EXPERIMENTS AND ANALYSIS OF VIBRATION SIGNALS FROM A FAILED COMPONENT IN A HELICOPTER GEARBOX

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This paper investigates and analyses a failed component in a helicopter gearbox after metal flaking triggered a chip detector warning. Examination of the gearbox revealed spalling in one of the rollers of a cylindrical roller bearing. In-flight data was acquired and a pool of techniques has been suggested in this paper for detecting bearing faults. They are envelope demodulation, cepstrum analysis and statistical methods such as zero order figure of merit (FM0), spectral entropy (SE) and energy in the enveloped spectrum. Systematic failure analysis was carried out, using in-flight data and also data collected from a test rig under controlled laboratory conditions, i.e., a helicopter gearbox fitted with the same defective bearing. The gearbox was run at different speed and load conditions. Multiple vibration accelerometers were mounted on the bearing housing in the axial and radial directions to capture vibration signals for maximum signal coverage. Analysis of in-flight signals is a complex one as there are a number of shaft rotational frequencies as well as gear mesh frequencies (GMF) and their harmonics and these signals can easily mask bearing fault frequencies. The methods suggested above attempt to address this problem and the results are promising.

Keywords: Helicopter gearbox, bearing fault diagnostics, envelope analysis, statistical descriptors, condition monitoring

1. Introduction

Bearing elements are widely used in helicopters and their failure is one of the reasons for helicopter accidents [1]. The last few decades have seen significant strides in the research undertaken in the field of bearing diagnostics. Envelope analysis is a well known technique to extract low energy diagnostic information hidden in high frequency resonances [2], [3]. In conjunction with envelope analysis, spectral kurtosis has been implemented to recommend frequency bands of highest impulsiveness [4]. These methods have yielded high accuracy in bearing fault detection mostly due to creating seeded faults. They have, however, not been tested on composite signals arising from the interaction between different components of a helicopter main gearbox (MGB) [5].

In the present paper, the detection of bearing faults with such complex signals is investigated. Vibration signals were acquired from experiments carried out in a test rig and from in-flight data using a cylindrical roller bearing that had failed during normal course of flight operation. Various signal processing methods suggested in this paper such as cepstral analysis, envelope demodulation and statisti-
cal methods like FM0, SE and total energy were implemented on test rig and in-flight data for different speed and load conditions. The main objective of this study is to establish a correlation between failure and the various descriptors used.

2. Helicopter MGB & test rig details

The MGB used in the test rig was the same as that in the helicopter whose in-flight data was acquired. The transmission system which transfers power from the engine to the main rotor, tail rotor and other accessories has two stages, with a spiral bevel gear input stage followed by a spiral bevel gear collector stage. The main rotor hub is directly attached through a stub shaft to the collector gear, which drives the tail rotor and transfers the necessary power in two stages. The first stage consists of a pinion, driven by the collector gear and the second stage consists of a helical gear driving a helical pinion. Figure 1 shows a typical helicopter drive train and Fig. 2, the general arrangement of gears. It consists of an MGB, AC motor and a loading unit to conduct closed loop testing. The AC motor generates an input speed of 6000 rpm, which is reduced via two gear reduction stages to an output rotor shaft speed of 314 rpm. To create the desired loading on the MGB, a closed loop test rig was installed. For the experiment carried out on the test rig, a failed cylindrical bearing component was sourced from a helicopter gearbox, which had given out a chip detector warning.

![Figure 1: A typical helicopter drive train [6].](image1)

![Figure 2: Gear arrangement.](image2)

3. Test conditions and signal recording

The test plan included two sets: (i) one with a healthy input cylindrical roller bearing to give baseline vibration values and (ii) another using a failed input bearing with spalling in one roller (Fig. 3).
3.1 Ground test plan

The test rig was isolated from the floor using vibration mounts. For this experiment, 3 uniaxial ICP accelerometers (PCB 352C34) were installed to capture vibration signals from the left hand side of the MGB. Table 1 shows the locations of the accelerometers which were glued on to the bearing housing. The locations were chosen such as to give minimum transmission path from the vibration source. An optical tachometer was installed on the input shaft for obtaining time synchronous averaged (TSA) data. For recording, preprocessing and storing the vibration signals, an LMS Scadas data acquisition system was used. A representative load test spectrum is given in Table 2 to show the operating conditions for the test. Safety protocols were adhered to in terms of maximum speed and rotor load conditions. The maximum speed the gearbox was operated under was around 7300 rpm. The maximum load was restricted to 17000 Nm. Each test case (load, speed combination) was run for 5 minutes, out of which 10 seconds of data was recorded using a sampling frequency of 51.2 kHz.

Table 1: Sensor locations

| Sensor 1 | Axial to the collector gear |
| Sensor 2 | Radial vertical to input bearing |
| Sensor 3 | Axial to input bearing |

Table 2: Testing schedule

<table>
<thead>
<tr>
<th>Test case</th>
<th>Time (minutes)</th>
<th>Speed (% rpm)</th>
<th>Input power (kW)</th>
<th>Rotor load (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state</td>
<td>5</td>
<td>100</td>
<td>568</td>
<td>9000</td>
</tr>
<tr>
<td>Overspeed</td>
<td>5</td>
<td>122</td>
<td>350</td>
<td>Minimum</td>
</tr>
<tr>
<td>Overload</td>
<td>5</td>
<td>100</td>
<td>568</td>
<td>17000</td>
</tr>
</tbody>
</table>

3.2 In-flight data collection

Accelerometer 2 was used for in-flight data collection from an on-board vibration monitoring system with a sampling frequency of 48 kHz. The same failed bearing was used for the in-flight tests also.

4. Processing techniques

A faulty roller hits the outer race while rolling and produces a series of impulses, whose repetitive rate can be found solely from the geometry of the bearing if the rotational speed is constant. However, often, the faulty bearing frequencies are obscured in the spectra due to vibrations from other rotating parts. Researchers have tried separating gear signals from bearing signals, but this is not studied in this work. Many studies are reported on signal processing techniques for diagnostics and prognostics [7].

4.1 Cepstrum analysis

It is well known that bearing signals, even though low in signal energy, are found throughout the spectrum. Cepstrum analysis is a signal processing tool to detect harmonic families in the spectra of gearbox and bearing signals and is defined as the inverse transform of the logarithm of the power spectrum. The power cepstrum reverts to the time domain and exhibits a family of peaks corresponding to the rahmonics of the quefrency of the modulating or defect frequency of the bearing or gearbox.

\[ c(\tau) = \mathcal{S}^{-1}\left\{ \log F_x(f) \right\} \]  

(1)
4.2 Envelope analysis and spectral kurtosis

Envelope analysis is a popular technique used for bearing diagnostics. It involves band-passing vibration signals from a high frequency band, where the resonant frequencies associated with bearings are dominant. The envelope of the signal band-passed around the resonance frequency is then demodulated. On examining the envelope spectrum of the band-passed signal, the fault frequencies of the faulty bearing signals can be extracted for defect identification. While this method is known to reveal repetitive information hidden in the signal envelope, it also mitigates the effect of speed fluctuation and additive noise. To implement this method for good results, one needs to have an idea of a suitable demodulating frequency band. Spectral kurtosis (SK) is a statistical tool found useful to detect a series of transients/impulses and their spectral bands; hence it is useful for depicting impulsive data. An optimum bandwidth and centre frequency is used as given by the recommendation of Kurtogram, a mathematical tool that gives a visual representation of short time frequency transform (STFT). The spectral kurtosis $K(f)$ of a signal $x(t)$ can be calculated using the STFT of the signal.

$$X(\tau, \omega) = \int_{-\infty}^{\infty} x(t)\psi^*(t-\tau)e^{-j\omega t}dt$$

where $\psi(t)$ is a window function. The spectral kurtosis is given as

$$K(f) = \frac{\left\langle |S(t, f)|^4 \right\rangle}{\left\langle |S(t, f)|^2 \right\rangle^2} - 2$$

4.3 Statistical descriptors

(i) FM0 is known to be a robust indicator of major faults and has been mainly used for detection of gear faults, but has been seen to be promising for bearing failures also in the present work.

$$FM0 = \frac{PP_x}{H} \sum_{N=0}^{H} P_N$$

where $PP_x$ is the peak-to-peak amplitude of the signal $x(t)$. $P_N$ is the amplitude of the $N^{th}$ harmonic and $H$ is the total number of harmonics in the spectrum.

(ii) SE of a signal is a parameter that quantifies its spectral power distribution [8], [9]. The steps involve calculating the power spectral density (PSD) of the signal and then normalizing it to result in a probability distribution function. Finally, Shannon entropy is computed to give the SE of the signal. Since this parameter can measure randomness, it is found useful in fault detection. For a signal $x(n)$ with discrete Fourier transform $X(m)$, the power spectrum and probability distribution are shown in Eq. (5) and spectral entropy and normalized spectral entropy in Eq. (6).

$$S(m) = |X(m)|^2 \quad (a) \quad P(m) = \frac{S(m)}{\sum_i S_i} \quad (b)$$

$$H = -\sum_{m=1}^{N} P(m)\log_2 P(m) \quad (a) \quad H_n = -\frac{\sum_{m=1}^{N} P(m)\log_2 P(m)}{\log_2 N} \quad (b)$$

where $N$ is the total number of lines in the spectrum. The denominator of Eq. (6b) represents the maximum spectral entropy of broad-band white noise.

(iii) The total energy in the enveloped spectrum has been computed from Eq. (7).

$$E = \sum_{k=0}^{N/4} |X(m)|^2$$
5. Test results

In-flight data and test rig data, both baseline and with the damaged bearing were processed. In-flight data came with only one sensor data and that was radial to the bearing. Similarly, in test rig data, that sensor was selected which had the highest peak-peak and root mean square (RMS) values of the signal.

5.1 Ground test data

Figure 4 shows the time waveforms and spectra of baseline and damaged bearing vibration data under steady state conditions. The figure shows tooth mesh frequency of the input gear pinion arrangement, apart from GMFs of the other components. Amplitude of the 2XGMF component of the damaged bearing is seen to be twice that of the healthy bearing. The spectra show no fault frequencies, either around 219.9 Hz which is the roller/ball fault frequency (BFF) or 260 Hz which is roller/ball fault frequency outer race (BPFO) or 14.88 Hz which is the fundamental train frequency (FTF); this indicates that the faulty signal is masked by strong background noise and other meshing frequencies.

![Time waveforms and magnitude spectra of vibrations with healthy and damaged bearings.](image)

Figure 4: Time waveforms and magnitude spectra of vibrations with healthy and damaged bearings.

Figure 5 shows the spectrograms of the healthy and damaged bearings. Apart from a high intensity band around the second GMF, higher intensity values are seen in higher GMFs of the spectrogram of the damaged bearing. This could be because the bearing fault could have modulated the GMF since the bearing was supporting the input gear; hence the explicit increase in GMF values. Other high frequency bands could also indicate roller bearing resonance. Figure 6 shows the envelope spectra. The kurtogram was used to indicate the spectral region of high impulsiveness, which was detected at 20 kHz. A few iterations of fine-tuning of the carrier frequency and bandwidth was done to arrive at optimum values and a band-pass filter was chosen accordingly. After filtering and zooming, the results are presented in Fig. 6. The BFF is clearly seen peaking at 220.7 Hz in the damaged bearing and is hardly visible in the healthy bearing. Figure 7 shows the cepstra with healthy and damaged bearings. It clearly shows the rahmonics of the quefrency corresponding to running speed of the intermediate shaft (one-third the input shaft speed), but not quefrency corresponding to defect frequencies. In this experiment, ceptrum did not pinpoint the fault. Table 3 summarizes the general findings of the statistical descriptors.
Figure 5: Spectrograms with healthy and damaged bearings.

Figure 6: Envelope spectra with healthy and damaged bearings.

Figure 7: Cepstra with healthy and damaged bearings.

Table 3: Statistical descriptors for healthy and damaged bearings

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>Healthy bearing descriptor values</th>
<th>Damaged bearing descriptor values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FM0</td>
<td>Energy (g²)</td>
</tr>
<tr>
<td>Steadystate</td>
<td>6.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Overload</td>
<td>3.6</td>
<td>3.22</td>
</tr>
<tr>
<td>Overspeed</td>
<td>33.49</td>
<td>9.72</td>
</tr>
</tbody>
</table>
5.2 In-flight Data

Figure 8 compares in-flight TSA data and magnitude spectra between healthy and damaged bearings. The peak-peak values of TSA signal for the damaged and healthy bearings are 95 g and 7 g respectively. Both TSA peak-peak values and spectral amplitudes have increased under damaged condition. Figure 9 shows the cepstra for the healthy and damaged bearings; rahmonics of the fault frequencies are clearly not present. Figure 10 shows the envelope spectrum for both conditions. Even though bearing fault frequencies are obscured, yet the total energy of the envelope spectrum is a good indicator to diagnose failure. Table 4 shows a comparison of the total energy for the two cases.

![Figure 8: TSA signal and magnitude spectrum comparison: Healthy and damaged bearings.](image1)

![Figure 9: Comparison of cepstra: Healthy and damaged bearings.](image2)

![Figure 10: Envelope spectrum: Healthy and damaged bearings.](image3)
6. Discussion and conclusions

This paper has explored its primary objective of correlating failure to the various signal processing techniques by analyzing data from a commercial helicopter MGB and test rig with a roller bearing fault. Envelope demodulation has successfully demodulated fault frequency, pointing to failure. The cepstrum did not exhibit the rahmonics of the fault quefrency. FM0 has proved to be a good descriptor of the failure condition, however it remains inconclusive for different load and speed conditions. The energy descriptor has steadily increased from baseline to failure cases. It has also recorded an increase, when the gearbox was subjected to higher loads and speeds. The spectral entropy descriptor clearly indicated healthy and failed conditions and worked well for different load conditions.

With such controlled test rigs with a single faulty component (a bearing in the present study), it is hoped that the degradation of the entire gearbox can be understood a little better. A combination of various descriptors can be employed with weights to detect failure. The indicators could also be further refined and newer techniques could be recognized to show in-depth fault characteristics.

REFERENCES