Bearing Envelope Analysis Window Selection

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ABSTRACT

Bearing envelope analysis (BEA) is a powerful technique in the detection of faults in bearings. The improper selection of the envelope window frequency and window bandwidth can render the analysis ineffective. This can reduce the ability of a health and usage monitoring system (HUMS) to correctly identify a degraded bearing. This occurred recently: a teardown analysis (TDA) of a utility helicopter oil cooler fan housing found extensive bearing damage. The HUMS did not detect the fault. This paper is an analysis of why the BEA failed to detect the damage bearing. A description of the BEA is given. Using raw data that was collected prior to the TDA, various windows where tested on the BEA, a measure of effectiveness for BEA window selection was developed, and a window is suggested that would have detected the bearing fault is given[*].

1. INTRODUCTION

Rotating equipment in general and helicopters in particular, are dependent on a transmission to condition the power for useful work. In the case of helicopters, the power of a low toque, high speed input shaft is converted into a low speed, high torque main rotor shaft. Integral to the reliable operation of this transmission, are bearings. Safety and readiness of the helicopter are improved if monitoring techniques are developed, which can detect when a degrading or faulty bearing requires maintenance. This is the essence of HUMS bearing monitoring.

A number of bearing analysis techniques have been developed. Because the vibration signals of a faulted bearing are small compared to shaft order and gear mesh, detection of fault at the bearing rate frequencies using Fourier analysis is difficult. This is "stage 1" fault detection. Bearing faults detected using these types of analysis are late stage and can be close to catastrophic failure. Ultrasonic emission can detect bearing inner and

outer race roughness (a "stage 3" fault), but the remaining useful life a bearing at this stage is relatively long compared to the overall life of the bearing. Bearing envelope analysis (BEA) can typically detect bearing faults 10s if not 100s of hours prior to when it is appropriate to do maintenance. It is for this reason that many HUMS manufactures are using envelope analysis techniques.

Given the known performance of BEA, there was consternation when a recent teardown analysis of an utility helicopter oil cooler fan bearing housing showed extensive wear to a monitored bearing (see figure 1 and 2. (McCain, 2008)). The HUMS had not indicated bearing damage and had been installed for over a year to the TDA. Numerous acquisitions had been made, yet the bearing condition indicator values where nominal. The damage seen in the teardown analysis showed corrosion and extensive spall/pitting damage of the bearing ball elements, inner and outer race. This type of damage occurs over an extended period of time and should have been detected. Fortunately, raw vibration data was collected in addition to the BEA condition indicator data prior to the TDA. This allowed post processing of the bearing data.

Figure 1. *Outer Race Showing Damage*

Prior experience with BEA has shown that the ability to detect a fault is based on the window (frequency and bandwidth) used(Bechhoefer, 2007). It is hypothesized that the poor window selection

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was the cause of the missed detection. In this paper, we show how the BEA functions and a method of determining the optimal window for fault detection.

Figure 2. *Inner Race Showing Defects*

2. THE BEARING ENVELOPE ANALYSIS

BEA is based on demodulation of high frequency resonance associated with bearing element impacts. For rolling element bearings, when the rolling elements strike a local fault on the inner or outer race, or a fault on a rolling element strikes the inner or outer race, an impact is produced. These impacts modulate a signal at the associated bearing pass frequencies, such as: Cage Pass Frequency (CPF), Ball Pass Frequency Outer Race (BPFO), Ball Pass Frequency Inner Race (BPFI), and Ball Fault Frequency (BFF). This periodic modulation also increases the envelop RMS. Mathematically, the modulation is described as:

$$\cos(a) \bullet \cos(b) = \tfrac{1}{2}\left[\cos(a+b)+\cos(a-b)\right] \quad (1)$$

This is amplitude modulation of the bearing rate (*a*) with the high frequency carrier signal (resonant frequency (*b*)). This causes sidebands in the spectrum surrounding the resonant frequency. It is sometimes difficult to distinguish the exact frequency of the resonance. It is usually not known *a priori* and cannot be determined easily. However, demodulation techniques typically do not need to know the exact frequency. The BEA multiplies the vibration signal by a high frequency, complex signal centered at a hypothesized resonant frequency (example, 22.5 KHz). This is then low pass filtered to remove the high frequency image, decimated, and the spectral power density is estimated. (Eq 2)

$$\cos(b) \bullet \cos(a+b) =$$

$$\tfrac{1}{2}\left[\cos(a+b+b)+\cos(a+b-b)\right] \quad (2)$$

$$\rightarrow H(\omega) \rightarrow \cos(a)$$

The bearing components have a number of vibration modes, which will correspondingly generate resonance at various frequencies throughout the spectrum. The selection of the tone used to demodulate the bearing rate signal (e.g. the window center frequency) should take into account two issues.

First, the gearbox spectrum contains a number of high-energy tones from shaft and gear harmonics, which would mask analysis at lower bearing frequencies. This suggests using one of the higher bearing modes, where there is less shaft/gear energy. Second, there are a number of accelerometers with natural resonance at frequencies that are similar to the bearing modes. Using a higher frequency window close to the accelerometer resonance can amplify the bearing fault signal, increasing the probability of fault detection.

BEA should be performed at frequencies higher than the shaft and gear mesh tones. This ensures that the demodulated bearing tones are not masked by the other rotating sources, such as shaft and gear mesh, which are present at CPF, BPFO, BPFI and BFF frequencies. Typical shaft order amplitudes of 0.1 G's and gear mesh amplitudes of 10s of G's, are common. Damaged bearing amplitudes are 0.001 G's.

For BEA, the bearing rates are calculated as:

Cage Pass Frequency (CPF):

$$\frac{f}{2}\left(1-\frac{d}{e}\times\cos(\beta)\right) \quad (3)$$

Ball Pass Frequency Inner Race (BPFI):

$$\frac{b \times f}{2}\left(1+\frac{d}{e}\times\cos(\beta)\right) \quad (4)$$

Ball Pass Frequency Outer Race (BPFO):

$$\frac{b \times f}{2}\left(1-\frac{d}{e}\times\cos(\beta)\right) \quad 5)$$

Ball Fault Frequency (BFF):

$$\frac{e \times f}{d}\left(1-\left(\tfrac{d}{e}\right)^{2}\times\cos^{2}(\beta)\right) \quad (6)$$

where,

- *f* is the driving frequency
- *b* is the number of rolling elements
- *d* is the ball bearing diameter
- *e* is the bearing pitch diameter
- β is the bearing contact angle

The amplitude associated with the bearing rates frequency can be used as a condition indicator (CI), which reflects the "health" of the bearing components.

2

3. HEALTH INDICATOR ALGORITHM FOR BEARING CONDITION INDICATORS

In any HUMS, there is need for a screening tool to identify those components that could be diagnosed as damaged or faulted (e.g. high CI value). For a bearing, the cage, ball, inner and outer race will have an associated CI. The health of the bearing is then some function of the CI values. A simple health function could be the maximum "normalized" CI value (an order statistic (Bechhoefer and Mayhew, 2007)). The component's health could then be presented by a health indicator (HI) where a HI greater than some threshold would be considered damage. In this case, the HI serves as a diagnostic.

Other health functions could be used. For example, given that the CIs have distributions that are Rayliegh, the square root of the normalized sum of square would have a Nakagami distribution. Given a known distribution and an acceptable false alarm rate, a threshold can be set statistically such that an HI greater than the threshold is most likely representative of a damaged component (see (Bechhoefer, 2007)). The methodology, coupled with an appropriate failure model, facilitates prognostics (Bechhoefer, 2008).

For a bearing, we will use four condition indicators to represent the health of the bearing. It is likely that each sub element (ball, cage, inner and outer race) of the bearing will have its own resonant mode. As a result, an optimal window for one sub element will not be optimal for the other 3 sub elements. Additionally, since the CI values represent different parts of a spectrum, each will have different nominal amplitude values.

4. ANALYSIS OF FAULTED DATA

It was hypothesized that the failure to detect the faulted oil cooler bearing was due to poor window selection. This hypothesis was tested. Some considerations that need to be accounted for are: the CI values for each bearing sub element window (resonant frequency and bandwidth) will have different nominal amplitude values. The evaluation required a mapping or normalization so that these disparate values can be compared across different windows.

4.1 The Available Data

The current bearing CI data did not reveal any fault signatures. Since the installation of the HUMS in July of 2007 until March of 2008, a total of 45, raw vibration data (32,768 data points sampled at 104 KHz) acquisitions were collected. The TDA reported that the oil cooler was removed from service in February, 2008, which gave 38 acquisitions of the damaged components and 7 acquisitions on a remanufactured oil cooler. This raw data, while a small data set, allowed reprocessing of the vibration data and evaluate of different envelope windows.

From prior bearing testing (Bechhoefer, 2007) it was found that a envelope window of 20 to 25 KHz worked well in detecting bearing faults. An initial test of the hypothesis was made: the 45 raw data files where processed to under the current default window (13 to 18 KHz) vs. and alternative window (20-25 KHz). If the window has an effect on envelope algorithm and since we have a known damaged bearing, one should see two things:

- In the spectrum, it should be possible to see elevated amplitudes associated with the bearing element rates.

- Since the damage was accumulated over an extended period of time, one should see an increasing trend in the bearing CI values, and once the component is replaced, the CI values should drop.

In Figure 3 and Figure 4, we can compare the spectrum of the default window vs. the alternative window.

Note: the default selection of the 13 to 18 KHz was based on an analysis of the spectrum from in service aircraft. Resonance was seen in the spectrum centered at 15 KHz. It was assumed that this was from bearing defects. However, it was later shown that this was flow induced resonance on the oil cooler fan itself.
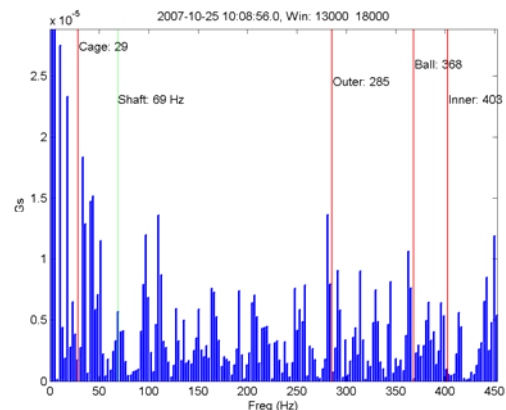

Figure 3. *Envelope Spectrum at 13 to 18 KHz*

Note that because of the window selection, y-axis is close to an order of magnitude different. In figure 4, the cage, outer race, and ball race magnitudes clearly identify the bearing as faulted.
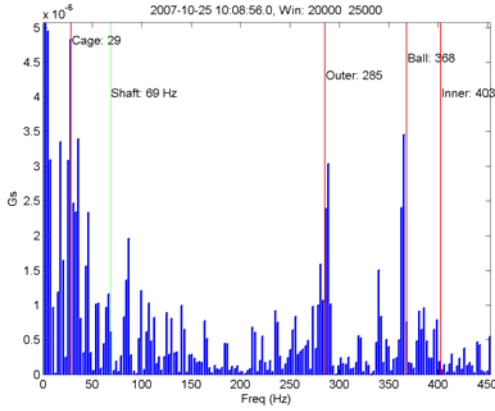
Figure 4. *Envelope Spectrum at 20 to 25 KHz*

Because of the large difference in absolute values between different window CIs, the 48 CIs generated by a given window where normalized between zero and one. See Figure 5
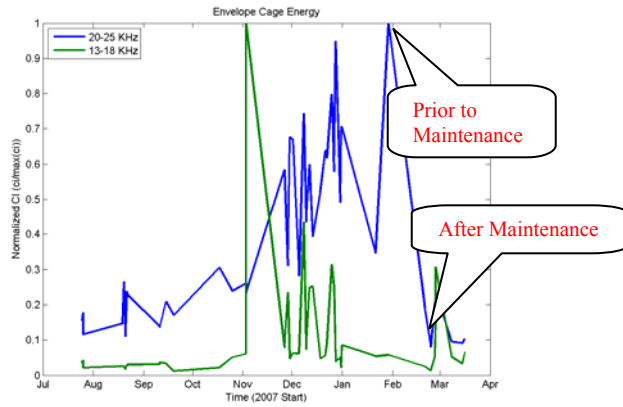

Figure 5. *Comparison of Cage (CPF) CI using different Envelope Spectrums*

Figure 5 supports the hypothesis that a different envelope window would have showed an increasing trend in the CIs, which could be used to trigger maintenance.

4.2 Optimal Selection of Envelope Window (EW)

Proper EW selection can result in a CI that is sensitive to bearing fault. In general, the EW will be different for different bearing sub elements, and will be different across bearings. This study will focus on the oil cooler bearing; we can make generalization about window selection for other bearing, and be specific with regard to component under test.

In comparing the CIs across EW it was necessary to normalize the CIs. Even with normalized CI, we need some metric or measure of effectiveness (MOE) to describe, at a system level, the ability of the CIs to be effective in triggering a maintenance action when appropriate. Subjectively, a good CI would trend

smoothly as damage progressed. A number of MOE functions come to mind:

- Minimizes CI RMS
- Maximize Slope (an indication of trend)
- Maximize Feature SNR

The MOE what was selected was the slope of the line that minimum mean square error divided by sum of square errors of the line.

The minimum mean square error is calculated as:

$$\mathbf{b} = \left(\mathbf{X^T X}\right)^{-1} \mathbf{X^T Y}$$

where

$$\mathbf{X} = \begin{vmatrix} 1 & 1 \\ 1 & 2 \\ .. & .. \\ 1 & 38 \end{vmatrix}, \quad \mathbf{Y} = \begin{vmatrix} CI_1 \\ CI_2 \\ .. \\ CI_{38} \end{vmatrix}, \quad \mathbf{b} = \begin{bmatrix} \text{intercept} \\ \text{slope} \end{bmatrix} \quad (7)$$

and the sum of square errors (SSE) is:

$$\hat{\mathbf{Y}} = \mathbf{X^T b}$$

$$SSE = \sum_{i=1}^{38} \left(\mathbf{Y} - \hat{\mathbf{Y}}\right)^2 \quad (8)$$

This MOE, slope/sse, quantifies how well a given EW will facilitate detection of a fault (e.g. low noise trend). The MOE was calculated from an EW low frequency of 13 KHz to 25 KHz with a bandwidth of 1KHz to 7 KHz, in 0.5 KHz step size. This resulted in 325 experimental ranging from an EW of 13 to 13.5 KHz up to an EW of 25 to 32 KHz. As an example of the appropriateness of this MOE, consider this example Outer Race example (Figure 6). Here we plot the highest MOE vs. the Lowest MOE.
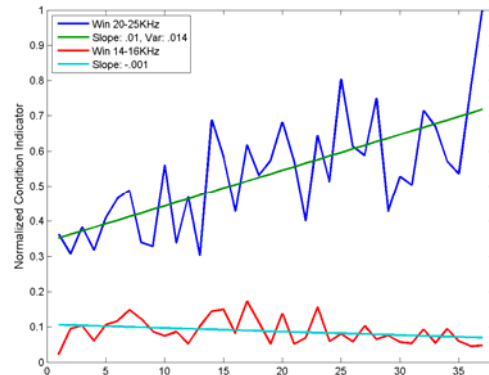

Figure 6. *Outer Race MOE, Best vs. Poorest*

4

4.3 Results

In an attempt to better visualize or map the MOE vs. EW, contour plots of the 325 experiments where made for ball, cage, inner and outer race and RMS envelope energies where made (figures 7 through 11). NOTE: This research does not recommend the use of envelope RMS as an indicator of bearing health. While envelope RMS is sensitive to bearing fault, it is also sensitive to a number of other conditions, such as gear backlash, pump value clatter, etc. Relying on envelope RMS may generate spurious maintenance actions.
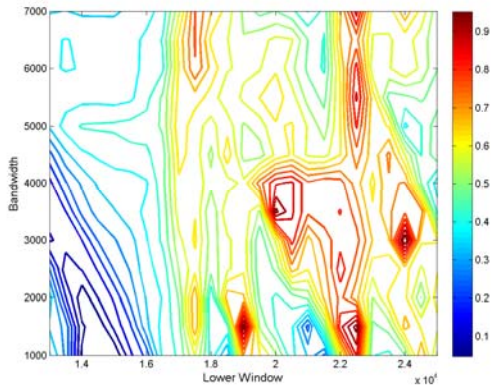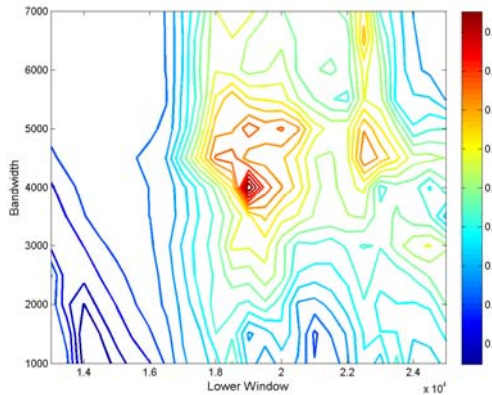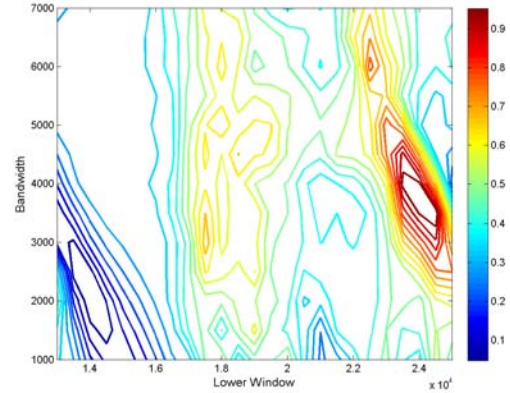

Figure 7. *Ball MOE*

Figure 8. *Cage MOE*
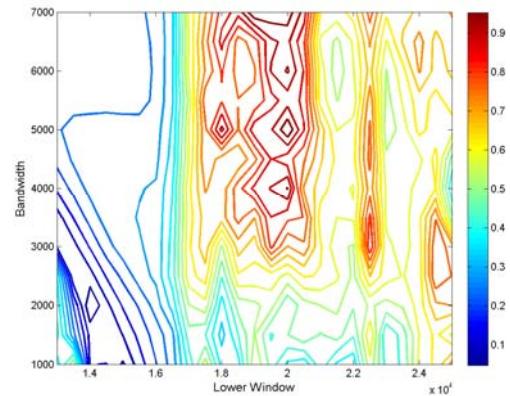

Figure 9. *Inner Race MOE*
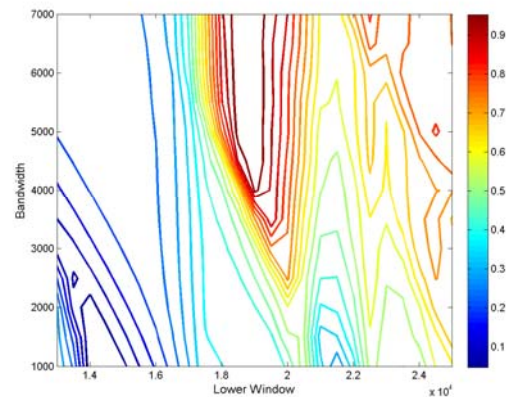

Figure 10. *Outer Race MOE*

Figure 11. *RMS MOE*

The "best" EW for each sub element is different. In application, the HUMS will process one EW for the bearing. This requires a compromise in the EW selection. The optimal MOE was chosen as the average of the ball, cage, inner and outer rate MOE. (figure 12). Table 1 gives the best 10 EW.
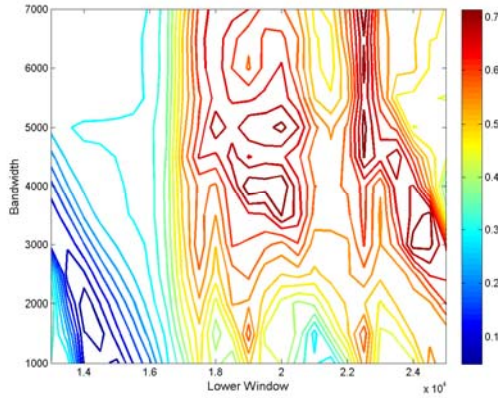
Figure 12. *Overall MOE for Cage, Ball, Inner and Outer Race*

TABLE 1: TOP 10 ENVELOPE WINDOWS

Window (KHz)	MOE
20 - 24	0.749
19 - 23	0.745
22.5 – 29.5	0.744
24.5 – 28	0.734
24 – 27	0.733
19.5 – 23.5	0.73
22.5 – 27.5	0.725
20 – 25	0.725
24.5 – 27.5	0.724
22.5 – 28.5	0.722

Using an EW of 20-25 KHz, the correlation of damage over time can be calculated. As an example, using the 38 data points prior to the replacement of the oil cooler, the correlation and variance of the CI/HI are presented in table 2.

TABLE 2: CORRELATION & VARIANCE OF CI/HI

CI/HI	R value (correlation)	Variance
HI	0.74	0.11
Cage CI	0.84	0.11
Ball CI	0.58	0.13
Inner Race CI	0.56	0.13
Outer Race CI	0.70	0.12

The HI, Cage CI and Outer Race CI are highly correlated with time, and presumably damaged.

5   CONCLUSION

Analysis has shown that EW selection is important for fault selection. We can hypothesize had the HUMS been configured differently, it is likely that the fault would have been detect. The acquisitions within HUMS are 200K points of data vs. the 32K points used in this analysis. The relationship between the number of points and noise in a spectrum can be shown to be proportional to $1/\mathrm{sqrt}(n/2)$, where n is the number of data points. Given 6.25 times as much data, we would expect the system noise to be reduced by 2.5 times. This suggests that trend data would have been significantly better then that shown in this analysis.

In a number of studies, from test stand to on-aircraft, we have observed that an EW of 20-25 KHz works well. We determined that a better window is 20-24KHz. Given any extenuating circumstances or actual data to show otherwise, this research recommends 20-24 KHz as the default values for EW.

Envelope analysis is a powerful tool for bearing diagnostics. Improper EW selection can render the algorithm almost useless. From a certification perspective (for both the FAA in applying for HUMS maintenance credits or the Army aviation in applying for an Air Worthiness Release) this suggests that either test stand or direct evidence must be demonstrated to show the effectiveness, at a system level, for detecting fault. The FAA's AC-29 MG 15 states as much.

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