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Analysis of the influence of crack location for diagnosis in rotating shafts based on 3 x energy

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ABSTRACT

The aim of condition monitoring is to detect faults before a catastrophic failure occurs. Cracks in rotating shafts are especially critical. The present work studies vibration signals obtained from a rotating shaft under different crack depths and locations. Tests were performed in a rig called Rotokit at a steady state at different rotation speeds. Signals obtained are analyzed by means of energy using the Wavelet theory, specifically the Wavelet Packets Transform. Nine crack depths in the shafts were tested, from 4% to 50% of the shaft diameter. Previous related work showed good reliability for crack diagnosis using 3 x energy for cracks in the middle section. In the present work, previous results are compared to the obtained for a crack in a change of section at one side. In both crack locations, large changes in energy are observed at 3 x at high speeds. Energy levels at this harmonic were used for the inverse process of crack detection, and probability of detection curves were calculated by thresholding. Cracks with depths above 12% can be detected with reliability in the locations tested using this method.

1. Introduction

Cracks in shafts are specially critical since they can lead to a catastrophic failure. Dynamic behavior of cracked rotors has allowed the diagnosis of cracks in some cases, however there is no standard methodology to detect cracks and detection not always takes place with time enough to avoid the failure. Besides, in some cases the results are theoretical and difficult to translate to experimental systems. These issues were highlighted in [1].

Acoustic Emission (AE) signals have been applied for condition monitoring since they contain information related to crack growth. Typical frequencies associated with AE activity range are from 20 kHz to 1 MHz. They have been used in shafts in works as [2] and [3]. In [4], a comparison between vibration and AE signature is carried out, and in both cases features related to the crack were found. Nevertheless, most of the work published is focused in vibration signals.

Studies about cracked rotors have been carried out with different methods to select proper features indicators of the presence of a crack. Fast Fourier transform (FFT) and Hilbert transform (HT) are traditional techniques used to observe changes in the dynamical response (1 x, 2 x and 3 x vibrational frequencies) or in eigenfrequencies when a crack appears, as can be consulted in the review by Sabnavis et. al. in [5]. In the last years, time-domain techniques, such as Hilbert–Huang transform (HHT) and Wavelet Transform (WT) have showed their effectiveness in this field. HHT has been applied to study transient vibration

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response in works as [6] and [7] . It was found that HHT appeared to be a good tool for crack detection in a transient rotor, even better than fast Fourier transform and continuous Wavelet Transform. The WT theory was applied to experimental vibration signals obtained from cracked shafts at steady state in works as [8], and [9]. Nevertheless, the Wavelet theory application is not a straightforward issue. There are several different methods when applying Wavelet Transform, such as Continuous Wavelet Transform (CWT), Multiresolution analysis (MRA) or Wavelet Packets Transform (WPT). Besides in each of them, the wavelet function and the range scales must be selected, and they are not standard methods to do those selections. All these drawbacks were stated in the review of the Wavelet theory to fault detection carried out by Peng and Chu in 2004 [10].

CWT coefficients were used in [11], [12] and [13], using sub-critical peaks and the first harmonics of the rotation speed. MRA coefficients have been applied in [14] and in [15], to signals coming from experimental system and to signals obtained from a Jeffcott rotor model. Features related to WPT coefficients have been also applied for crack detection in works as [16], [17] and [18], showing that WPT is a powerful tool for detailed feature extraction.

After the features extraction stage, a classification system is needed to interpret the information obtained. Thresholding methods can be used if the features are simple enough, as in [8]. When the features are complex, intelligent classification systems are required. Some examples like artificial neural networks (ANN) [19], Fuzzy Logic (FL) [20], Genetic Algorithms (GA) [21] and Support Vector Machines (SVM) [22] have attracted considerable attention. The results of the classification system are useful to estimate the reliability of the technique. Examples of works using ANN for crack detection can be consulted in [18,23], and SVM were used in [24].

As it has been reviewed, there are a lot of works published based on different methodologies that resulted successful when they were applied to diagnose cracks. The aim of condition monitoring is to establish a general method. Therefore there is a need of works benchmarking the techniques applied at different conditions (mounting, speed, load, multiple faults, different location of the fault). POD curves [25] are a universally accepted parameter to evaluate a Non-Destructive Evaluation technique. POD curves can be defined as the probability of detecting a crack within a certain range of sizes under specific conditions and procedures that can be used for measuring the capability of an inspection method.

The present work studies the robustness of the technique proposed in [8] that was used for diagnosing cracks located at the middle section. In this case, previous results are compared to those obtained when it is applied to cracks located in a change of section at one side, where they are more kind to appear. Experimental vibration signals obtained from a mechanical system at a steady state under different crack depths (from incipient to severe) are analyzed. WPT energy and threshold methods are used for the analysis. Results can be used for crack detection, showing that different phenomena occurs depending on the location of the crack. Probability of detection curves are obtained for each case to quantify the results.

2. The Wavelet Transform

The WT is a modern mathematical development that treats signals and obtains information both in time and in frequency domain. Most of the techniques derived from FFT are inappropriate to treat non-stationary signals due to the absence of temporary information. WT is specially useful to carry out local analysis of non-stationary signals, or patterns changing with time. The same way as FFT obtains correlation coefficients of the signal with a sinusoidal function, the WT obtains the correlation of the signal with the wavelet function selected. There are a lot of of different families of wavelet functions such as Daubechies, Coiflet, Symlet, Morlet or Meyer. Coefficients obtained depend on the scale and position of the wavelet function. The WT can be applied in a continuous way, (Continuous Wavelet Transform (CWT)), or a discrete way, (Discrete Wavelet Transform (DWT)).

CWT allows the analysis of structures of the signals through the correlation coefficients, instead of using the whole signal. The mathematic formulation of the CWT is shown in Eq. (1).

$$T(a,b;\psi) = w(a)\int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt \tag{1}$$

Where $x(t)$ is the temporary signal, ψ is the wavelet function, and $w(a)$ is a weighting function. The parameter a is related to the scale and b to the position of the wavelet function. $T(a,b;\psi)$ represent the resulting coefficients, as a function of a, b and the wavelet function ψ.

Nevertheless, the application of the Wavelet theory by means of the DWT using the developments of Mallat in [26] is more effective. Those developments are based on the use of filters related to the wavelet function. The decomposition is carried out using a low pass filter g, which obtains information of *aproximation*(A), and a high pass filter h, which obtains information of *detail*(D), according to Fig. 1.

After applying filters to a signal S of a frequency band $[0,\pi]$ and number of samples N, the frequency band is halved obtaining both approximation information (A) $[0,\pi/2]$ and detail information (D) $[\pi/2,\pi]$. Therefore, applying Nyquist rule [27], it is justified downsampling by two without losing relevant information, resulting the number of samples is $N/2$ [28].

The recursive application of DWT decomposition derives in Multiresolution Analysis (MRA) and Wavelet Packets Transform (WPT). The MRA decomposes the information of approximation of a signal recursively, until the decomposition level selected, and the divisions generated have different frequency resolution.