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Cyclostationary-based tools for bearing diagnostics of helicopter planetary gearboxes

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Abstract

The components of a helicopter gearbox are vulnerable to fatigue defects and therefore Health and Usage Monitoring Systems have been developed, focusing towards early, accurate and on time fault detection with limited false alarms and missed detections. The main aim of HUMs is to enhance the helicopters' operational reliability and functionality and to improve flight airworthiness. A plethora of methods have been proposed in order to perform fault detection and diagnosis of gearboxes. IESFOgram has been recently proposed by the authors, based on Cyclic Spectral Correlation (CSC) and Coherence (CSCoh), focusing on the accurate selection of a filtering band for demodulation. The integration of CSC and CSCoh along the selected band leads to an Improved Envelope Spectrum. In this paper the performance of the tool is evaluated and compared to the literature on a dataset captured during an endurance test of a UH-60 Black Hawk helicopter main gearbox transmission.

Keywords: Condition monitoring, Bearing diagnostics, Cyclic Spectral Coherence, HUMS

Introduction

Helicopters are used in a variety of civil applications. In order to ensure safety and improve their efficiency during operation they are equipped with Health and Usage Monitoring Systems (HUMs) monitoring the health condition of critical components, such as the Main Gearbox (MGB). MGBs provide torque to key components of the helicopter and operate often under heavy load and speed conditions, which may cause fatigue and degradation of its rotating components. However, helicopter MGBs are complex rotating machinery and incipient defects on internal components, such as bearings, are commonly hidden beneath the noise level or masked by other rotating components' signals, making their early, accurate and on time detection rather challenging [1, 2].

As diagnosis via the direct analysis of raw time domain vibration signals is rather difficult, condition monitoring of rotating structure is based on advanced signal processing techniques in order to extract the fault information. A common approach is to demodulate the signals in order to detect modulations, which correspond to the characteristic fault frequencies describing the health condition of the rotating structure. Before the demodulation process, usually a band pass filter around the resonant frequencies, excited due to the fault impulses, is applied. The band can be selected either by engineering experience or by band selection tools such as the Fast Kurtogram [3].

Lately, specific attention has been paid to cyclostationary based tools for condition monitoring of bearings and gears, including Cyclic Spectral Correlation (CSC) and Cyclic Spectral Coherence (CSCoh), as they are able to reveal hidden modulations on weak signals masked by noise [4, 5]. The results of these methods are represented in a difficult to analyse 2D bi-variable map but the integration along one of its axis results in an equivalent demodulated spectrum, where fault identification can be easily performed. Estupinan and White [6] detected the ball spin and the cage frequencies on a CSCoh bi-variable map while analysing a degradation test of a helicopter MGB. Even though diagnosis through the analysis of the bi-variable map requires high expertise, the method achieved high performance in detecting the characteristic ball spin frequency of defect bearings that were non-detectable using classical methods [7, 8].

The objective of this paper is to propose the use of cyclostationary-based tools, such as the CSC and CSCoh, as methods for bearing diagnostics of helicopter gearboxes, introducing also the recently proposed IESFOgram (Improved Envelope Spectrum via Feature Optimisation-gram). The performance of different demodulated spectra estimated, based on the integration of the CSC and CSCoh bi-variable map in specific frequency bands, are analysed and their corresponding advantages are explained. The methods are tested, validated and compared on a degradation dataset containing roller damage on a bearing mounted on a UH-60 Blackhawk helicopter Main Gearbox (MGB). The rest of the paper is organised as follows. The theory of the methods is briefly presented in the following section. Then the MGB experiment setup and the dataset is detailed. Moreover the results are analysed and the paper is closing with some conclusions.

Cyclic Spectral Correlation (CSC) and Coherence (CSCoh)

Rolling element bearing signals can be described as second-order cyclostationary signals, due to the slippage of elements, presenting a periodic autocorrelation of period T:

$$R_{2x}(\tau,t) = \mathbb{E}\{x(t)x(t-\tau)^*\} = R_{2x}(\tau,t+T) \tag{1}$$

where x(t) is the time signal, $\mathbb{E}$ is the ensemble average and τ is the time-lag. Cyclostationary based tools, such as Cyclic Spectral Correlation (CSC) and Coherence (CSCoh) have received an ever increasing interest due to their ability in extracting hidden modulations. CSC estimates the correlation between a modulating frequency (the cyclic frequency α) and a carrier frequency (the spectral frequency *f*) presented in a bi-variable map [9, 10]:

$$CSC(\alpha,f) = \lim_{T\to\infty} T^{-1}\mathbb{E}[\mathcal{F}\big(x(t)\big)^*\mathcal{F}\big(x(t-\tau)\big)] \tag{2}$$

The Cyclic Spectral Coherence (CSCoh) is the whitened version of the CSC:

$$CSCoh(\alpha,f) = \frac{CSC(\alpha,f)}{\sqrt{CSC(0,f).CSC(0,f-\alpha)}} \tag{3}$$

where F(x(t)) is the Fourier transform of the signal x(t). The integration of the bi-variable maps over a band [F_1, F_2] of the spectral frequency *f* leads to the Improved Envelope Spectrum (IES) and to the Enhanced Envelope Spectrum (EES) (F_1=0, F_2=F_s/2, F_s is the sampling frequency] which are equivalent to a demodulation spectrum:

$$IES(\alpha) = \frac{1}{F_2-F_1}\int_{F_1}^{F_2} |CSCoh(\alpha,f)|df \tag{4}$$

Recently the IESFOgram has been proposed as a tool is order to automatically select the optimal integration band, similarly to the Kurtogram. A series of integrating iterations for different combinations of bandwidth and centre frequency are performed following a 1/3 binary tree. A diagnostic feature, equal to the sum of the amplitude of k=3 harmonics of the bearing fault frequency f_{fault} normalized by the surrounding noise level (estimated at a band [f_{fault}-/+1/4f_{shaft}])

[11], is estimated at each band. The highest feature value corresponds to the optimal integration band as described in Figure 1.

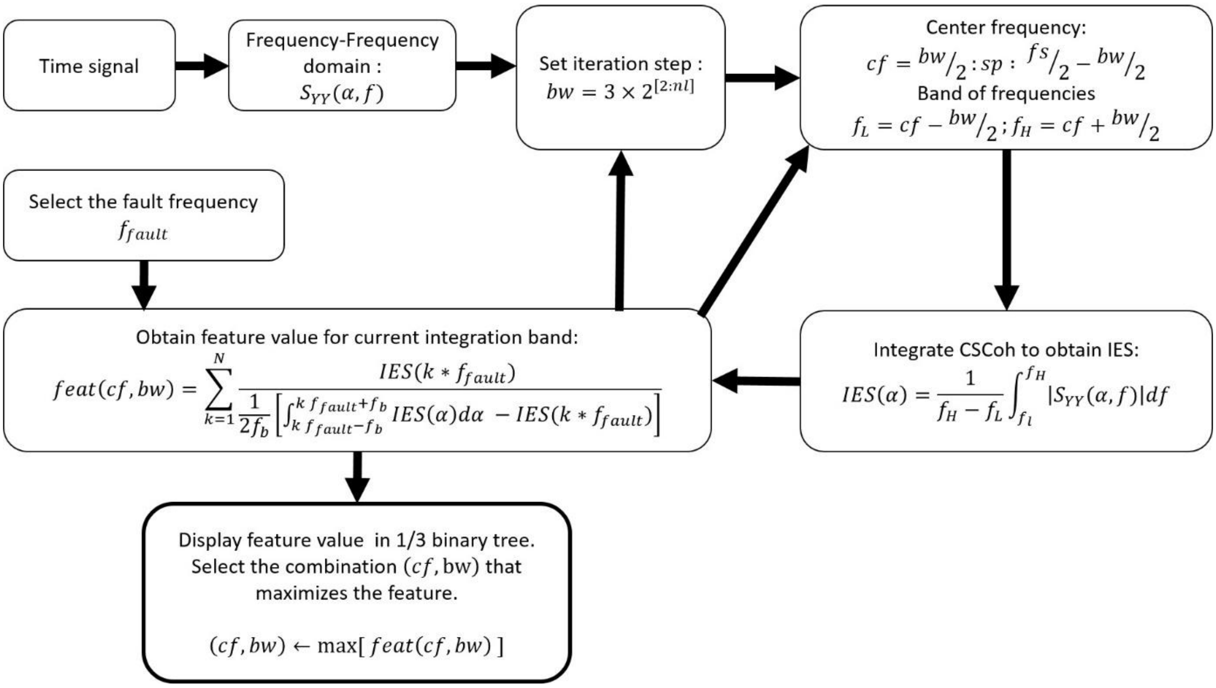
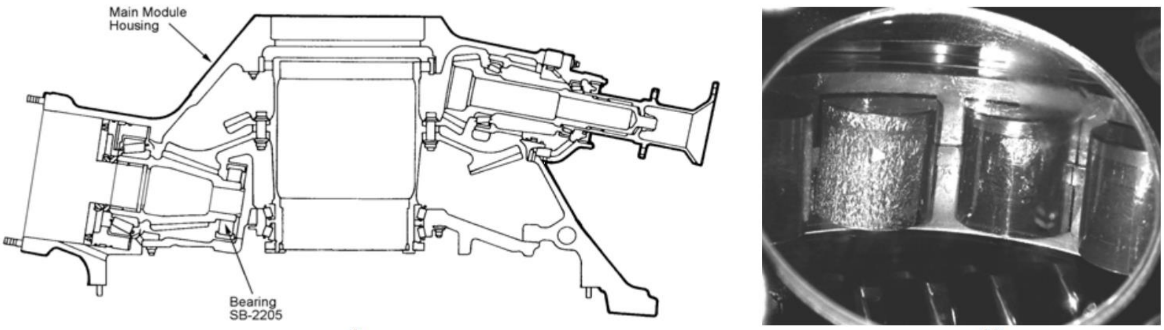


Fig. 1: Procedure for the generation of the IESFOgram

Experimental Setup of a helicopter gearbox

More than 10 years ago a number of measurements have been conducted on the main gearbox transmission of a UH-60 Black Hawk helicopter on a test bed located at the U.S. Navy's Helicopter Transmission Test facility at Patuxent River in Maryland, USA. This study focuses on the analysis of a fault detected in the inboard roller bearing SB-2205, which supports the combining bevel pinion in one of the input modules of the two main gearboxes (Figure 2a). The detection of a fault in this particular bearing is extremely challenging as it is located deep inside the gearbox and the fault signature may be masked by the background noise and by the gear transmission periodic components. During a component endurance test, 153 vibration signals of 10 seconds duration each have been recorded at irregular intervals, at a rate of 100 kHz per channel using a DataMax system and Endevco 6259M31 accelerometers. During the endurance test severe degradation of the inboard bearing SB-2205 occurred and six chip lights have been retrieved. The first gearbox chip light went on after 10300 minutes of run time had elapsed. A photograph presenting the final condition of the bearing rollers after the completion of the endurance test is shown in Figure 2b. Unfortunately from the 153 signals, only 3 signals, measured by the starboard main accelerometer were available and used on this study. Among them, two signals were measured before the chip light and one after. The timeline of the experiment, the measurements and the first chip detection is shown in the timeline of Figure 3. The Ball Spin Frequency BSF and the Fundamental Train Frequency are respectively equal to 180.75 and 35.5 Hz.



a) b)

Fig. 2: a) Location of the SB-2205 bearing, b) Spalling damage on the bearing rollers

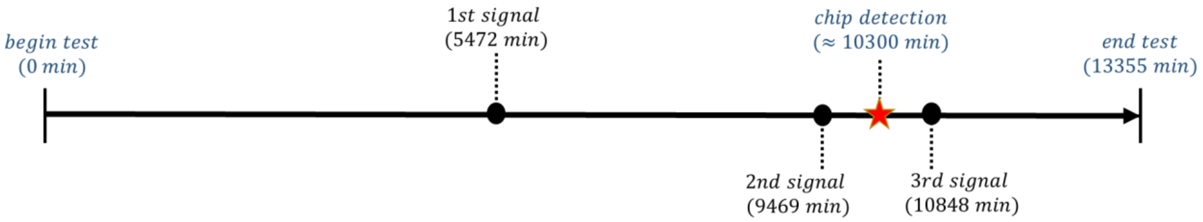


Fig. 3: Timeline of the available signals

Cyclostationary analysis based on CSC & CSCoh

The Enhanced Envelope Spectrum (EES) of the 3 measurements (1st , 78th and 113rd signals) based on the Cyclic Spectral Correlation (CSC) are estimated and presented at Fig. 4. At the first sight the amplitudes of the FTF harmonics appear to be relatively high. A closer zoom at the low frequency band of the 1st and the 78th signals shows that these peaks correspond to background noise around the deterministic harmonics related to gears and shaft speeds. In the case of the 113rd signal the FTF harmonics are clearly detected. On the other hand the BSF harmonics cannot be identified in any of the 3 spectra.

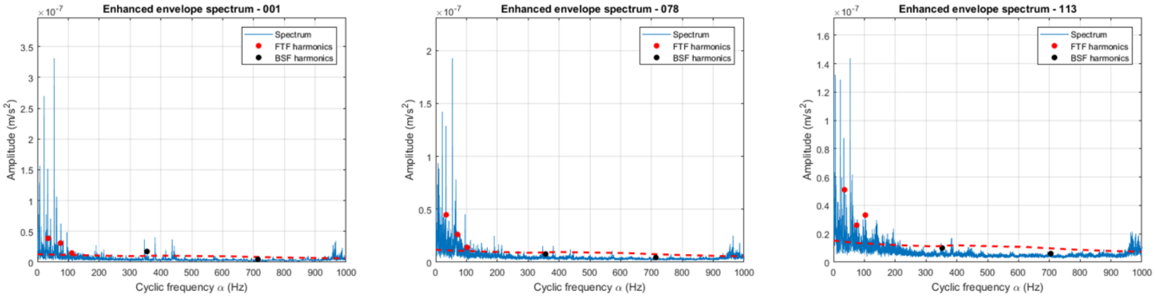


Fig. 4: EES estimated using CSC: (left) 1st signal; (middle) 78th signal; (right) 113rd signal.

Moreover the EES is estimated over the Cyclic Spectral Coherence (CSCoh) achieving a better detection of the fault frequencies as shown in Fig. 5. The FTF harmonics are present in all signals. On the EES of the 1st signal, the amplitudes of the FTF harmonics are above the noise level and they increase with the degradation level, as can be seen from the EES of the 78th and 113rd signals. Additionally, the first harmonic of the BSF is clearly identified on all signals, but its amplitude remains relatively constant. It should be noted that the 1st signal has been captured 5472 min after the start of the experiment as presented in Fig. 3. These results are in line with the findings of [7], where the previously non-detected BSF harmonics are detected by the analysis of the CSCoh map in the case of the highest level of roller degradation. However, the fault harmonics had not been detected on the previous cases, possibly due to the Adaptive Line Enhancer strategy used to remove the deterministic harmonics, along with the removal of values below the 7.5% of the confidence interval [7]. Based on this analysis, it can be concluded that the CSCoh based EES achieves a better performance in revealing hidden bearing defect frequencies.

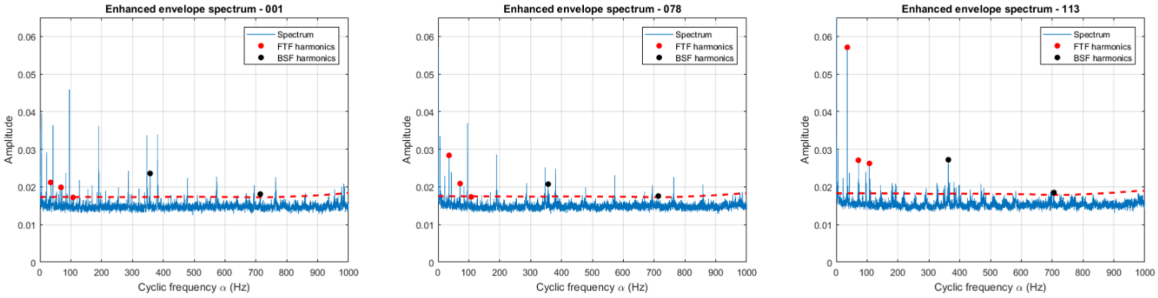


Fig. 5: EES estimated using CSCoh: (left) 1st signal; (middle) 78th signal; (right) 113rd signal.

Furthermore the Improved Envelope Spectra (IES) of the signals are estimated based on the band integration derived from the IESFOgram (Fig. 6) and presented in Fig. 7. The FTF is selected as characteristic frequency for the estimation of the IESFOgram which retrieves the optimal band of integration around the same carrier frequencies for the 3 signals. This indicates that the same structural resonant frequency is excited due to the ball spalling damage which is developing from signal to signal. The selection of a feature based on the BSF instead of the FTF results in a similar IESFOgram with the same diagnosis performance of the fault frequencies. The method demonstrate excellent performance in revealing the fault frequencies present on the signals. Both the FTF harmonics and the BSF harmonics are clearly identified in the IES presented in Fig. 7 compared to the previously methods. The Ball Spin Frequency (BSF=180.75 Hz) with sidebands spaced apart at the FTF equal to 35.5 Hz can be clear identified, indicating the expected modulation structure of roller damage according to the theory [8]. The 2nd harmonic of BSF is also revealed well above the noise level.

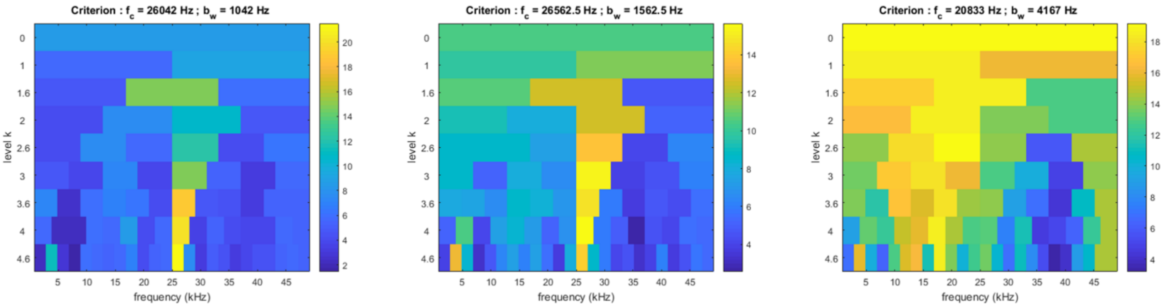


Fig. 6: IESFOgram (CSCoh) for the: (left) 1st signal, (middle) 78th signal, (right) 113rd signal.

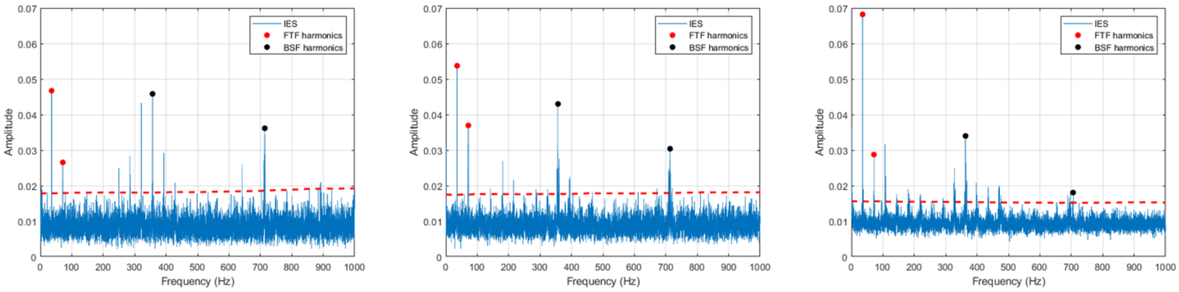


Fig. 7: Improved Envelope Spectra using the IESFOgram estimated over the CSCoh of the: (left) 1st signal, (middle) 78th signal, (right) 113rd signal.

Conclusions

In this paper cyclostationary tools have been applied over signals captured during a degradation test of a UH-60 Black Hawk helicopter main gearbox transmission. The EES and the IES based on the recently proposed IESFOgram have been analysed and compared with the literature. The methods demonstrate robust results and detect the damage at a very early stage. The IESFOgram selects successfully the optimal demodulation band. The integration of the CSCoh using the band selected from the IESFOgram results in spectra where BSF and the FTF are clearly identified. Additionally, the EES estimated over CSC and CSCoh presents an increasing amplitude at the fault frequencies harmonics over time. Therefore early detection of the faults can be extracted with the use of IESFOgram and the amplitude of the fault frequencies related to the severity level of the damage can be tracked in the EES of the CSC or CSCoh.

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