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Application of Acoustic Emission in Diagnostic of Bearing Faults within a Helicopter gearbox

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Abstract

Acoustics Emissions (AE) technology has emerged as a promising diagnostic approach. AE was originally developed for non-destructive testing of static structures, however, in recent times its application has been extended to health monitoring of rotating machines. This paper introduces a novel method for application of AE in monitoring of helicopter gearboxes. In addition this paper investigates the application of signal separation techniques in detection of bearing faults within the epicyclic module of a large helicopter (CS-29) main gearbox using Acoustic Emissions (AE). The results showed successful of AE in detection bearing fault within the helicopter gearbox. Detection of the small bearing defect gives the AE an indisputable diagnosis advantage and prove ability of application of AE in helicopter gearboxes.

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Keywords: Condition Monitoring, Helicopters, Gearbox, Fault Diagnosis;

1. Introduction

Helicopter transmission integrity is critical for safe operation. Approximately 16% of mechanical failures, resulting in the loss of helicopter operation, can be attributed to the main gearbox (MGB)[1]. In addition, 30% of the total maintenance cost of helicopters can be attributed to the transmission system [1]. The need to employ advanced fault warning systems for such transmission systems cannot be understated [2, 3]. Health and Usage Monitoring Systems (HUMS) are commonly used for fault detection of helicopter transmissions in which detection is based on extraction of predefined features of the measured vibration such as FM4, NA4, etc. [2, 4, 5]. HUMS was developed in North Sea operations, motivated in part by the crash to a Boeing Vertol 234 in 1986 which was caused by disintegration of the forward main gearbox. After development in the 1990s, the UK's Civil Aviation Authority CAA mandated fitment of HUMS to certain helicopters. One article suggests that HUMS "successes" are found at a frequency of 22 per 100,000 flight hours [6]. A HUM system consists of two complimentary subsystems: health monitoring and usage monitoring. Health monitoring is a process of diagnosing incipient damage or degradation that could ultimately lead to a system failure. Usage monitoring is a process by which the remaining life of different gearbox components and auxiliary systems is determined by assessing operation hours, current components condition and load history [7, 8]. Several vibration signature analysis methods are developed and applied in the commercial HUMS to detect faults in bearings, gears and shafts. Condition Indicators (CI) refer to the vibration characteristics extracted from these signatures and are used to reflect the health of the component [9]. Numerous condition indicators are calculated from vibration data to characterize component health and these indicators are often determined based on statistical measurement of the energy of the vibration signal, such as rms, kurtosis and crest factors.

The majority of helicopters utilises epicyclic reduction modules gears as transmission systems due to their high transmission ratio, higher torque to weight ratio and high efficiency [10]. As such this type of gearbox is widely used in

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many industries such as aerospace, wind turbines, mining and heavy trucks [11-15]. Different planetary gearbox configurations and designs allow for a range of gear ratios, torque transmission and shaft rotational characteristics. The planetary gearbox generally operates under severe conditions, thus the gearbox components are subject to different kinds of fault conditions such as gear pitting, cracks, etc. [16-19]. Recent investigations on applications of planetary gearboxes have shown that failures initiate at a number of specific bearing locations, which then progress into the gear teeth. In addition bearing debris and the resultant excess clearances cause gear surface wear and misalignment [19]. More recently the accident to the helicopter registered G-REDL [20], resulting in the loss of 16 lives, was caused by the degradation of a planet gear bearing, interestingly, the HUM system condition indicators showed no failure evidence before this accident.

2. Planetary gearbox diagnostics

The use of Acoustics Emissions (AE) technology has emerged as a promising diagnostic approach. AE was originally developed for non-destructive testing of static structures, however, in recent times its application has been extended to health monitoring of rotating machines and bearings [21-24]. In machinery monitoring applications, AE are defined as transient elastic waves produced by the interface of two components or more in relative motion [25-27] . AE sources include impacting, cyclic fatigue, friction, turbulence, material loss, cavitation, leakage, etc. It provides the benefit of early fault detection in comparison to vibration analysis and oil analysis due to the high sensitivity to friction offered by AE [28]. Nevertheless, successful applications of AE for health monitoring of a wide range of rotating machinery have been partly limited due to the difficulty in signal processing, interpreting and manipulating the acquired data [29-31]. In addition, AE signal processing is challenged by the attenuation of the signal and as such the AE sensor has to be close to its source. However, it is often only practical to place the AE sensor on the non-rotating member of the machine, such as the bearing housing or gearbox casing. Therefore, the AE signal originating from the defective component will suffer severe attenuation and reflections, before reaching the sensor. Challenges and opportunities of applying AE to machine monitoring have been discussed by Sikorska et. al and Mba et. al. [27, 32]. To date, most applications of machine health monitoring with AE have targeted single components such as a pair of meshing gears [33], a particular bearing or valve [34, 35]. This targeted approach to application of AE has on the whole demonstrated success. However the ability to monitor components that are secondary to the main component of interest such as a bearing supporting a gear, as is the case with planetary gears in an epicyclical gearbox, has not been well-explored. This is the first known publication to explore the ability to identify a fault condition where the AE signature of interest is severely masked by the presence of gear meshing AE noise. Also notably it is the first known application on a commercial helicopter main gearbox. The application of AE to this field is still in its early stages [28, 36, 37]. Moreover, there are limited publications on application of AE to bearing fault diagnosis within gearboxes [30]. This paper discusses the analysis of vibration and AE data collected from a CS-29 category 'A' helicopters industrial test facility and compares their effectiveness in diagnosing a bearing defect in the epicyclic module of helicopter main gearbox. The data was collected for various bearing fault conditions and processed using an adaptive filter algorithm to separate the non-deterministic part of the signal and enhance the signal-to-noise ratio for both AE. The resultant signatures were then further processed using envelope analysis to extract the fault signature.

3. Signal processing and data analysis

Bearing and gear fault identification involves the use of various signal processing algorithms to extract useful diagnostic information from measured vibration or AE signals. Traditionally, analysis has been grouped into three classes; time domain, frequency domain and time-frequency domain. The statistical analysis techniques are commonly applied for time domain signal analysis, in which descriptive statistics such as rms, skewness, and kurtosis are used to detect the faults [38, 39]. A fast Fourier transform (FFT) is commonly used to obtain the frequency spectra of the signals. The detection of faults in the frequency domain is based on identification of certain frequencies which are known to be typical symptoms associated with bearing or gear faults. The time-frequency domain methods are composed of the short-time Fourier transform (STFT) [40], Wigner-Ville [38], and wavelet analysis [41, 42]. The use of these detection techniques are feasible for applications where a single component is being monitored however for applications that include several components, such as gearboxes, it is essential to employ separation algorithms.

Signal separation was achieved using adaptive filter technique; methodology of using such technique is described by authors in [43-45]

4. Experimental Setup

Experimental data was obtained from tests performed on CS-29 Category 'A' helicopter gearbox which was seeded with defects in one of the planetary gears bearing of the second epicyclic stage. The test rig was of back-to-back rig configured and powered by two motors simulating dual power input.

4.1. CS-29 'Category A' helicopter main gearbox

The transmission system of a CS-29 'Category A' helicopter gearbox is connected to two shafts, one from each of the two free turbines engines, which drive the main and tail rotors through the MGB. The input speed to the MGB is typically in the order of 23,000 rpm which is reduced to the nominal main rotor speed of 265 rpm.

The main rotor gearbox consists of two sections, the main module, which reduces the input shaft speed from 23,000 rpm to around 2,400 rpm. This section includes two parallel gear stages. This combined drive provides power to the tail rotor drive shaft and the bevel gear. The bevel gear reduces the rotational speed of the input drive to 2,405 rpm and changes the direction of the transmission to drive the epicyclic reduction gearbox module. The second section is the epicyclic reduction gearbox module which is located on top of the main module. This reduces the rotational speed to 265 rpm which drives the main rotor. This module consists of two epicyclic gears stage, the first stage contains 8 planets gears and second stage with 9 planets gears, see figure 1. The details of the gears are summarised in table 1.

Figure 1 Second stage epicyclic gears

Table 1 number of teeth for the gearbox gears

First parallel stage	Pinion teeth	Wheel teeth	
	23	66	
Second parallel stage	Pinion teeth	Wheel teeth	
	35	57	
Bevel stage	Pinion teeth	Bevel teeth	
	22	45	
1st epicyclic stage	Sun gear	Planets gear – 8 gears	Ring gear
	62	34	130
2nd epicyclic stage	Sun gear	Planets gear – 9 gears	Ring gear
	68	31	130

The epicyclic module planet gears are designed as a complete gear and bearing assembly. The outer race of the bearing and the gear wheel are a single component, with the bearing rollers running directly on the inner circumference of the gear. Each planet gear is 'self-aligning' by the use of spherical inner and outer races and barrel shaped bearing rollers (see Figure 1).

4.2. Experimental conditions and setup

This investigation involved performing the tests for fault-free condition, minor bearing damage and major bearing damage. The bearing faults were seeded on one of the planet gears of the second epicyclic stage. Minor damage was simulated by machining a rectangular section of fixed depth and width across the bearing outer race (10mm wide and 0.3mm deep), see figure 2, and the major damage simulated as a combination of both a damaged inner race (natural spalling around half of the circumference) and an outer race (about 30mm wide, 0.3mm deep), see figure 3. Three load conditions were considered for the each fault condition, 110% of maximum take-off power, 100% and 80% of maximum continuous power; the power, speed and torque characteristics of these load conditions are summarised in table 2.

Figure 2 Slot across the bearing outer race

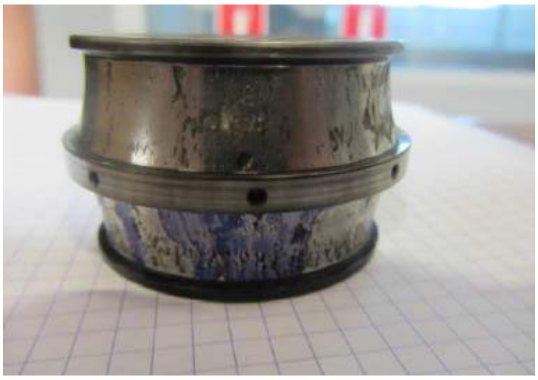

Figure 3 Inner race natural spalling

Table 2 Test Load conditions characteristics

Load Condition	Power (Kw)	Rotor speed (RPM)	Right input torque (Nm)	Left input torque Nm)
110% Max take-off power	1760	265	368	368
100% Max continuous power	1300	265	272	272
80% Max continuous power	936	265	196	196

4.3. *Fault frequencies*

To aid diagnosis all characteristic frequencies were determined, see table 3. These included gears mesh frequencies of the different stages and the bearing defect frequencies for planet bearing.

Table 3 Gearbox characteristic frequencies

Frequency components	Frequency HZ
Gears Meshes	
First parallel GMF Hz	8751.5
Second parallel GMF	4640.94697
Bevel stage GMF (Hz)	1791.24269
1st epicyclic stage GMF	1671
2nd epicyclic stage GMF	573
Faulty planet bearing	
Ball spin	45.31426
Outer race	96.69819
Inner race	143.9603
Cage	7.438322

4.4. Data acquisition and instrumentation

Acoustic Emission data was collected using a PWAS sensor [46], 7mm diameter and approximately 0.2mm thick, bonded to the upper face of the planet carrier, see figure 4. The sensor was connected to a conditioning board attached to the planetary carrier and transmitted wirelessly using two coaxial copper coils and a new wireless transfer technique. The new wireless transfer technique utilise two single turn brass coils of approximately 400 mm diameter which were cut to size using water jets for accuracy. The stationary (upper) coil was suspended from two clamping rings which were attached to the top case of the gearbox with a spacer through the holes to retain location. The moving (lower) coil was attached to a circular mounting ring which was in turn mounted on top of the oil caps on the planet carrier, see figures 4 and 5. Electrical isolation of the coils from the mounts and surrounding metallic structure was achieved through the use of nylon washers and bushes. AE data was acquired at a sampling rate of 5 MHz using an NI PCI-6115 card connected to a BNC-2110 connector block.

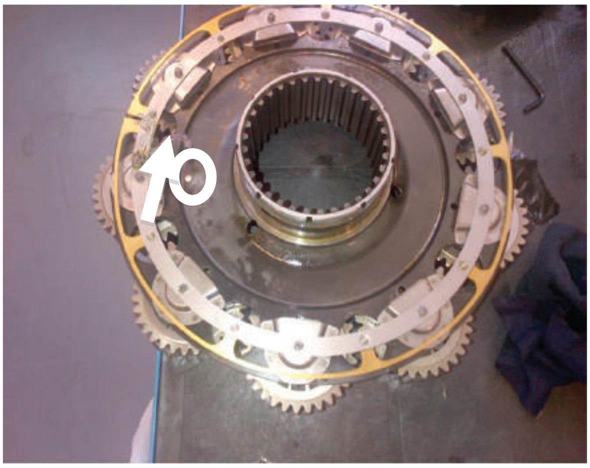

Figure 4 Moving coil mounted on the planetary carrier (coil arrowed, sensor circled)

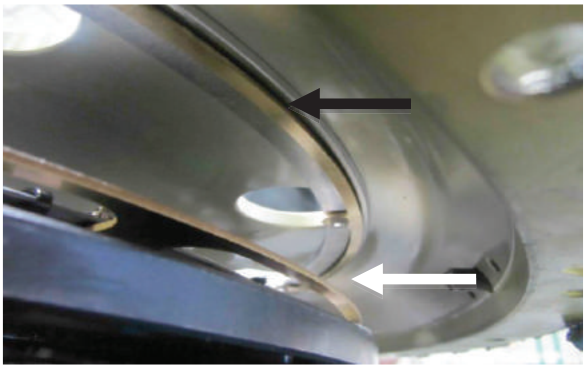

Figure 5 Coils in position prior to assembly (static coil black arrow, moving coil white arrow)

5. Acoustic Emission observations

The Spectral Kurtosis was employed to extract the filter characteristics which were utilised for envelope analysis on measured AE signatures. Associated typical kurtograms of SK analysis are shown in Figure 6. The result of maximum kurtosis showed there were no noticeable differences between healthy and faulty conditions.

The envelope analysis was undertaken using the central frequency F_c and bandwidth (Bw) estimated by SK analysis, see table 4. Observations of figures 7, 8 and 9 showed the presence of the bearing outer race defect frequency (96 Hz) and its harmonic (192 Hz) for both minor and major damages under different loading conditions. The results showed the AE is very capable in detecting the faults of different sizes, in addition the results showed the defect amplitude increased significantly for major fault compared to minor fault, which provide measure for fault severity. Moreover, the fault detection was independent of load condition. However, comparisons of defect amplitude should be performed under similar condition.

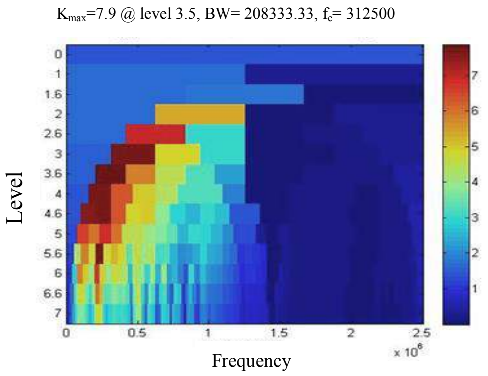

Figure 6 SK kurtograms major defects (110% maximum take-off power)

Table 4 Filter characteristics estimated based on SK for AE signals

Case	Load condition	Center frequency Fc (Hz)	Band Width (Bw) (Hz)	Kurto sis
Fault-free	110% of maximum take-off power	1093750	312500	12
Minor damage		234375	52083	9
Major damage		312500	208333	7.9
Fault-free	100% of maximum continuous power	1093750	312500	12
Minor damage		234375	52083	9
Major damage condition		312500	208333	7.9
Fault-free	80 % of maximum continuous power	1093750	312500	12
Minor damage condition		234375	52083	9
Major damage		312500	208333	7.9

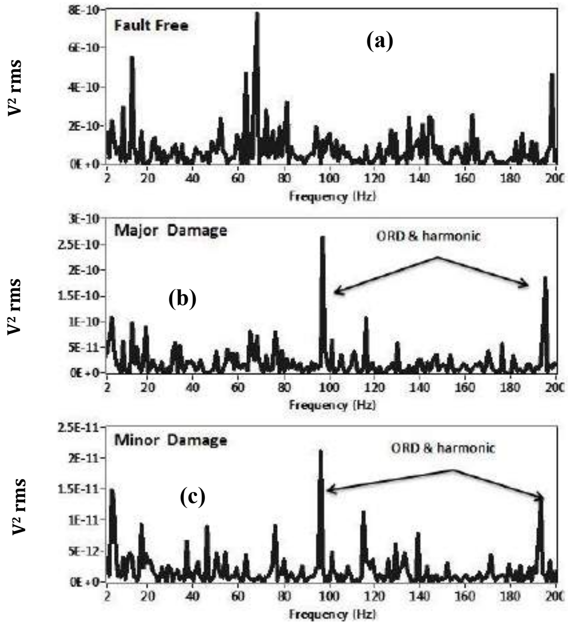

Figure 7 Enveloped spectra of AE signal (a) Fault-free (b) Major (c) Minor bearing defects at 110% maximum take-off power

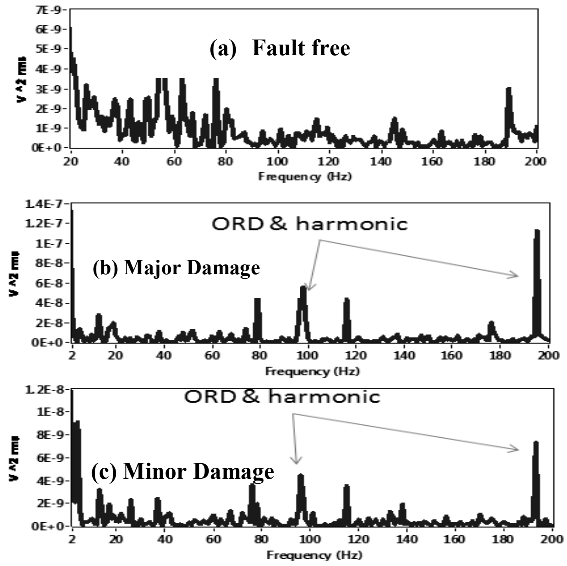

Figure 8 Enveloped spectra of AE signal (a) Fault-free (b) Major (c) Minor bearing defects at 100% maximum continuous power

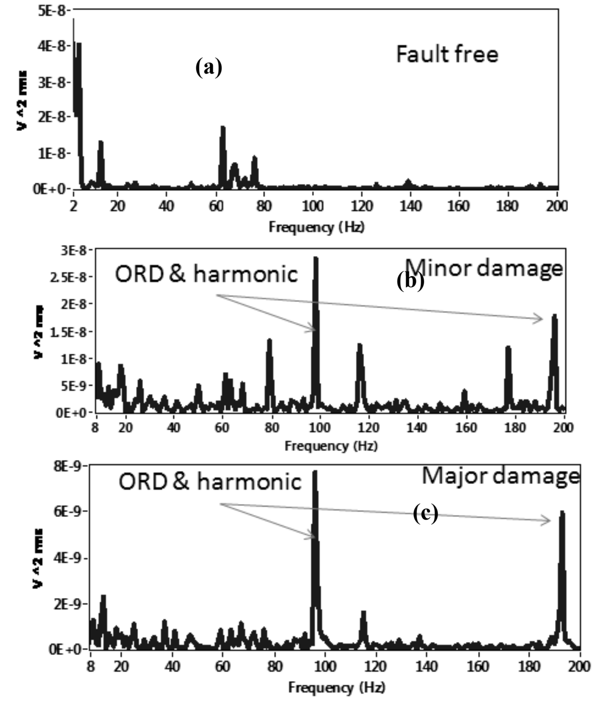

Figure 9 Enveloped spectra of AE signal (a) Fault-free (b) Minor (c) Major bearing defects at 80% maximum continuous power

6. Discussion and conclusion

The techniques used in this paper are typically used for applications where strong background noise masks the defect signature of interest within the measured vibration signature. The AE signal is more susceptible to background noise and in this case, the arduous transmission path from the outer race through the rollers to the inner race and then the planet carrier makes the ability to identify outer race defects even more challenging. However the use of the wireless system incorporated into the main gearbox has contributed significantly to improving signal-to-noise ratio.

AE analysis was able to identify both the minor and major defect conditions. Detection of the small bearing defect gives the AE an indisputable diagnosis advantage and proves ability of application of AE in helicopter gearboxes.

The ability of applied signal processing techniques to identify the presence of bearing fault is based on removing the masked signal and the identification of particular frequency regions with high impact energy; these impacts are due to presence of bearing defect which affect bearing sliding motion. Results of vibration analysis show sensitivity to the direction of vibration measurement.

In summary an investigation employing external vibration and internal AE measurement to identify the presence of a bearing defect in a CS-29 'Category A' helicopter main gearbox has been undertaken. A series of signal processing techniques were applied to extract the bearing fault signature, which included adaptive filter, Spectral Kurtosis, and envelope analysis. The combination of these techniques demonstrated the ability to identify the presence of the various defect sizes of bearing in comparison to a typical frequency spectrum. From the results presented it was clearly evident that the AE offered a much earlier indication of damage.

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