Advanced signal processing techniques for helicopter’s gearbox monitoring

A Mauricio\textsuperscript{1, 2}, W Wang\textsuperscript{3}, J Antoni\textsuperscript{4}, K Gryllias\textsuperscript{1, 2}

\textsuperscript{1}Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, BOX 2420, 3001, Leuven, Belgium
\textsuperscript{2}Dynamics of Mechanical and Mechatronic Systems, Flanders Make, Belgium
\textsuperscript{3}Air Vehicles Division, Defence Science and Technology Organization (DSTO), Melbourne, VIC 3011, Australia
\textsuperscript{4}Laboratoire Vibrations Acoustique, University of Lyon, INSA-Lyon, 69621, Villeurbanne, France

E-mail: konstantinos.gryllias@kuleuven.be

Abstract. Planetary gearboxes nowadays serve as the heart of complicated structures such as helicopters, presenting a number of advantages. They have compact size and low weight, achieving high power density and high efficiency. Moreover, the gearing can be very accurate with virtually no backlash and modular, as most stages can be stacked. Furthermore, the last years planetary gearboxes have been introduced in the area of air breathing engines, helping to deliver improved efficiency over a wide range of thrusts. Planetary gearboxes consist of various shafts, gears and bearings and operate under varying conditions under excessive friction, heat and high mechanical forces. Their use in such critical applications demands for monitoring systems that can track the health condition of different components, such as bearings and gears, focusing towards early and accurate fault detection with limited rate of false alarms and missed detections, and on trending of the system degradation targeting to prognostics. Therefore the aim of this paper is the analysis of a dedicated dataset using a basic diagnostic indicator named Squared Envelope Spectrum. The indicator is applied and evaluated on a comprehensive dataset that has been generated in 1992 by Westland Helicopters Ltd (WHL), at their Universal Transmission Test Rig, testing a CH46 aft transmission, for the United States Navy.

1. Introduction

Helicopters are employed in a wide number of civil applications. Correct maintenance of their rotating components is required to guarantee the safety of the helicopter during operation, as well as maintaining its efficiency. The main gearboxes are critical mechanisms of helicopters, but are as well difficult to be maintained appropriately, mainly due to their complexity and their high number of rotating components [1]. Condition monitoring can be performed based on the analysis of vibration signals, which usually carry information on the health condition. Direct analysis of the raw signals in the time domain is not efficient, while analysis on the frequency domain allows for a more direct monitoring by detecting more easily the presence of certain components [2]. One of the most widely used approaches of this frequency domain based monitoring is the analysis of the Squared Envelope Spectrum (SES) where the high resonance carrier frequencies are shifted to the lower frequency range. The estimation is performed by demodulation techniques, such as the Hilbert transform, that envelope the signal. The envelope
is processed using the Fourier transform and the envelope spectrum is further analysed for the detection of relevant frequencies of interest that may provide information on the health condition of the structure [3].

Various scalar indicators, which describe the information of a frequency spectrum or a raw signal, have been proposed extensively in the field, as they allow for the abbreviation of the spectral analysis into single values that represent the state of the machine, albeit at the loss of some information. These features can be divided into two major categories: the statistics based and the frequency based. The statistics based features are statistical metrics estimated on the time signals or the spectra. Several statistics features have been proposed targeting to gear damages, such as FM4, NA4, M6A among others [4]. Frequency based features usually target a specific characteristic frequency of interest that is connected to the rotating component to be monitored. Usually are equal to a sum or a weighted average of amplitudes at gear-related frequencies, such as the SER and the SI among others [5, 6]. Often they result in a better description of the health condition of the component, due to tracking the specific component. On the other hand, knowledge of the gearbox kinematics and its characteristic frequency is required, while the statistic based features are completely blind features by nature.

This paper aims to analyse the capabilities for gear diagnostics in helicopter gearboxes of a frequency-based feature extracted from the SES. The feature is validated on a CH46 aft helicopter gearbox for 5 isolated cases, each one with a specific damaged rotating component. The rest of the paper is structured as follows: the theory of SES and the feature definition are shortly given in Section 2, while section 3 describes the experimental setup and each of the acquired datasets. The results are discussed in Section 4, and the paper closes with some conclusions.

2. Diagnostic indicator based on the Squared Envelope Spectrum (SES)

The diagnostic indicator used to analyse the condition of the helicopter gearbox is based on the sum of the amplitudes of the first 3 harmonics of one relevant gear-related frequency. The shaft and the gear meshing frequencies are usually present on the signal and they represent the strength of their signature. Therefore, it is assumed that by tracking the amplitude or their frequencies, the evolution of their condition can be in turn tracked. To obtain this indicator, first the envelope of the signal is obtained, using the Hilbert transform. The objective is to shift high frequency content of the signal to the low frequencies related to the gear damages, ideally resulting in clear peaks related to the gear in the resulting SES. Then, the peak amplitudes of the first 3 harmonics of the characteristics frequencies of interest are extracted and summed together, to obtain the indicator described by equation (1):

\[
\text{Diagn.Indicator} = \sum_{k=1}^{3} SES(k \cdot \alpha_{gear})
\]  

where \( \alpha_{gear} \) is the characteristic frequency related to the damaged gear to be analysed (shaft frequency or gear mesh frequency).

3. Experimental setup

The United States Navy produced an experimental study using a CH46 aft gearbox to generate the Westland universal transmission test rig data set which could be used to carry out a full investigation on health monitoring capabilities [7]. The Westland universal transmission test rig was primarily intended for fatigue testing of helicopter gearboxes having one, two or three driving inputs and single outputs to the main and tail rotor of a conventional helicopter. It also had the capability to test the rear and the forward transmissions of tandem rotor helicopters. It was not intended for routine production acceptance testing and it could be adapted to test any other
gearbox having similar input/output speeds and torque. The rig is of "open loop" form using electric motors as drivers and water dynamometers as means of loading the test gearboxes. The rig (figure 2) comprises of 3 x 3500 SHP electric drives coupled with suitable gearboxes giving speed capabilities up to 25000 rpm, 1 water dynamometer capable of absorbing 6000 SHP over the speed range 1300 rpm - 3600 rpm and 1 water dynamometer capable of absorbing 2500 SHP over the speed range 2200 rpm - 6000 rpm. In both cases, the lower speed limits the maximum torque which can be absorbed. For testing helicopter type gearboxes, means were provided for applying up to 78000 lbf lift and 720000 lbf inch head moment to the main rotor gearbox and 14500 lbf thrust to the tail rotor gearbox.

Measurements were first acquired under healthy conditions for a total of 9 hours 54 minutes. Oil samples were taken and partial strip examination at the end of the test did not reveal any damage to the gearbox. The data was acquired from eight ‘Endevco 7259A’ accelerometers, whose positions and numbers are defined in figure 2, and measured under various constant loads: 27%, 40%, 45%, 50%, 60%, 70%, 75% and 100% of the maximum torque available from the dynamometers. The acquired signals in this healthy condition are defined as the benchmark. The planned tests then proceeded in acquiring data involving propagating fatigue cracks. As components containing fatigue cracks were not available from in-service, cracks had to be generated. Electro discharge machining (EDM) was used to introduce a notch into the component to provide a fatigue crack initiation site into 5 different gear components of the gearbox transmission described in figure 1. Each of the tests and the corresponding damaged component are described in the following subsections.

3.1. Spiral Bevel Input Pinion Spalling
During this test an ex-service spiral bevel input pinion with spalling/scuffing damage to the gear teeth was used, as shown in figure 3. A total of 8 hours 5 minutes testing was completed. Oil samples were gathered during the test and partial strip examination of the end of each test did not reveal any secondary damage in the gearbox. In total 15 datasets with the damaged pinion
shown in figure 3 were provided. Among them, 6 have been captured at the beginning of the test and the remaining 9 at the end, close to the 8 hour mark. The characteristic frequencies of interest are: the bevel pinion shaft speed at 42.7 Hz and its gear meshing frequency at 1109 Hz.

3.2. Helical Input Pinion Chipping
During this test an ex-service helical input pinion with gear tooth chipping was used, as shown in figure 4. A total of 15 hours 51 minutes testing was completed. Oil samples were gathered during the test and partial strip examination of the end of each test did not reveal any secondary damage in the gearbox. In total, 4 datasets with the damaged helical pinion shown in figure 4 were provided from the end of the experiment, close to the 15 hour mark. The characteristic frequencies of interest are: the helical pinion shaft speed at 324.6 Hz; and its gear meshing frequency at 9089 Hz.

3.3. Helical Idler Gear Crack Propagation
The gearbox was tested with a helical idler gear containing a spark eroded flaw in the roots of two teeth. A fatigue crack was generated from each spark eroded flaw during the test, as shown in figure 5. A total of 36 hours 34 minutes testing was completed. Oil samples were gathered during the test and partial strip examination of the end of each test did not reveal any secondary damage in the gearbox. In total, 4 datasets with the damaged idler gear shown in figure 5 were provided from the end of the experiment, close to the 36 hour mark. The characteristic frequencies of interest are: the helical idler shaft speed at 126.2 Hz; and its gear meshing frequency at 9089 Hz.

Figure 3. Spiral bevel pinion and zoom to the spalling damage.

Figure 4. Helical Input Pinion and zoom to the chipping damage.

Figure 5. Helical Idler Gear and zoom to the eroded crack.
3.4. Collector Gear Crack Propagation
The gearbox was tested with a collector gear with four increasing levels of spark eroded flaws in the root of one tooth installed. During the test, a fatigue crack was generated from the spark eroded flaw. The crack propagated across the root of the tooth and finally led to tooth detachment. A total of 148 hours 31 minutes testing was completed. Oil samples were gathered during the test and partial strip examination of the end of each test did not reveal any secondary damage in the gearbox. In total, 4 datasets with the damaged collector gear shown in figure 6 were provided from the end of the experiment, close to the 148 hour mark. The characteristic frequencies of interest are: the collector shaft speed at 42.7 Hz; and its gear meshing frequency at 3156 Hz.

![Figure 6. Collector Gear and zoom to the crack.](image)

3.5. Quill Shaft Crack Propagation
The gearbox was tested using a quill shaft containing two spark eroded flaws with two holes of different sizes drilled through it. At the end of the test the quill shaft failed by fatigue from the second size of hole. A total of 58 hours 11 minutes testing was completed. Oil samples were gathered during the test and partial strip examination at the end of the test revealed that a significant amount of debris had been generated; however this had not caused any secondary damage in the gearbox. In total, 4 datasets with the damaged quill gear shown in figure 7 were provided from the end of the experiment, close to the 58 hour mark. The characteristic frequency of interest is the quill shaft speed at 42.7 Hz.

![Figure 7. Quill shaft and zoom to the eroded crack.](image)

4. Results
The analysis for each type of damage is performed on the accelerometer mounted on the casing of the gearbox that is close to the damage component and whose frequency of interest shows the highest amplitude level. For example, the amplitude at the gear mesh frequency of the Spiral Bevel Input Pinion on the healthy conditions returns the highest average value for all signals
on the accelerometer 7, shown in the schematic of figure 2. Therefore, damages related to the bevel pinion are based on this accelerometer 7. The comparison of healthy condition’s SES and damaged bevel pinion’s SES under the same 27% load, acquired from accelerometer 7, shown in figure 8 exhibits the harmonics of the gear mesh frequency with higher amplitudes for the damaged case. Extraction and summation of the amplitude of the first 3 gear meshing frequency harmonics result on the indicator for health assessment of the spiral bevel pinion. This feature value described as a function of time, in figure 9, exhibits an increasing trend with the passage of time and increasing gear spalling.

![Squared Envelope Spectra comparison between healthy and damaged spiral bevel input pinion spalling at 27% load.](image)

**Figure 8.** Squared Envelope Spectra comparison between healthy and damaged spiral bevel input pinion spalling at 27% load.

![Amplitude at GMF as function of time.](image)

**Figure 9.** Amplitude at GMF as function of time.

![Amplitude at GMF as function of load.](image)

**Figure 10.** Amplitude at GMF as function of load.

It can also be seen that the feature is correlated with the transmission torque, as it describes a decreasing trend in figure 10, presenting lower feature values for higher load. The accelerometer selection for the health monitoring of the helical input pinion is defined as accelerometer 8, in the same procedure as the case before. The highest average amplitude of the 3 shaft frequency harmonics corresponds to accelerometer 4 in the healthy state, therefore the analysis of the helical input pinion condition is performed based on this accelerometer. The sum of the amplitude of the 3 harmonics of the shaft frequency as function of time does not show a clear trending with passing time, as seen in figure 11. On the other hand, when load is taken into account, the features of the damaged case appear to be higher than the healthy state for the same applied load, as seen in figure 12. The results also show the same decreasing trend on the
features for higher load levels, similar to the previously seen results of figure 10. Following the same procedure for the accelerometer selection, monitoring of the helical idler gear condition is performed with accelerometer 2. However, the sum of the amplitude of neither the gear mesh frequency nor the shaft frequency harmonics show any correlation, trending, or possible diagnostics as shown from the results in figure 13 and figure 14. The last two remaining cases, the collector gear damage and the quill shaft crack, show similar results. Neither show a correlation with load, but the amplitudes of the shaft frequencies are heavily dominant on the spectra and are sensitive to the damage size, providing thus a simple diagnostic tool. The features for the sum of the amplitude of the 3 harmonics of the collector shaft can be seen in figure 15 and figure 16, and for the quill shaft in figure 17 and figure 18.

5. Conclusion
In this paper, the degradation of 5 different rotating components of a CH46 aft helicopter gearbox has been analysed. The diagnostic capabilities of the SES-based feature was investigated under different load levels and at different damage severities. Vibrations data of 8 accelerometers mounted on the casing of the gearbox were acquired. The diagnostics of a specific component was performed on the accelerometer signal whose Frequency of Interest showed the highest amplitude at the healthy condition. Analysis of the SES exhibited the presence of all gear-related harmonics and an indicator based on the sum of 3 harmonics has been used as a diagnostics tool. The feature showed good capabilities in describing the severity evolution of the damage.

![Figure 11. Amplitude at pinion shaft speed as function of time.](image1)

![Figure 12. Amplitude at pinion shaft frequency as function of load.](image2)

![Figure 13. Amplitude at idler shaft speed as function of time.](image3)

![Figure 14. Amplitude at idler shaft frequency as function of load.](image4)
as an increasing trend in 3 of the 5 damaged components, when analysis function of time is performed. When load is also taken into account, 4 out of 5 damaged components can be detected. Therefore it can be concluded that the degradation of rotating machinery, namely in gear damage, can be tracked by the sum of harmonics of relevant characteristic frequencies at the SES when combined with the load varying analysis.

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