A crack in the planetary carrier of a UH-60A Blackhawk main transmission was investigated through analysis of the measured vibration time synchronous average. Vibration measurements of faulted and non-faulted transmissions were acquired at a range of torque settings in a controlled test cell environment and on-aircraft conditions. Several standard diagnostic parameters were modified for the special case of an epicyclic gearbox and applied to the measured data. Only two of the diagnostic parameters investigated in this paper were consistently successful at detecting the presence of a fault in test cell conditions. None of the diagnostic parameters were able to detect the crack in the on-aircraft conditions, measured only at low torque.

Notation

- $a$: Amplitude modulation due to planet passage
- $b$: Gear mesh vibration
- $d$: Difference signal
- $f$: Frequency
- $\mathcal{F}$: Fourier transform
- $i,I$: Index and total number of samples
- $j,J$: Index and total number of averages
- $m,M$: Index and total number of gear mesh harmonics
- $n,N$: Index and total number of shaft harmonics
- $n_p,N_p$: Index and total number of planets
- $N_t$: Number of teeth in ring gear
- $Q$: Rotor system torque
- $r$: Regular signal
- $s$: Residual signal
- $t,T$: Time and sampling period
- $x$: Time averaged vibration signal
- $y$: Raw vibration signal
- $\tau$: Planet phase angle
- $(\cdot)^e$: Epicyclic gearbox
- $(\cdot)^f$: Fixed axis gearbox
- $(\cdot)^s$: Shaft
- $(\cdot)^b$: Sideband

Introduction

Many rotorcraft main transmission systems are constructed using an epicyclic, or “planetary”, gear train. Planetary gear trains consist of an inner “sun” gear, which is surrounded by two or more rotating “planets”. The planets then also rotate inside the outer ring gear, which is usually stationary. Torque is transmitted through the sun gear to the planets, which ride on a planetary carrier. The planetary carrier, in turn, transmits torque to the main rotor shaft and blades.

The H-60 main transmission employs a 5-planet epicyclic gear train. Recent inspections of two Army UH-60A Blackhawk main transmissions, initiated by indications of low or fluctuating oil pressure, revealed a crack in the planetary carriers. This is the first time this problem has been encountered in approximately 3.6 million UH-60A flight hours in the Army. The 10-inch crack in the first carrier, which was later cut apart for material inspection, is shown in Figure 1. Since the planetary carrier is a flight critical part, failure could cause an accident resulting in loss of life and/or aircraft. This resulted in flight restrictions on a significant number of Army UH-60A’s. Manual inspection of all 1000 transmissions is not only costly in terms of labor, but also time prohibitive. A simple, cost-effective test capable of diagnosing this fault is highly desirable.
Related Research

The analysis of vibration data to detect damage in fixed axis gears has been the focus of much research and experimentation. Gear health is typically described in terms of a single number, called a condition indicator (CI). The majority of CIs for fixed axis gears are developed by time synchronous averaging the vibration signal for the gear of interest. In this method, the vibration signal is measured by an accelerometer mounted on the gearbox housing and the raw vibration signal is time-averaged over numerous rotations with a pulse signal synchronized to the rotation of the gear. Random vibrations, which are asynchronous with the rotation of the gear, tend to average out. Stewart [1], Swanson [2], Favaler [3], Martin [4] and Sztasz [5] developed the first CIs using the time-averaged signal. Zakrajsek, Decker et al [6-9] developed evolutionary CIs using the time-averaged signal excluding particular shaft or gear mesh frequencies. More recently, Polischuck et al [10] have developed CIs using demodulation techniques originally proposed by McFadden [11].

As stated earlier, these CIs were developed to detect damage in fixed axis gear systems. For an accelerometer mounted to the housing, damage to individual gear teeth modulates the vibration signal at the shaft frequency. In the frequency domain, the damage appears in the form of symmetric sidebands around the gear meshing frequency, which is still the dominant component. The sidebands are located at integer multiples of the shaft frequency. Many of the CIs for fixed axis gears detect damage based upon the signal amplitude at the gear meshing frequency and/or modulating sidebands.

The measured vibrations produced by epicyclic gear systems are fundamentally different from fixed axis gear systems. An accelerometer mounted to the housing will measure a periodic amplitude-modulated vibration signal as each planet rotates past the sensor. Thus, even healthy gears will produce a vibration spectrum resulting in naturally occurring sidebands. Furthermore, because the vibrations produced by the planets are generally not in phase, the dominant frequency component often does not occur at the fundamental gear meshing frequency. In fact, the gear meshing frequency component is often completely suppressed. This phenomenon was first recognized and explained by McFadden and Smith [12] and later McNames [13]. Thus, the CIs developed for fixed axis gears will give erroneous results even for an undamaged epicyclic gearbox. Clearly, the CIs require modification for application to an epicyclic gearbox. McFadden [14], Blunt and Hardman [15] and Pines [16] have also conducted research and experimentation on vibration monitoring of faults in individual planets of epicyclic gearboxes using windowing techniques.

Objectives

The U.S. Army Aviation Engineering Directorate, Aeromechanics Division conducted an investigation to determine if a fault in the planetary carrier of an H-60 transmission could be successfully detected via vibration monitoring. Experimental measurements of H-60 transmissions with both faulted and unfauluted planetary carriers were taken in a test cell and on-aircraft. In this paper, the several CIs for fixed axis gears are modified for the special case of an epicyclic gearbox and used to compare the vibration levels of known faulted and non-faulted transmissions.

Approach

Epicyclic Gearbox Vibrations

A brief explanation of the asymmetric sidebands produced by epicyclic gearboxes, based on McFadden [12], is presented here for reference. The gear mesh vibration produced by each planet can be expressed as

$$\beta_n(t) = \sum_{m=1}^{\infty} \beta_n \sin(mN_{t}r_{n})$$

(1)

Where the phase for each planet is

$$r_{n} = 2\pi \left( f't + \frac{n_{p}-1}{N_{p}} \right)$$

(2)

As the planets periodically rotate past the sensor, the vibration is modulated at the shaft frequency

$$a_{n}(t) = \sum_{a=0}^{\infty} \alpha_{a} \cos(n\tau_{n})$$

(3)

The measured vibration in the fixed frame is the sum of the vibration from the individual planets

$$y(t) = \sum_{n=1}^{N_{t}} a_{n} \beta_{n}$$

(3)

Using the trigonometric identity

$$\sin A\cos B = \frac{1}{2}\sin(A+B) + \frac{1}{2}\sin(A-B)$$

(4)

Yields

$$y(t) = \frac{1}{2} \sum_{n_{p}=1}^{N_{t}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \alpha_{n} \beta_{n} \sin \left( \frac{mN_{t}+n}{N_{t}} \tau_{n} \right)$$

(5)

The time-averaged signal is then

$$x(t) = \frac{1}{f} \sum_{j=1}^{J} y(t + jT')$$

(6)

The frequency content of the time-averaged signal can be found using the Fourier Coordinate Transform. Only terms with frequencies $mN_{t} \pm n$ that are multiples of the number of planets, $N_{p}$, are measured by a sensor in the fixed frame

$$f_{w,n} = \phi_{w,n} \left( mN_{t} \pm n \right) f'$$

$$\phi_{w,n} = \begin{cases} 1 & \text{if } \frac{mN_{t}+n}{N_{p}} \text{ is integer} \\ 0 & \text{if } \frac{mN_{t}+n}{N_{p}} \text{ is not integer} \end{cases}$$

(7)
In contrast, for a fixed axis gearbox the gear meshing frequencies simply occur at
\[ f_n^g = mN_p f^x \]  
(8)

The computed frequency spectra around the fundamental gear mesh for a “damaged” and an undamaged H-60 main transmission \((N_p = 5, N_l = 228)\) are shown in Figure 2. For the undamaged transmission, the gear meshing component at \( n = 0 \) (order 228) is almost completely suppressed but several apparent meshing frequencies occur naturally at \( n = -3, +2 \) and +7. The largest amplitude, or dominant, component at \( n = +2 \) occurs closest to the gear mesh frequency. For the “damaged” transmission, it is assumed that one planet generates a vibration signal of different amplitude than the other planets. This assumption is for demonstrative purposes only; it is not used for data analysis. This results in the reappearance of the gear meshing component and larger sidebands around the apparent frequency components.

\[
\text{Apparent Freq. n = -3, Dominant Freq. n = +2, Apparent Freq. n = +7}
\]

**Figure 2. Simulated H-60 Main Transmission Vibration Spectra**

**Modified Condition Indicators**

In this section, only the CIs requiring modification for the special case of an epicyclic gearbox are presented. Standard definitions are in Refs. 1-5.

**Regular Mesh Components.** Many of the CIs for fixed axis gears are based on the time signal average excluding “regular” mesh components, RMC. These “regular” components are defined as the fundamental shaft frequency, the fundamental and harmonics of the gear meshing frequency and their first order sidebands. The first order sidebands are generally due to run-out of the gear because of machining or assembly inaccuracies [17] and thus can be considered regular components.

Because of the asymmetry effect in the frequency spectrum for an epicyclic gearbox, Eqn. (7) must be used to identify analogous frequency components. For an epicyclic gearbox the “regular” mesh components are defined as the fundamental shaft frequency, all the apparent gear mesh frequency components for each harmonic and the first-order sidebands of the dominant gear mesh frequency for each harmonic.

\[
\begin{align*}
\text{RMC}^e(x) &= \mathcal{J}[x]_e^r \\
\text{RMC}^{e, +2}_{m, n} (x) &= \mathcal{J}[x]_{m, n} \\
\text{RMC}^{e, +7}_{m, n} (x) &= \mathcal{J}[x]_{m, n} + f^r
\end{align*}
\]

(9)

**Regular, Difference and Residual Signals.** The regular signal is defined as the inverse Fourier transform of the regular mesh components. The difference signal is defined as the time signal average excluding the regular mesh components. The residual signal is similar to the difference signal, but includes the first-order sidebands of the dominant gear mesh frequency.

\[
\begin{align*}
\text{r}^e &= \mathcal{J}^{-1}[\text{RMC}^e(x) + \text{RMC}^{e, +2}(x) + \text{RMC}^{e, +7}(x)] \\
d^e &= x - r^e \\
s^e &= x - \mathcal{J}^{-1}[\text{RMC}^e(x) + \text{RMC}^{e, +2}(x)]
\end{align*}
\]

(10)

**Zero-Order Figure of Merit.** For a fixed axis gearbox, the zero-order Figure of Merit, FM0, is defined as the peak-to-peak value of the time-averaged signal normalized by the sum of amplitudes of the regular mesh frequencies [1]. For an epicyclic gearbox FM0 is defined using the dominant mesh frequencies.

\[
\text{FM0}^e = \frac{\max |x| - \min |x|}{\sum_{n=1}^N \text{RMC}^{e, +2}_{m, n} (x)}
\]

(11)

**Energy Ratio.** For a fixed axis gearbox, the energy ratio, ER, is defined as the standard deviation of the difference signal normalized by the standard deviation of the regular signal [2]. For an epicyclic gearbox the energy ratio, ER\(^e\), is defined using the appropriately calculated difference and regular signals.

\[
\text{ER}^e = \frac{\text{RMS}(d^e)}{\text{RMS}(r^e)}
\]

(12)

**Sideband Level Factor.** For a fixed axis gearbox, the sideband level factor, SLF, is defined as the sum of the first-order sideband amplitudes about the fundamental gear meshing frequency normalized by the standard deviation of the time signal average [3]. For an epicyclic gearbox the sideband level factor, SLF\(^e\), is defined using the first-order sideband amplitudes about the fundamental dominant meshing component.

\[
\text{SLF}^e = \frac{\text{RMC}^{e, +2}_{m, n} \text{RMC}^{e, +7}_{m, n}}{\text{RMS}(x)}
\]

(13)

**Sideband Index.** For a fixed axis gearbox, the sideband index, SI, is defined as the average amplitude of the sidebands of the fundamental gear meshing frequency [5]. For an epicyclic gearbox the sideband index, SI\(^e\), is defined using the only the first-order sidebands of the fundamental dominant frequency component.
Normalized Kurtosis. The normalized Kurtosis, $NK$, is a standard statistical definition. It is defined as the fourth statistical moment of the signal about the mean of the signal (or absolute Kurtosis, $AK$) normalized by the square of the variance of the signal \[ NK(x) = \frac{\sum_{i=1}^{I}(x_i - \bar{x})^4}{\left[ \sum_{i=1}^{I}(x_i - \bar{x})^2 \right]^2} \] (15)

Fourth-Order Figure of Merit. For a fixed axis gearbox the normalized Kurtosis of the difference signal has been termed FM4 [1]. “Good” gearboxes have a near Gaussian amplitude distribution of the vibration, resulting in a normalized Kurtosis of nearly 3. For an epicyclic gearbox, FM4 is defined using the appropriately calculated difference signal.

\[ FM4^e = NK(d^e) \] (16)

CIs similar to FM4 such as FM4*, NA4, NA4*, NB4 and NB4* have also been proposed [6-9]. These CIs use the residual or analytic signals and are normalized by a running average of the variance, which may even be “locked” when it reaches a predefined limit. However, these CIs are not the subject of this paper because they require vibration data for an extended period of time as the gearbox accures damage.

**Experimental Testing**

**Test Cell Measurements.** The Helicopter Transmission Test Facility (HTTF) at Patuxent River NAS, MD was utilized for all test cell measurements. The HTTF is a unique test facility that uses actual aircraft engines to provide power to all the aircraft drive systems except the rotors and is a significant improvement over single component test rigs [19-20]. An H-60 test transmission was instrumented with several sets of accelerometers. A list of the accelerometers and their locations is included in Table 1 and shown in Figure 3.

**Table 1. Accelerometers**

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Location</th>
<th>Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACC GBX 1</td>
<td>Left Accessory Module</td>
<td>Vert.</td>
</tr>
<tr>
<td>2</td>
<td>ACC GBX 2</td>
<td>Right Accessory Mod.</td>
<td>Vert.</td>
</tr>
<tr>
<td>3</td>
<td>INPT GBX 1</td>
<td>Left Input Module</td>
<td>Vert.</td>
</tr>
<tr>
<td>4</td>
<td>INPT GBX 2</td>
<td>Right Input Module</td>
<td>Vert.</td>
</tr>
<tr>
<td>5</td>
<td>MAIN 1</td>
<td>Main Module, Left Side</td>
<td>Rad.</td>
</tr>
<tr>
<td>6</td>
<td>MAIN 2</td>
<td>Main Module, Right Side</td>
<td>Rad.</td>
</tr>
</tbody>
</table>

The vibration data was acquired using the US Army’s Vibration Management Enhancement Program (VMEP) system. Measurement setups were created to simultaneously acquire and synchronize the six input accelerometers to the carrier rotational frequency. The VMEP system was programmed to calculate and save the raw time domain data, the time synchronous waveform, and the condition indicators. A list of the VMEP setup parameters is included in Table 2. Time synchronous vibration data were included for each accelerometer at torque settings ranging from 20% to 100%. Both faulted and unfaulted planetary carriers were tested. The faulted planetary carrier, the second cracked UH-60A carrier discovered during a field inspection, had a 3¼-inch crack when installed in the test transmission. Because of the need for destructive material testing on the cracked carrier, the amount of
run time was limited. Thus, the transmission was not run for an extended period. Only “snapshots” of data at each torque setting were measured.

Table 2. Data Acquisition and Processing

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Accelerometers: 6</td>
</tr>
<tr>
<td></td>
<td>Sample rate: 48 KHz</td>
</tr>
<tr>
<td></td>
<td>Tachometers: 1</td>
</tr>
<tr>
<td>Asynchronous Time</td>
<td>Save to File: yes</td>
</tr>
<tr>
<td>Domain (ATD)</td>
<td>Number of Points: 1,200,000</td>
</tr>
<tr>
<td>Synchronous Time</td>
<td>Save to File: yes</td>
</tr>
<tr>
<td>Average (STA)</td>
<td>Target shaft: planet carrier</td>
</tr>
<tr>
<td></td>
<td>Revs averaged: 80</td>
</tr>
<tr>
<td></td>
<td>Points per rev: 8192</td>
</tr>
<tr>
<td>Asynchronous Frequency Domain (AFD)</td>
<td>Save to file: yes</td>
</tr>
<tr>
<td></td>
<td>( f_{\text{max}} ): 2000 Hz</td>
</tr>
<tr>
<td></td>
<td>Points per AFD: 6400</td>
</tr>
<tr>
<td></td>
<td>Number of Averages: 10</td>
</tr>
<tr>
<td></td>
<td>Window: Flat Top</td>
</tr>
<tr>
<td></td>
<td>Overlap: 50%</td>
</tr>
</tbody>
</table>

On-Aircraft Measurements. Similar to the test cell measurements, several UH-60A transmissions were instrumented. However, for the on-aircraft tests only accelerometers 3 through 6 were used. Time synchronous vibration data were measured for each accelerometer using the same data acquisition equipment that was used in the test cell. The same faulted carrier and main gearbox used in the tests at the HTTF was installed in a UH-60A at the Corpus Christ Army Depot (CCAD) and used as a test aircraft. Three different UH-60As from the Birmingham, Alabama National Guard (BNG) with unfaulted carriers were selected as test aircraft to establish how vibration levels change across aircraft. Because of safety issues with the cracked carrier only ground runs were completed. Single and dual engine data were taken at torque settings of 20\(\%Q\) and 30\(\%Q\). For each test state, the aircraft was stabilized for 5 minutes before vibration measurements were taken. For all tests, winds were less than 10 knots with the nose of the aircraft pointed into the wind.

Sample Results

Time Synchronous Averages (TSAs)

Example TSAs measured by accelerometer 5 (left main module) at 30\(\%Q\) are shown in Figure 4 for the test cell measurements. Both the gear meshing frequency and the amplitude modulation effect as each of the 5 planets pass the accelerometer is easily identifiable. Also note the amplitudes are slightly larger for the faulted carrier. The same measurements taken on-aircraft are shown in Figure 5. The planet passage effect is not nearly as noticeable as in the test cell measurement. Also, in this case the aircraft with an unfaulted carrier resulted in higher amplitude vibration than the aircraft with the faulted carrier. Clearly a faulted carrier will be much more difficult to detect in field conditions than in the controlled test cell environment.
Synchronous Order Domain (SOD) spectra were calculated using the synchronous time averaged waveforms saved by the data acquisition system. Example spectra for the test cell and on-aircraft measurements are shown in Figure 6 and Figure 7. For the test cell measurements, the unfaulted carrier only has significant amplitude the apparent frequencies predicted by Eqn. (7) at \( n = -3, +2 \) and \( +7 \) (orders 225, 230 and 235). In contrast, the faulted carrier has increased energy at the \( n = -1, 0, +1 \) and \( +3 \) sidebands around the dominant sideband at \( n = +2 \).

Modified Condition Indicators
In this section, the sample results for some standard condition indicators and the condition indicators modified for the special case of an epicyclic gearbox are presented. Each condition indicator is shown as a function of rotor system torque for the sensor of interest. Test cell and on-aircraft measurements are shown separately for clarity.

The normalized Kurtosis of the time synchronous average for accelerometer 5 (left main module) is shown in Figure 8. For the test cell measurements, the NK for both the faulted and unfaulted gearboxes ranges from 2.4 to 3.2. The value of 3.0 expected for a “normal” gearbox is shown as a dashed line. For the 20% and 30% torque settings, the unfaulted carrier has the higher NK. For all other torque settings, the faulted carrier has the higher NK. For the on-aircraft measurements, most NK values range from 2.5 to 3 while two unfaulted measurements have increased NK values of nearly 4. However, the faulted measurements all have NK values of 2.5 to 2.6.
The Crest Factor (CF) of the time signal average for accelerometer 5 (left main module) is shown in Figure 9. The CF, defined as the maximum value of the TSA normalized by the RMS value, does not need to be modified for an epicyclic gearbox. For the test cell measurements, the CF for both the faulted and unfaulted gearboxes ranges between 2.5 and 4. For the on-aircraft measurements, the CF ranges between 2.8 and 4. In both figures, no consistent trend between faulted and unfaulted gearboxes is apparent.

FM0 for accelerometer 5 (left main module) is shown in Figure 10. For the test cell measurements, FM0 ranges from 2.2 to 4. FM0 is also consistently 10% to 40% larger for the faulted gearbox than for the unfaulted gearbox. For the on-aircraft measurements, FM0 also ranges from 2.2 to 4; however, in almost all cases it is significantly larger for the unfaulted gearboxes than for the faulted gearbox.

b) On-aircraft
Figure 8. Normalized Kurtosis (Left Main)

The Crest Factor (CF) of the time signal average for accelerometer 5 (left main module) is shown in Figure 9. The CF, defined as the maximum value of the TSA normalized by the RMS value, does not need to be modified for an epicyclic gearbox. For the test cell measurements, the CF for both the faulted and unfaulted gearboxes ranges between 2.5 and 4. For the on-aircraft measurements, the CF ranges between 2.8 and 4. In both figures, no consistent trend between faulted and unfaulted gearboxes is apparent.

FM0 for accelerometer 5 (left main module) is shown in Figure 10. For the test cell measurements, FM0 ranges from 2.2 to 4. FM0 is also consistently 10% to 40% larger for the faulted gearbox than for the unfaulted gearbox. For the on-aircraft measurements, FM0 also ranges from 2.2 to 4; however, in almost all cases it is significantly larger for the unfaulted gearboxes than for the faulted gearbox.

b) On-aircraft
Figure 9. Crest Factor (Left Main)
The \( \text{SLF}^e \) for accelerometer 5 (left main module) is shown in Figure 13. For the test cell measurements, the \( \text{SLF}^e \) is consistently larger for the faulted gearbox than for the unfaulted gearbox. However, for the on-aircraft measurements, the \( \text{SLF}^e \) is larger in almost all cases for the unfaulted gearboxes.

The \( \text{ER}^e \) for accelerometer 2 (right input module) is shown in Figure 12. For the test cell measurements, the \( \text{ER}^e \) varies widely with torque. For the 90% and 100% torque settings, the faulted \( \text{ER}^e \) is approximately 2 times the unfaulted \( \text{ER}^e \). For the on aircraft measurements, the \( \text{ERE} \) is larger for the unfaulted gearbox than the faulted gearbox for the majority of the test points.
Similarly, the SLF for accelerometer 4 (right input module) is shown in Figure 14. Once again for the test cell measurements, the SLF is consistently larger for the faulted gearbox than for the unfaulted gearbox, especially for the 20% and 30% torque settings. However, for the on-aircraft measurements, SLF is larger in almost all cases for the unfaulted gearbox measurements and shows a wide variation across aircraft, ranging from 0.05 to 0.35.

The SI for accelerometer 5 (left main module) is shown in Figure 15. For the test cell measurements, the SI is consistently larger for the faulted gearbox than for the unfaulted gearbox, especially at the 90% and 100% torque settings. However, for the on-aircraft measurements, the SI is again larger in almost all cases for the unfaulted gearboxes and shows a wide variation from aircraft to aircraft, ranging from 0.05 to 0.45.
Conclusions

A crack in the planetary carrier of a UH-60A Blackhawk main transmission was investigated with time synchronous averaging of the vibration measured at six different locations on the main, input and accessory gearboxes. Vibration measurements of faulted and non-faulted transmissions were acquired in a controlled test cell environment and on-aircraft conditions at torque levels from 20% to 100%. Several standard diagnostic parameters were modified for the special case of an epicyclic gearbox and applied to the measured data. Of the diagnostic parameters investigated in this paper, only the sideband index (SI) and sideband level factors (SLF) were consistently successful at detecting the presence of a fault in test cell conditions. None of the diagnostic parameters were able to detect a crack in on-aircraft conditions at the low torque levels tested. This indicates that a cracked carrier is detectable in controlled test cell conditions, but noise from other rotating components and differences in the vibration levels from aircraft-to-aircraft may overshadow the effect of a cracked planetary carrier. It is also possible that the low torque values of the on-aircraft testing were not sufficient to expose the fault.

Acknowledgments

The authors would like to thank the staff at the Helicopter Transmission Test Facility (HTTF) at Patuxent River, MD including Mr. Frank Dawson and Mr. William Hardman; Corpus Christi Army Depot and the Birmingham, Alabama National Guard for their help in the experimental testing. The authors would also like to thank Mr. Eric Bale, Mr. Ronald Bednarczyk, Mr. Robert Branhof and Dr. John Berry of USAAMCOM, AED, Redstone Arsenal, AL for assistance in gathering and analyzing the data.

References