Rolling element bearings are common but crucial components of rotating machines, being the interface between stationary and rotating parts and are responsible for many machine failures and breakdowns. Condition monitoring of machinery using vibration analysis often provides insight and early detection of damage on the bearings. The most widespread method for detection of bearing faults is Envelope Analysis, where the raw signal is first filtered around an excited frequency band presenting a high Signal-to-Noise Ratio (SNR) and is further demodulated, extracting the fault information. The selection of this band is commonly done using the Fast Kurtogram which detects the filter band by maximizing the spectral kurtosis of the filtered signal. In some cases the vibration signals are polluted by Electromagnetic Interference (EMI), commonly emitted by the Variable-Frequency Drives of motors. EMI presents an impulsive behaviour similar to the behaviour of faulty bearing signals. As a result the Kurtogram might lead Envelope Analysis to erroneous results. Recently, Cyclic Spectral Coherence (CSC) has been proposed as a powerful diagnostic tool, revealing in the frequency domain all the information of second-order cyclostationary signals. In this paper an automated methodology for bearing fault detection under strong EMI is proposed based on CSC. The vibration signals are processed and the CSC map (cyclic frequency, frequency) is extracted. The integration of the CSC map along the frequency axis results in an enhanced version of the traditional squared envelope spectrum (i.e. spectrum of the squared envelop). Furthermore an optimization criterion is proposed in order to select the optimum integration limits leading practically to the selection of the optimal demodulation band, avoiding the influence of the EMI effect. The methodology is further validated and evaluated on vibration signals captured on an experimental planetary gear-box operating under strong EMI.

Keywords: Condition Monitoring, Cyclostationarity, Cyclic Spectral Coherence, Electromagnetic interference EMI

1. Introduction

Electromagnetic interference (EMI) is a common unwanted component on signals (electric noise) that are usually captured by vibration sensors (accelerometers) and microphones. This type of noise is often emitted, conducted or radiated from the Variable Frequency Drives that control the motors’
shaft speed, providing power to various rotating machinery. Smith et. al. [1] analysed well the EMI contamination and how it can be simulated using a phenomenological model. The simulation of EMI results in the same broadband impulsiveness that real measurements with EMI contamination present. The nature of this signal is particularly problematic for the diagnostics of rolling element bearings, as both EMI polluted signals and signals emitted by defected rolling element bearings present an impulsive behaviour and finally a similar signature. The most common signal processing methods used for fault detection tend to exploit and/or enhance the impulsiveness of signals and as both the fault and the EMI contamination present an impulsive nature, the methods may enhance the EMI instead of the fault signature or detect the modulations of the EMI effect instead of the modulations caused by the bearing fault.

Envelope Analysis has dominated as a common practice in bearing diagnostics. The signal is demodulated using often the Hilbert Transform and the envelope spectrum of the demodulated signals is analysed. In order to enhance the detection, the signal is usually filtered around an excited frequency band (resonance) that contains the fault information and where the Signal-to-Noise Ratio (SNR) is high. The frequency band selection can be done by human expertise or by methodologies which select the filter band automatically without human intervention optimising a specific criteria, such as the spectral kurtosis (Fast Kurtogram) [2] and the peak energy criterion [3]. Following the methodology of the Fast Kurtogram, a series of filters with different bandwidths and center frequencies is applied on the signal, following a 1/3 binary tree. The kurtosis level of the filtered signal is calculated for each applied filter and the parameters of the filter that maximises the kurtosis are finally selected. The method shows good fault diagnosis results [4] as the signal generated by the bearing faults tends to be rather impulsive and the selection of the filter based on the maximisation of kurtosis, maximizes further the impulsiveness of the filtered signal. On the other hand, the presence of impulsive noise or of outliers may reduce the performance of the method [5]. The EMI is an impulsive phenomenon and often masks the impulsive signature of a bearing fault, leading fast kurtogram to the selection of a non optimal frequency band. Using a specific experimental case based on a planetary gearbox, Smith et. al. [1] explained that the Fast Kurtogram failed to select the optimal filter parameters because the allowed bandwidth was too wide, thus concluding that by selecting a narrow and constant bandwidth, improved filter parameters could be selected. A methodology entitled Optimised Spectral Kurtosis (OSK) has been proposed, introducing a series of filters with a constant narrow bandwidth instead of a variable one. The method has been successfully applied on vibration signals strongly contaminated by EMI captured on a planetary gearbox with a defective bearing positioned on one of the planets [1].

Among others, Cyclic Spectral Correlation has been recently introduced in the area of condition monitoring. It has been successfully applied in a number of cases and presents good performance on the diagnostics of damaged rolling element bearings [5]. Moreover Cyclic Spectral Coherence, which is derived from the Cyclic Spectral Correlation, appears to be more sensitive to the level of cyclostationarity of signals [7]. The method generates a two dimensional map in which the signal can be described in two axes: the spectral frequency axis, which contains the excited natural frequency components; and the alpha frequency, which contains the characteristic modulation frequency component. When this 2D matrix is integrated along the spectral frequency it results in a spectrum which is equivalent to the Squared Envelope Spectrum (SES) from which the demodulated fault frequencies can be detected.

In this paper a method based on the integration of the Cyclic Spectral Coherence CSCoh is proposed focusing towards the automatic rolling element bearing fault detection and diagnosis in rotating machinery. The integration is realised on a specific area of the 2D Cyclic Spectral Coherence map, specially selected using an optimisation criterion, leading to a filtered version of the Enhanced Envelope Spectrum. The methodology is able to successfully detect bearing faults in presence of other impulsive phenomena such as electromagnetic interference. The approach is tested, validated and evaluated on an experimental case of a planetary gearbox. Inner and outer race bearing faults located at one of the planets and operating under the influence of strong EMI are analysed and the
performance of the methodologies are compared to state of the art diagnostic tools.

The rest of the paper is organised as follows. The principle of the EMI generation and bearing fault detection are introduced in Section 2. Moreover the new methodology based on the CSCoh is presented in Section 3. Furthermore the experimental setup is introduced in Section 4. The methodology is further applied, evaluated and compared to state-of-the-art methods in Section 5. Finally some conclusions are drawn in Section 6.

2. Bearing fault signals with electromagnetic interference

When a localized defect in one surface of a rolling element bearing strikes another surface, it produces an impulse which may excite resonances in the bearing and in the machine. As the bearing rotates, these impulses will occur with a frequency which is determined uniquely by the geometry of the bearing and the location of the defect on the inner race (BPFI), the outer race (BPFO), the rolling elements (BSF) or the cage (FTF). Mainly due to the slippage of the rolling elements of a bearing, the vibration signal present a cyclostationary behavior. The impacts caused by the generation of a bearing fault lead to the excitation of natural frequencies of the bearing and/or the structure, which appear usually at high frequencies, and are modulated by the characteristic frequency of the bearing fault. EMI appears usually in a form of a series of transients with a complex modulation structure. The spectrum of an EMI signal presents usually harmonics of the switch frequency (carrier frequency which is usually between 2 and 16 kHz) modulated by harmonics of a frequency which corresponds to the pseudo-line frequency (depends on the number of poles and the slip of the motor) and possibly by harmonics of the line frequency ($f_L = 50$ Hz). Defective bearing signals and EMI polluted signals present a similar behaviour, including periodicity and impulsiveness and classical diagnostic tools are often misled selecting as a demodulation band the frequency band which corresponds to one of the harmonics of the switch frequency and not the frequency band around the excited natural frequency. As a result the envelope spectrum is dominated by harmonics of the motor speed and/or of the line frequency and not by the characteristic frequency of the defect, leading to a wrong diagnosis.

3. Enhanced Envelope Spectrum by Feature Optimization (EESFO)

In this paper a new approach based on the CSCoh is proposed focusing towards the detection of a bearing fault under the influence of strong EMI. Bearing signals present slip and can be characterised as cyclostationary signals of second order having a periodic autocorrelation function:

$$R_{xx}(t, \tau) = R_{xx}(t + T, \tau) = \mathbb{E}\{x(t - \tau/2)x(t + \tau/2)\}$$  \hspace{1cm} (1)

where $R_{xx}$ is the autocorrelation function, $\mathbb{E}$ stands for the ensemble average operator, $x(\cdot)$ is the signal and $T$ is the period of the function. Cyclic Spectral Correlation (CSCor) has been proposed as a powerful diagnostic tool, which may reveal hidden periodicities masked by noise and is expressed by Eq. (2):

$$S_{xx}(\alpha, f) = \lim_{T \to \infty} \mathbb{E}\{X_T(f + \alpha/2)X_T^*(f - \alpha/2)\}$$  \hspace{1cm} (2)

where $X_T(f)$ stands for the Fourier transform of the signal $x(t)$ over a time interval $T$. The frequency $f$ is the dual of time-lag $\tau$, indicating the frequency of the carrier signal while the frequency $\alpha$, called "cyclic frequency", is the dual of time $t$ and indicated the frequency of the modulation. CSCor measures the correlation level between two frequency components of the signal at $f - \alpha$ and $f + \alpha$. The CSCor leads to a 2-D map which reveals the modulation frequencies in the $\alpha$ axis and their carrier frequency $f$. Antoni [6] extensively explained the power of CSCor and further suggested the CSCoh which is calculated using Eq. (3):

\hspace{1cm}
\[ \gamma_{xx}(\alpha, f) = \frac{S_{xx}(\alpha, f)}{\sqrt{S_{xx}(0, f + \alpha/2)S_{xx}(0, f - \alpha/2)}} \]  

(3)

where \( S_{xx}(\alpha, f) \) is the Cyclic Spectral Correlation.

The CSCoh may also be interpreted as the Cyclic Spectral Correlation of a whitened signal, which tends to equalize regions with very different energy levels and thus to magnify weak cyclostationary signals [6]. The integration of the CSCoh over the full frequency band of spectral frequencies \([f_1; f_2]\) results to a one-dimensional function, termed as "Enhanced Envelope Spectrum" (EES, \( S_{x}^{EES}(\alpha) \)) and is described by the Eq. (4).

\[ S_{x}^{EES}(\alpha) = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} |\gamma(\alpha, f)| df \]  

(4)

where \( f_1 = 0, f_2 = f_s/2 \) and \( f_s \) is the sampling frequency. For numerical implementations, Eq. (4) is replaced by discrete sums over the spectral frequency \( f \). The EES, when estimated based on the full band is equivalent to the Square Envelope Spectrum (SES). On the other hand the integration over the full frequency band introduce much noise in the EES in analogy to the estimation of SES in case a filter has not been selected. Based on this fact, the EES may be estimated by integrating only over a carefully selected frequency band around the carrier frequency, enhancing the result in analogy to a filtering. An approach in order to automatize the procedure and select in an optimum way the integration frequency limits is therefore proposed, based on the optimisation of a criterion. In this paper, the maximization of the sum of the amplitude of three harmonics of the characteristic bearing fault frequencies is selected as a criterion (K=3):

\[ Ind = \sum_{i=1}^{i=K} A(\alpha_i = i \ast f_{def}) \]  

(5)

where \( f_{def} \) are the characteristic bearing fault frequencies and \( K \) the number of harmonics taken into account and equal to three (3) in this paper. The method is termed "Enhanced Envelope Spectrum by Feature Optimization" (EESFO) and tries to select the frequency band \([f_1; f_2]\) which optimizes the above mentioned criterion. Similar to Kurtogram, a series of frequency bands along the spectral frequency axis \( f \) with different bandwidths \( bw \) and center frequencies \( cf \) are selected in a 1/3 binary tree and the EES is estimated for each one by integration of the CSCoh over each frequency band. Starting from the full band from 0 Hz up to half the Nyquist frequency, the bandwidths decrease for each increasing order of the binary tree. For each bandwidth, the EES is estimated and the IC value is calculated. Finally a 2D map is created, just like Kurtogram, where the Ind is plotted as a function of the center frequency and the order (which is a logarithmic relation with the size of the bandwidth). The colour of each band corresponds to the value of the Ind. The highest value of the Ind corresponds to the optimal integration frequency band, which practical results to an Enhanced Envelope Spectrum where the amplitude of the K harmonics of the characteristic fault frequency are dominant (or at least more prominent compared to all the other bands).

4. Experimental Setup

In order to evaluate the effectiveness of the proposed methodology, data from the planetary gearbox test rig, presented in Fig. 1 have been used. The gearbox’s torque is provided by a hydraulic system driven by a three-phase induction motor. A torque transducer is attached to measure the applied torque on the gear set while the speed of the driving shaft is controlled by a VFD. A schematic of the planetary gearbox is shown in. The gear ratio of the planetary stage is 1:3 (speed up) consisted of a 40 tooth sun gear, three 20 tooth planetary gears and a 80 tooth ring gear. The planet carrier is the
input of the planetary stage, the sun gear is the output while the ring gear is fixed. The overall transmission ratio of the test rig is approximately 1:1 as an initial 90:32 reduction stage is attached. An accelerometer is mounted on the planet carrier to measure acceleration in the axial direction focusing towards the investigation of internal vibration measurements. The vibration signal is final transmitted to the signal conditioner by the use of a slip ring. Faults have been seeded in the inner race and the outer races of the planet gear bearings using spark erosion. Needle roller bearings are used, containing 15 rollers of 2 mm diameters and a pitch diameter of 18 mm. The depth of the faults is 0.4 mm while the width is 1.2 mm for the outer race and 1.0 mm for the inner race respectively. The measurements have been realised for each type of defect (inner and outer race) at a constant input shaft speed of 6 Hz for three torque loads 30, 50 and 70 Nm. The sampling frequency has been selected equal to 131,072 Hz, the switching frequency of the VFD was set at 14 kHz, and the control frequency of the VFD was 24 Hz (giving a nominal 6 Hz shaft speed for the 8-pole motor). The PWM carrier and the PWM message are equal respectively to 14000 Hz and 24 Hz. Based on the geometry of the bearing and its speed, the BPFO is equal to 55 Hz and the BPFI is equal to 69 Hz.

**Figure 1: Planetary gearbox: (left) Test rig, (right) CAD representation.**

### 5. Experimental data analysis and results

In order to test and validate the effectiveness of the new methodology, the experimental data captured under the three above mentioned loads and described in Section 4 are further processed estimating the classical Squared Envelope Spectrum (SES) without filtering, the EES (where the 2D CSCoh map is integrated over all frequency axis) and the proposed EESFO. In the high load (70 N.m.) case the inner race defect cannot be detected in the classical SES (Fig. 2) as no characteristic fault frequency harmonics (BPFI) can be recognised being masked by the noise and the discrete gear frequencies, while the EMI component of 100 Hz (twice the line frequency) and its harmonics are present. On the other hand, the harmonics of BPFI are clearly detected in EES although the EMI components are more dominant in the spectrum (Fig. 2). The analysis of outer race defect signals leads to similar results and for sake of brevity are not presented at this paper. Furthermore the signals captured under 30 N.m. and 50 N.m. are processed. The fault frequencies are no longer clearly detected in the EES as can be seen in Fig. 3. The EMI components are dominant in the spectra and the BPFI harmonics are not clearly identified among other frequency components.

In order to better understand the existing phenomena, the signals are further analysed selecting manually different filters along the spectrum. The analysis led to the conclusion that for both inner and outer race cases, the frequency bands which provide a clear fault diagnosis are centred around the 42 KHz which corresponds to the 3rd harmonic of the PWM carrier frequency. The frames presented in Fig. 4 correspond to the optimal (manually selected) bands of demodulation where the amplitude of the harmonics of the defects is enhanced, avoiding a band which includes the 3rd harmonic of the carrier of the PWM at 42 KHz, where the fault frequencies are still present but the spectra are dominated by the EMI components (Fig. 5). Therefore the feature maximisation approach is applied.
creating the map presented in Fig. 6. The criterion presents the largest value near the 42 KHz for the 30 N.m. and the 70 N.m. and near 44 KHz for the case of the 50 N.m. as presented in Fig. 6. The integration of CSCoh at those bands leads to the EESFO where the harmonics of the characteristic fault frequencies are clear and dominant, for all the load cases and both types of defect. The manual analysis of the signal showed that the amplitude of the EMI related frequencies are dominant in teh spectra when the Signal-to-Noise Ratio of the fault signature is low. For this reason, an evaluation indicator EvInd is introduced in order to evaluate the detection efficacy and efficiency as well as the performance of different methodologies. The indicator is defined as:

\[ EvInd = \frac{2}{K} \sum_{i=1}^{K} \frac{A(f = i \cdot f_{def})}{\max(A(f))}, \]  

(6)

where K is the number of the harmonics of teh defect. The parameter \(2/K\) is chosen in order to normalise the indicator between 0 and 2. In an ideal case, the K harmonics of the fault frequency (e.g. BPFI, BPFO) would simultaneously present high values and the indicator value would be close to 2. On the worst case, the non existence of the fault frequencies in the spectrum would lead to a null indicator value. Based on the definition, a method performs well if the evaluation indicator is close to 2. Furthermore based on a visual comparison of the evaluation indicator value and the corresponding spectrum, it is assumed that the fault frequencies are clearly identified with confidence only when the indicator takes values above a Threshold equal to 1. The indicator values estimated on a) the SES of the unfiltered signals, b) the SES of the filtered signals based on Kurtogram, c) the EES and d) the EESFO are presented in Fig. 7. Based on the evaluation indicator and verified by visual analytical inspection of the spectra the defects are better identified for all the load cases at the...
6. Conclusion

In this paper a novel approach for bearing diagnostics under strong Electromagnetic Interference (EMI) has been presented based on the integration of Cyclic Spectral Coherence at a frequency band specially selected by the optimisation of a criterion. The sum of three harmonics of the characteristic defect frequency has been considered as the criterion to be maximized. The integration leads to the estimation of the EESFO. The performance of the methodology has been evaluated and compared to other state-of-the-art methods, using vibration signals captured on a planetary gearbox and polluted by strong EMI. The methodology was tested on signals captured under different load conditions and provided good results in all the load cases, detecting accurately faults in the inner and in the outer race. The methodology can be therefore used successfully into the general condition monitoring context, able to acquire good results even in the case of highly impulsive (non Gaussian) noise.

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Figure 6: Methodology applied to the inner race fault case with load 50 N.m. (left) Criterion band selection, (right) Resulting EESFO

Figure 7: Evaluation Indicator for all loads for the inner race and the outer race fault.

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