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Shaft angular misalignment detection using acoustic emission

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ABSTRACT

Shaft angular misalignment (SAM) is a common and crucial problem in rotating machinery. Misalignment can produce several shortcomings such as premature bearing failure, increase in energy consumption, excessive seal lubricant leakage and coupling failure. Vibration analysis has been traditionally used to detect SAM; however, it presents some drawbacks i.e. high influence of machine operational conditions and strong impact of the coupling type and stiffness on vibration spectra. This paper presents an extensive experimental investigation in order to evaluate the possibility of detecting SAM, using acoustic emission (AE) technique. The test rig was operated at under different operational conditions of load and speed in order to evaluate the impact on the AE and vibration signature under normal operating conditions. To the best of the author's knowledge, this is the first attempt to use AE for the detection of SAM under varying operational conditions. A comparative study of vibration and AE was carried out to demonstrate the potentially better performance of AE. The experimental results show that AE technique can be used as a reliable technique for SAM detection, providing enhancements over vibration analysis.

1. Introduction

Generally throughout industry there is a direction towards increased speeds and loads of rotating machinery, which causes the machines to operate close to critical speeds and for this reason misalignment is becoming an increasingly important consideration for rotor bearing systems [1]. Misalignment problem may cause up to 70% of the vibration problems observed in rotating machines [2]. To date, the most common technique applied to detect shaft misalignment is vibration analysis; however, the speed, the coupling type and the stiffness have a strong effect on the vibration spectra that may lead to an inaccurate diagnosis [3].

Shaft misalignment occurs when the shafts are not on the same centreline. Misalignment is one of the most common faults and yet it is still not fully understood [4]. There are two different types of shaft misalignment: (i) SAM in which shaft centrelines intersect and (ii) shaft parallel misalignment in which shaft centrelines are parallel (Fig. 1). In fact, in the most cases the misalignment is caused by a combination of both.

Several studies have been accomplished about misaligned shaft dynamics, including modelling its effects. Most of these studies show the main peak at the shaft rotation frequency (1X) and smaller peaks at the harmonic frequencies (2X, 3X and 4X) in the vibration spectra. Pennacchi et al. [5] presented a study in order to model this fault accurately. The ratios of 1X/2X, 1X/3X and 1X/4X harmonics of vibration signals in bearings were investigated, showing changes according to the severity of parallel and angular misalignment. They concluded that (i) nonlinear effects are evident in both types of misalignment and (ii) the ratio between the higher harmonic components and the 1X component in angular misalignment is greater than parallel misalignment. Hili et al. [6] carried out a study about angular misalignment characterisation and developed a theoretical model. They found three characteristic peak frequencies in the shaft behaviour: (i) the most prominent being at 1X; (ii) a smaller peak at 2X; and (iii) the last peak corresponding to the natural frequency of the system. Sidebands of the rotation frequency around it were also visible. Al-Hussain [7] presented a study of the effect of angular misalignment of two rigid rotors connected through a flexible mechanical coupling. The results showed that an increase in angular misalignment, or mechanical coupling stiffness terms, leads to an increase of the model stability region. However, the variability of the signature, produced by misalignment at different operational conditions of load and speed in the vibration spectra, is one of the main drawbacks of vibration analysis [3].

AE is widely used as a NDT technique for several applications. AEs are defined as transient elastic waves generated from a rapid release of strain energy, caused by a deformation or damage within, or on the surface of a material [8]. This mechanical process can be produced by different sources such as cracks, plastic

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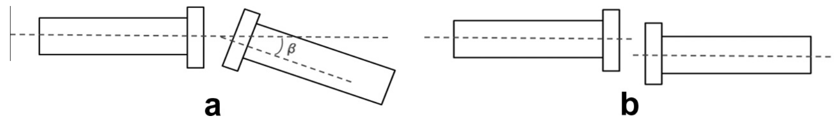

Fig. 1. Graphical explanation of (a) SAM and (b) parallel misalignment.

deformation, rubbing, cavitation and leakage. [9]. In particular, AE applied in rotating machinery is produced by two surfaces in relative motion. Asperity contact, between two surfaces, generates AE waves that can be measured and analysed to investigate the deterioration state of the components. AE has been traditionally used in rotating machinery to detect bearing, gearbox and pump faults, including friction processes producing seizure, flaking, fluting, spalling, pitting, etc. However, the majority of the investigations have been performed using artificially defected components [10]. Al-Dossary et al. [11] studied application of the AE technology for characterising the defect sizes in a radially loaded bearing. The authors concluded that the energy value correlated with increase defect severity for inner and outer race. Furthermore, burst duration was shown to be as a good parameter to find the size of outer race defects. However, this does not apply to the inner race. Tandon et al. [12] investigated the detection of inner and outer race bearing defects of different sizes at different loads. They observed that AE peak amplitude and AE maximum normalised value level increase as defect size increases. They concluded that AE was more reliable at identifying defects than vibration analysis and motor current signature analysis. An extensive review of AE applied to rotating machinery (bearings, gearboxes and pumps) was presented by Mba and Rao [13].

Although several AE studies have been conducted to detect crack onset and propagation, spalls and wear using AE technique, the detection of rotordynamic faults such as misalignment using AE technique has not been fully investigated. One of the few studies regarding this problem was carried out by Gu et al. [14]. The combination of wavelet transform and envelope analysis was applied to the AE signals captured from a misaligned and defected gearbox. Misalignment was created by a twisted case caused by arc-welding to fix the base. They found a peak at 1X in the spectra of the envelope AE signal that was attributed to gear misalignment. Toutountzakis and Mba [15] presented an experimental investigation on the application of AE for gear defect diagnosis. They observed that the AE root mean square (RMS) and energy were greater with misalignment than was observed for background noise under defect free conditions.

The main aim of this study is to develop an approach based on AE signal analysis in order to achieve SAM detection. This work attempts to link the shaft displacement, measured with proximity sensors installed in the shaft, with signals derived from accelerometers and AE sensors. In the author's knowledge, this research is the first attempt to investigate and compares the performance of AE and vibration analysis for SAM fault detection and also studies the influence of different operational conditions (load and speed).

2. Proposed method for SAM detection

Misalignment produces periodic changes in the lubricant film thickness and the frictional moment between the bearing and the shaft [16,17], which can be characterised as AE sources, leading to AE signal amplitude modulation. The proposed method applied to the AE signals is described in Fig. 2. The main objective is to find the frequency of the peaks, generated in the AE envelope spectrum. These peaks have been traditionally used to inform about bearing

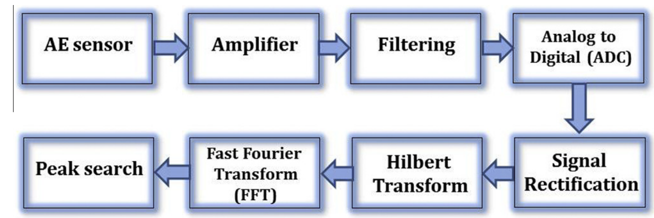

Fig. 2. Schematic of the proposed method.

defects [18]. Nevertheless, in this study, the effect of SAM in the AE envelope spectrum under varying operational conditions is investigated.

The signal acquisition is carried out, using an AE sensor, followed by amplification, filtering and analog to digital conversion. More detailed information about this acquisition procedure is presented in Section 3.2.1. After the acquisition module, envelope analysis was applied. It is mostly used in vibration analysis to detect bearing defects; however, it has been successfully applied to bearing and gearbox defect detection using AE [19,20]. The process of extracting the envelope of a signal has two different steps: signal rectification and a Hilbert Transform (HT). The HT application to the signal provides additional information about the amplitude, instantaneous phase and frequency of vibrations [21]. The Hilbert Transform $h(t)$ of a function $x(t)$ is defined as:

$$h(t) = H\{x(t)\} = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau \quad (1)$$

The HT of $x(t)$ ($H\{x(t)\}$) is the convolution of $x(t)$ with the signal $1/\pi t$. Hence, it can be interpreted as the output of a system linear time-invariant system with input $h(t)$ and impulse response $1/\pi t$. When the envelope is extracted, the time domain signal is transformed into frequency domain using the Fast Fourier Transform (FFT) to obtain the frequency spectrum of the enveloped AE signal, which is used to define peaks which will lead on to misalignment detection [22].

3. Experimental setup and measurements

3.1. Test rig

The test rig used in this work (Fig. 3) was developed by Romax Technology Ltd (Intelwind project participant, see acknowledgement) in order to investigate bearing skidding and its effect on the bearing useful life. The test rig was designed to represent the shaft arrangement in a typical 2 MW wind turbine. The shaft was supported by three test bearings; one cylindrical roller bearing and two tapered roller bearings. Gear load was simulated by hydraulic actuators, applying axial and radial loads through the slave bearings. A thrust bearing was used as the axial slave bearing and a spherical bearing as the radial slave.

A 30 KW motor was used to power the test rig with a nominal speed of 1650 RPM. It was controlled through a variable frequency drive that modified the rotational speed. The rated axial and radial load of the rig was 40 KN and 140 KN, respectively. The test rig is