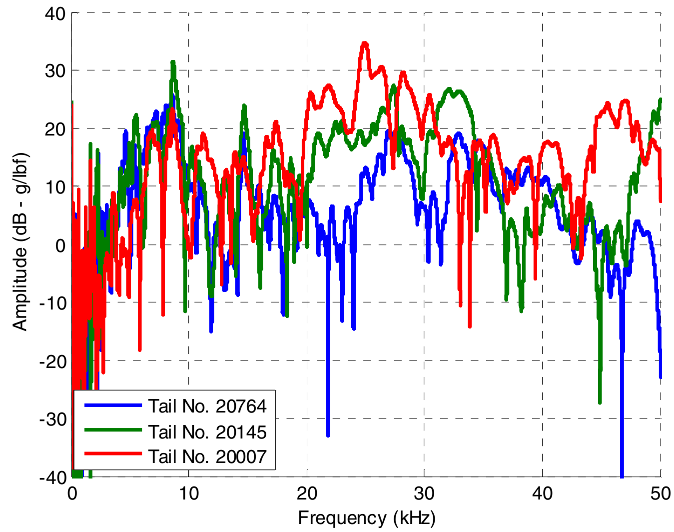

Figure 7. FRF repeatability between serial numbers

IV. Waveguide Vibration Sensor

As outlined above, the difficulty in mounting piezoelectric sensors near components due to temperature or other environmental concerns has forced the vibration analyst to accept many compromises when measuring data on aerospace systems. For example, turbine engine main bearings must be monitored from the case, which is relatively far from the bearings – the measured vibration data has poor signal to noise characteristics and much masking vibration from other sources. In fact, even the case of a turbine engine can be a very hostile environment for a sensor, sometimes reaching 1200°F [4]. Another example is gears and bearings in large transmissions – case mounted accelerometers are often too remote for good quality data to provide early fault detection. A pragmatic solution to this problem is an innovative sensor design which 'guides' the desired vibration information along a mechanical waveguide from the component of interest to a convenient location where the sensor can be mounted and easily serviced. The mechanical waveguide can be made from materials which are resistant to hot or corrosive environments; additionally, the ability to 'transmit' the desired vibration signal permits monitoring components which are otherwise inaccessible. Testing of this sensor has shown that high-fidelity vibration information can be reliably transmitted over one meter from the component to the sensor.

Mechanical waveguides have been used for sensing and process measurement in hot, caustic, or inaccessible environments for many years [7, 8]; however, waveguide usage for broadband measurement has been impeded by reflections, or standing waves inherent in typical waveguides.

Recent developments for reflection elimination have enabled waveguides to be used as broadband vibration sensors.

Figure 7 shows an early prototype waveguide mounted to a Chinook T55 engine and Figure 8 shows measured FRFs comparing the response from the waveguide to a high-frequency accelerometer mounted in approximately the same position. The differences are similar to that between different models of accelerometers, due to different mass loading and cross-axis sensitivity characteristics; 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, as the reaction-mass shaker does not provide much energy below this frequency.

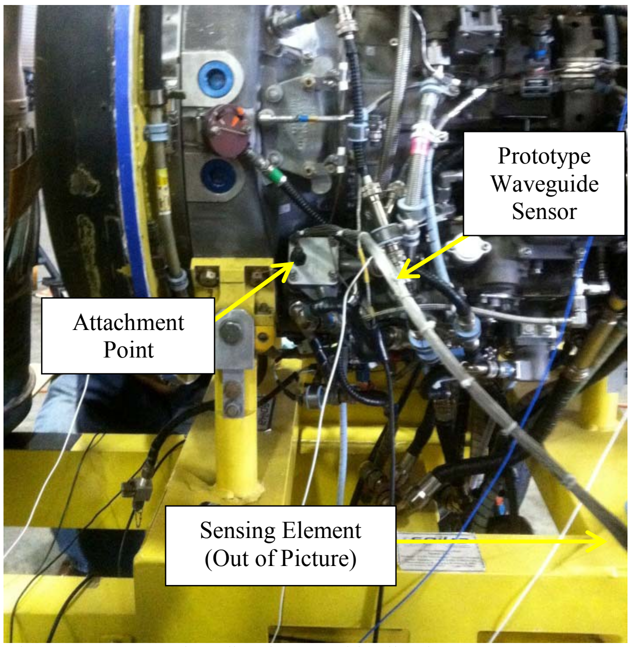

Figure 8. Prototype broadband waveguide vibration sensor mounted to Chinook T55 turbine engine.

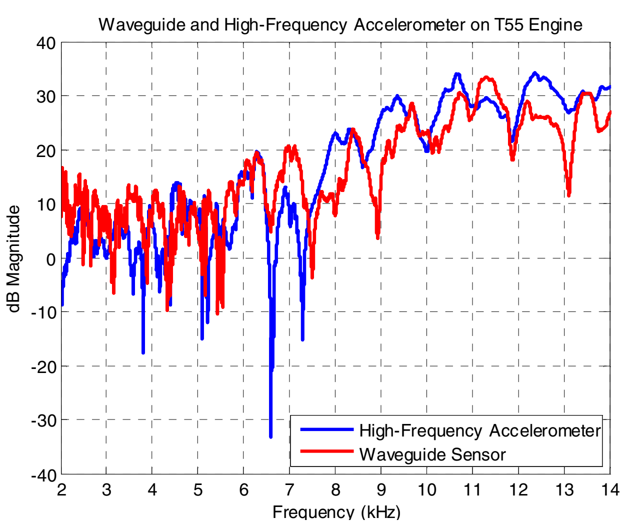

Figure 9. Transfer path comparison between high-frequency accelerometer and broadband waveguide.

V. CONCLUSIONS

Vibration health monitoring of aerospace applications presents many challenges: sensor selection and placement for high-fidelity data must be balanced with sensor longevity and masking noise. Measurement of the vibration transfer path provides valuable insight for the selection of frequency bands for high-frequency health-monitoring algorithms. Defect transfer paths for bearings near the gearbox surface can be easily approximated by measuring FRFs at the surface. Waveguide sensors provide high-fidelity measurements where traditional sensors cannot due to environmental conditions or access.

ACKNOWLEDGMENT

The funding for making high-frequency transfer path measurements on helicopter gearboxes came from the US Army, AMRDEC. Waveguide vibration sensor development was funded under a US Air Force Phase I SBIR contract, “Very High Frequency (CHF) monitoring System for Engine Accessories Health Management (Contract #FA8650-09-M-2981, Topic AF083-105).

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