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Bearing signal separation of commercial helicopter main gearbox

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Abstract

Gears are significant component in a multiplicity of industrial applications such as machine tool and gearboxes. An unforeseen failure of gear may result in significant economic losses. Therefore this research propose fault detection improvement throught series of vibration signal processing techuiques. These techniques have been tested experimentally using vibration data collected from the transmission system of a CS-29 'Category A' helicopter gearbox under different bearing damage severity of the second planetary stage. Results showed successful improvement of bearing fault detection.

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Keywords: Helicopters, Gearboxes, Vibration, Diagnosis

1. Introduction

According to industry reports, more than 50% of maintenance costs are spent on rotating equipment wear and failure [1, 2]. In addition to the maintenance costs, machine downtime gravely affects the productivity and profitability of a business. This is a common issue in various industries, including the oil and gas, power generation and water sectors. [3-6]

Unsurprisingly, improving the reliability of rotating machines is one of the key challenges maintenance professionals face today. While preventive maintenance strategies (i.e. scheduled maintenance activities) have been in use for quite some time now, it does have its drawbacks. For example, it could call for intensive labour and long unplanned shutdowns. More importantly, this maintenance approach does not allow end-users to fully benefit from the machine's capability and operational life. In other words, performing scheduled maintenance can be too early and sometimes even too late. Even worse, it may introduce failures to the machine during the maintenance activities.

A more effective approach would be to base the maintenance approach on the actual condition of the machine, rather than basing it on a pre-determined schedule. In other words, adopting a condition-based maintenance program would be more efficient than a time-based maintenance program. Consequently, this methodology will increase the machine's operational life and availability, reduce equipment downtime, lower costs for labour and spare parts hence resulting in significant cost savings. Most importantly, condition based monitoring significantly reduces the risk of catastrophic machine failure by detecting potential degradation in the respective component and making the end-user aware of this issue. [7, 8]

This paper compares the effect of time synchronous averaging in improving the bearing signal separation. For these purpose vibration data collected from a CS-29 category 'A' helicopters industrial test facility was used for diagnosing a

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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 and with combination of TSA algorithm to separate the non-deterministic part of the signal. The resultant signatures were then further processed using envelope analysis to extract the fault signature. [9, 10]

2. Signal separation algorithms

For this study vibration signals acquired were processed using two different paths. For the first path an adaptive filter algorithm to estimate the deterministic component of the signal was employed. Then, the wavelet and combination indicator was used to estimate the filter characteristics of the deterministic signal for envelope analysis. Lastly a frequency spectrum of the enveloped signal was determined. The second path is very similar to the first path, the only difference is the performing the TSA before signal separation, The signal processing procedures were summarised in figure 1. The signal separation was performed with an adaptive filter using fast block algorithm least mean square algorithm FBLMS described by Elasha et. al [8]. The Fast Block LMS (FBLMS) algorithm was proposed to reduce the processing time [11] and as such is more suitable for online diagnostics where an instant response is required. This algorithm is based on the transforming the time signal to the frequency domain and the filter coefficient is updated on the frequency domain; details of the procedure have been summarised [12].

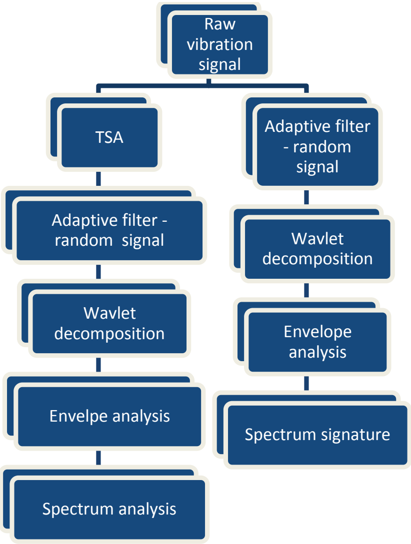

Figure 1 Signal Processing procedures

3. Time Synchronous Averaging

Time Synchronous Averaging (TSA) method is one of the robust tools for analysis of machine vibration. The time synchronous average (TSA) is a technique used to separate the noise or random parts from the signal. TSA is performed by dividing the signal into segments using a synchronous signal. In the case of a rotating machine, the synchronous signal can be the pulses from the shaft tachometer. The number of points in each segment should be equal; therefore, interpolation is performed to extend the number of points in the segment. Then the segments are averaged. The technique is illustrated in figure 3 [13, 14].

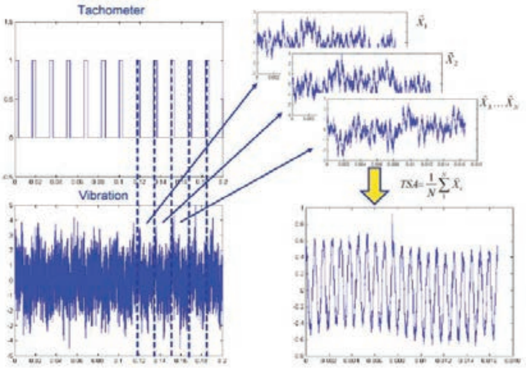

Figure 2 TSA layout [15]

4. Experimental setup

The test was carried out on a SA 330 Puma helicopter MGB with seeded defects located at bearing outer race. Gearbox layout and parameter ratios are illustrated in Figure 3 [1]. Tests under different output power and speed conditions were performed for MGB 2nd epicyclic stage bearing with healthy, minor damaged and major damaged outer race respectively. The maximum output of 1760 kW was designed to simulate the flight regime of 100% take-off power, while a minimum output of 92 kW represented the condition of helicopter being ground-idle. Maximum speed output reached 275 rpm at second epicyclic carrier of MGB, reflecting an engine input speed of 23000 rpm. In case of signal saturation, vibration sensors with sensitivity of 10 mV/g were adopted (PCB 352C03 and Endevco 6251M4) and placed at six carefully chosen locations. Vibration signal was sampled at 51.2 kHz before anti-aliasing filtered at 25.6 kHz. Bench parameters including output torques and a 60-pulse tacho signal were recorded simultaneously for the purpose of post processing. Specific experiment setup and data collections schemes are fully described in [1].

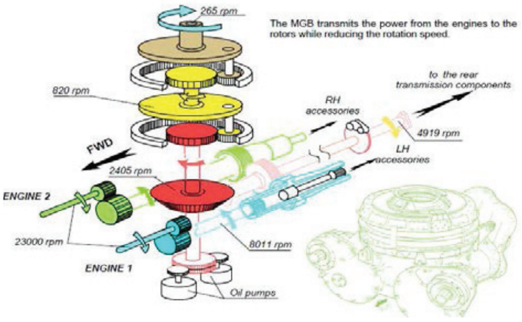

Figure 3 Gearbox internal parts [16]

To aid diagnosis all characteristic vibration frequencies were determined, see table 1. These included gears mesh frequencies of the different stages and the bearing defect frequencies for planet bearing.

Table 1 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

5. Vibration analysis prior to TSA

The measured vibration data was processed to estimate the power spectrum of the vibration signal for damaged conditions, see figure 4. This analysis was performed to assess the ability of FFT spectrum to determine the fault signature. The results show clearly that no distinctive planetary bearing fault frequency was evident in the spectrum, and it was observed that the gear mesh frequencies (GMFs) dominate the spectrum. Therefore the data was further processed using signal separation and wavelet decomposition to identify the fault signature as described earlier.

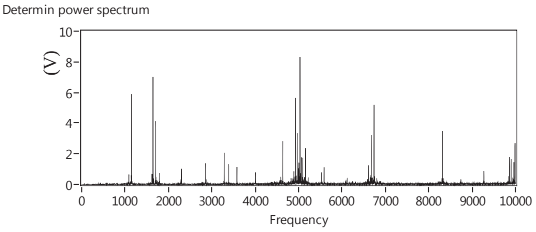

Figure 4 Power spectrum of original vibration signal for the major defect condition

Wavelet decomposition and combination indicator estimation were undertaken on the non-deterministic part of data sets collected from the gearbox for the different fault cases and this yielded the frequency bands and center frequencies which were then used to undertake envelope analysis. As discussed earlier the signal separation was undertaken with adaptive filter FBLMS algorithm. Spectral plots of enveloped vibration signals following filtration, whose characteristics were determined with the aid of the wavelet decomposition, is shown in figure 5

Table 2 Filter characteristics estimated based on combination indicator for all three vibration axes at 100% maximum take-off power

Case	Center frequency F_c (Hz)	Band Width Bw (Hz)	Combination indicator
Fault-free condition	5200	266	1.95E05
Minor damage condition	6000	266	3.47E05
Major damage condition	20266	2133	7.76E05

Observation from the spectra of the enveloped signal at 100% maximum continuous power, see figure 10, showed no presence of fault frequencies associated with the defective planetary bearing in the spectrum. It is apparent that the signal separation had not completely removed the gear mesh and shaft frequencies, particularly the sun gears frequencies and its harmonics for first and second epicyclic stages (38.8 and 13.2 Hz respectively), which were detected by envelope analysis, see figure 10. Existence of these frequencies is due to fact that the vibration signal used in this analysis wasn’t synchronised to any particular shaft.

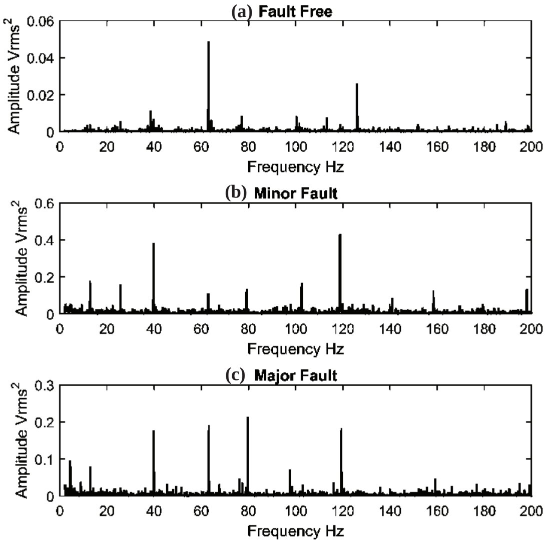

Figure 5 Enveloped Spectra of non-deterministic signal for a) Fault-free (b) Major (c) Minor damage (100% maximum continuous power, X direction).

6. Vibration analysis after TSA

The vibration and tachometer signals acquired have been processed to build the time synchronous averaging signals, and then the non-deterministic part of TSA signal has been obtained using adaptive signal separation as descried earlier. Spectrum analysis of the separated signal showed no indication of the bearing failure, therefore the signal processed further using envelope analysis, the frequency bands required for envelope analysis have been obtained using wavelet decomposition as detailed earlier. In order to detect the faults all related frequencies have been estimated as orders of rotor speed (265 RPM), see Table 3.

Table 3: Frequencies in orders of rotor rotation

Frequency components	Order (of rotor speed 265 RPM)
Gears Meshes	
First parallel GMF Hz	1982.7
Second parallel GMF	1050
Bevel stage GMF (Hz)	405
1st epicyclic stage GMF	378.33
2nd epicyclic stage GMF	129.73
Faulty planet bearing	
Ball spin	10.25
Outer race	21.9
Inner race	32.6
Cage	1.7

Observation from the spectra of the enveloped signal at 100% maximum take-off power, see Figure 11, showed existence of outer race defect frequency (21.9 orders) for both minor and major faults. In addition inner race defect has been detected for the major fault condition at 32.6 orders. Also second harmonic of outer race (43.8 orders) has been detected for the minor fault.

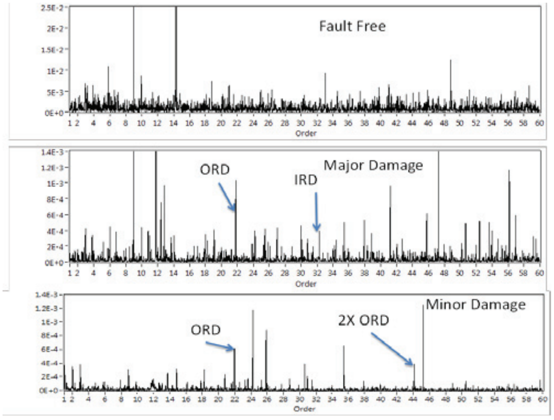

Figure 6 Enveloped Spectra of TSA non-deterministic signal for a) Fault-free (b) Major (c) Minor damage (100% maximum continuous power, X direction).

7. Discussion and concluion

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 vibration signal is 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 signal separation has contributed significantly to improving signal-to-noise ratio.

Comparisons of the results prior and after application of TSA to the vibration signal showed superiority of TSA in improving the signal separation performance leading to detection of the bearing faults for both minor and major fault conditions. While results prior to application of TSA technique showed no fault existence. Though the results after TSA showed sensitivity to measurement direction and load condition, result of measurement taken under miner fault for Z direction showed existence of no faults for all loading conditions, where the measurement taken in X and Y direction showed existence of the minor fault.

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 showed successfully detection of bearing faults using both new condition indicator and improved signal separation based on TSA

In summary an investigation employing external vibration 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, wavelet decomposition, TSA 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 application of TSA prior to vibration signal separation offered a much earlier indication of damage than vibration signal without employing of TSA.

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