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Ultrasonic-based monitoring of tapered roller bearings in frequency and time domains

Monitoreo de rodamientos cónicos usando ultrasonido en dominios del tiempo y la frecuencia

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ABSTRACT

In this paper the ultrasonic signal is used for early failure detection in tapered roller bearings. The faults studied were localized in outer race, inner race, cage and the rolling elements. The implemented failures emulate three distinct levels of severity. The ultrasonic signal analysis is performed using time domain parameters i.e. kurtosis and RMS, and in the frequency domain using the power spectral density obtained by the Welch periodogram. Although none of the studied parameter was able to extract the fault location, the RMS parameter presents the best performance as a feature to monitor allowing to identify faulty conditions and evaluate qualitatively the severity of the fault.

Keywords: Fault detection, ultrasonic signal, Kurtosis, RMS.

RESUMEN

En este artículo se utiliza la señal de ultrasonido para detectar fallas incipientes en rodamientos cónicos. Las fallas estudiadas se ubican en la pista externa, interna, canastilla y elementos rodantes. Estas fallas se implementan en cada ubicación para emular tres niveles de severidad distintos. El análisis de la señal de ultrasonido se realiza usando los parámetros de curtosis y RMS, en el dominio tiempo, y la densidad espectral, usando el periodograma promediado de Welch, en el domino de la frecuencia. Aunque no fue posible ubicar la falla, el parámetro RMS presenta el mejor desempeño como variable a monitorear permitiendo detectar la condición de falla y realizar una evaluación cualitativa de la severidad de esta.

Palabras clave: Detección de fallas, ultrasonido, curtosis, RMS.

INTRODUCTION

High operational reliability is expected in productive systems to satisfy production requirements. Ideally, any machine's abnormal operation must be detected during its early stages to successfully avoid disturbances, failures, breakdowns and unplanned shut-downs.

Well-developed condition monitoring techniques enable monitoring any system's actual condition; they allow maintenance resources to be prioritized and optimized for obtaining the maximum useful life for each physical asset before taking it out of service. A condition monitoring system is usually able to determine a system's current state by using information processed online regarding vibration,

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stator currents, temperature, etc. A CBM (Condition Based Maintenance) must be able to infer the presence, location and severity of the faulty condition.

The trend towards increasing power, complexity and efficiency regarding rotating machinery has limited rolling element design and early fault identification as requirements for ensuring reliable operation. Mass imbalance, misalignment and overload are common problems concerning rotating machinery, thereby reducing bearing service life. Different methods have been used for detecting and diagnosing bearing defects; current techniques can be classified as vibration or acoustic measurements. Vibration monitoring of bearings is probably the most established diagnostic technique for rotating machinery. Vibration signals are predominantly analyzed in the frequency domain; this usually provides enough information for estimating fault location (i.e. inner race, outer race, rolling element and retainer) but it is not suitable for detecting incipient faults.

Recently, ultrasonic-based bearing fault detection has captured researcher's attention. In [1-2] the high reliability of the ultrasonic-based bearing condition monitoring is demonstrated. Some abnormal bearing conditions produce signals in the ultrasonic range such as the friction between races and rolling elements due to inappropriate lubrication or crack formation. In this paper the ultrasonic signal in time and frequency domains are studied for a tapered roller bearing under fault condition. The faults are located in outer race, inner race, rolling elements and the cage. Three fault levels of severity are emulated; incipient, intermediate and severe. The experimentation is performed in a dedicated test bench used for fault detection purposes.

BEARING MONITORING

There are several causes of bearing failure such as: incorrect installation, corrosive environments, manufactured defects, excess or lack of lubrication, overload and fatigue. Some diagnostic techniques have been proposed for bearing monitoring such as vibration analysis, thermography, and recently ultrasonic. Mainly, two methodologies of ultrasonic analysis are used: ***pulse-echo*** and ***high frequency vibration analysis***. Pulse-echo ultrasonic has been widely studied; some research works are reported by [3-5]. In [6] a neuronal classifier is proposed using the Welch periodogram information, to classify bearing health, and more specifically the bearing operating condition using ultrasonic signals in a bandwidth between 20 and 120 kHz.

In [7], it is presented results of an experimental comparative study on the application of the ultrasonic technique for condition monitoring in low speed rolling element bearings and conventional vibration measurements with seeded faults on inner-race defect. In this study time domain parameters such as asymmetry, Kurtosis and RMS value are used as fault indicators. Additionally, the frequency spectrum information is also used.

In [8] the effectiveness of two ultrasonic sensors, namely, air-coupled (noncontact) and piezoelectric ultrasonic (contact) transducers for rolling element bearings damage diagnostics, it investigated running with defective and undamaged bearings under variable shaft speeds and several radial loads. The results showed that certain acoustic features were responsive to the variation of operational condition and the damage; the detection capability of the sensors fluctuated depending on the defect size, its location, as well as the applied signal analysis technique.

Some lately research works have explored the use of statistical parameter such as kurtosis and/or the crest factor. Nevertheless, the signal used has been the acoustic emission [9] and mechanical vibrations [10]. One of the limitations of the use of statistical parameters in time domain such as kurtosis is that it shows the presence of defect but it does not provide any further information such as localization and type of fault [9].

THEORETICAL FRAMEWORK

Time and frequency domain features

In this work time domain and frequency domain parameters of the ultrasonic signal are used as fault indicators. In a first stage, various time domain parameters were considered as features to monitor this type of bearing; among them, the crest factor and the skewness; which do not present a satisfactory performance for the studied scenarios. Therefore, from now on we only consider in this paper the parameters with a decent behavior i.e. Kurtosis and RMS. In order to estimate these statistical parameters, equations (1-3) are presented as follows. Standard deviation, equation

(1), Kurtosis, equation (2) and RMS, equation (3) are defined by the vector $X = (x_1, x_2, x_3 \dots x_i \dots x_n)$ where x_i is each captured ultrasonic sample.

$$\sigma = \sqrt{\frac{1}{K}\sum_{i=1}^{K}\left(x_i - \langle x \rangle\right)^2} \tag{1}$$

Where $\langle x \rangle$ is the mean value of the vector X of length K.

$$Kurt = \frac{1}{K}\sum_{i=1}^{K}\left(\frac{x_i - \langle x \rangle}{\sigma}\right)^4 - 3 \tag{2}$$

$$RMS_X = \sqrt{\frac{x_1^2 + x_2^2 + x_3^2 + \ldots + x_i^2 + \ldots + x_n^2}{K}} \tag{3}$$

Frequency domain parameters used in this work are obtained using the information provided by Welch periodogram. In signal processing, the Welch method is used for estimating the reduced noise spectral density. This method is employed in this approach due to the noise caused by imperfect and finite data in the ultrasonic signal. To reduce the variance Welch's technique breaks the captured signal into segments to compute a modified periodogram for each segment and then averages these estimates to produce the estimate of the power spectral density. The segments are typically multiplied by a window function, in this investigation Hanning window is implemented to produce a smooth PSD and to reduce the frequency leakage. Because of the overlapping of the segments no information is lost caused by windowing.

In order to obtain the Welch PSD, the data sequence $x(n)$, $n = 0, 1, 2, \ldots, N\text{-}1$ is divided into L segments of M samples each. The segments are given by $x_i(n) = x\,[n + (i - 1)M]$, where $0 \le n \le M - 1$ and $1 \le i \le L$. Now, a window $w(n)$ is applied to the original signal segments before Fourier transformation. The periodograms of the windowed segments L are defined as equation (4).

$$Sw_i\left(w\right) = \frac{1}{ME_w}\left|\sum_{n=0}^{M-1} x_i\left(n\right) w\left(n\right) e^{-iwn}\right|^2 \tag{4}$$

Where E_w is the average power of the window given by equation (5).

$$Ew = \frac{1}{M}\sum_{n=0}^{M-1} w\left(n\right)^2 \tag{5}$$

The Welch PSD estimate is calculated using equation (6).

$$S_w\left(w\right) = \frac{1}{K}\sum_{i=1}^{L} Sw_i\left(w\right) \tag{6}$$

EXPERIMENTATION

Figure 1 shows the dedicated test bench used in this work. The bench is comprised by three bearing supports, two of them are ball bearings and they are used as a support of power shaft of the electric motor, and the third is a tapered rolled bearing under which the fault condition is studied. The test bench consists of an 0.125 hp, 1800 rpm induction motor, two ball bearings (ref 6000), the bearing under test (tapered roller NSK 30203), and a steel metallic frame to support the motor and bearings.

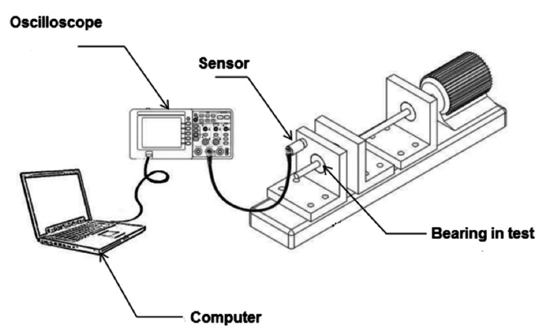

Figure 1. Scheme of the test bench.

The three emulated faults: incipient, intermediate and severe, are located in outer race, inner race, cage and rolling elements. An ULTRA TRAK 750™ piezoelectric sensor is used to capture the ultrasonic signal produced by the system in the different scenarios. Then the ultrasonic signal is acquired by a Rigol DS1102-E oscilloscope using a sampling frequency of 500 Khz, no averaging or overlapping is setup in the osciloscopy. The acquired data is processed in Matlab using Welch method for Power Spectral Density and Hanning windowing.

In Figures (2-4), the faults in the outer race for all levels of severity are shown. All the pictures are obtained using a KH-7700 Digital Microscope System of Hirox with a 140X lens. In Figures (5-8), it is shown the values of width and depth for each fault studied scenario are shown. In Figures (9-12), it is presented a zoomed window of the power spectral density of the ultrasonic signal in the bandwidth of interest for outer race, inner race, cage and rolling elements faults is presented.

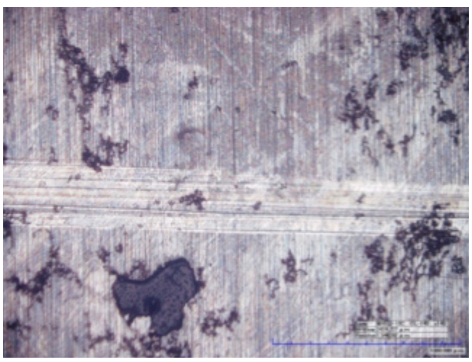

Figure 2. Incipient fault in outer race.

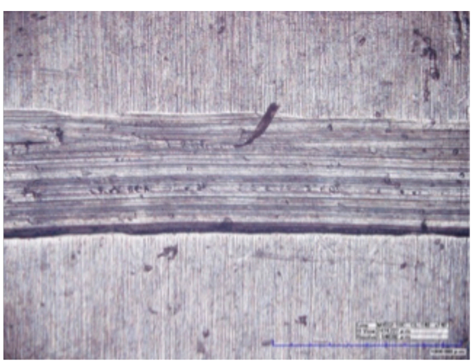

Figure 3. Intermediate fault in outer race.

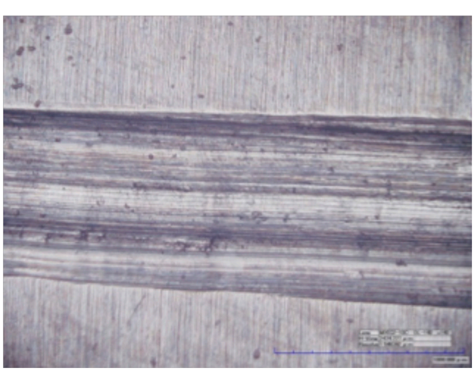

Figure 4. Severe fault in outer race.

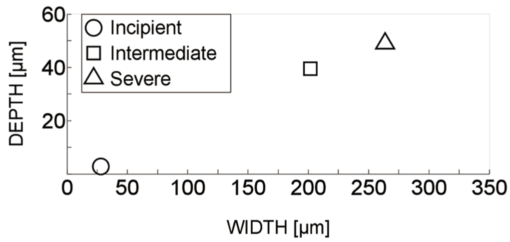

Figure 5. Width vs Depth Inner Race.

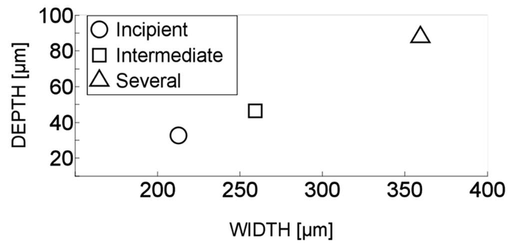

Figure 6. Width vs Depth Rolling elements.

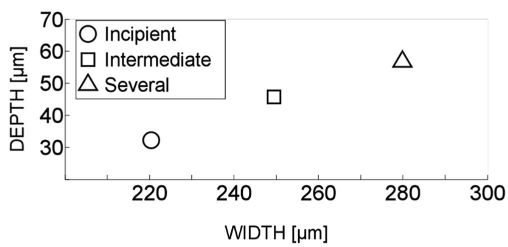

Figure 7. Width vs Depth Cage.

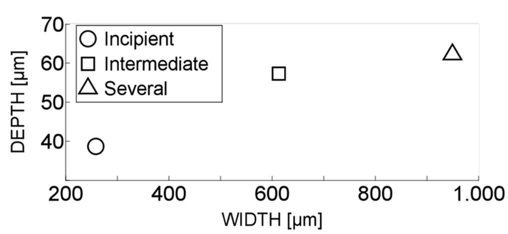

Figure 8. Width vs Depth Inner Race.

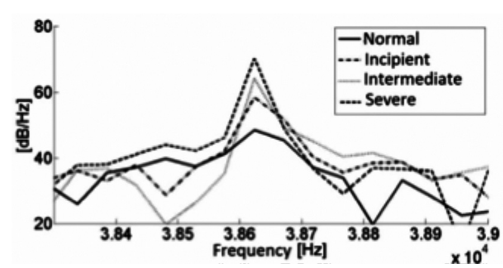

Figure 9. PSD for the three levels of severity in outer race.

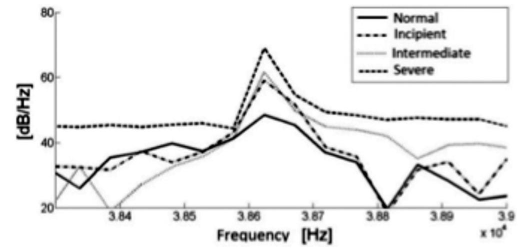

Figure 10. PSD for the three levels of severity in inner race.

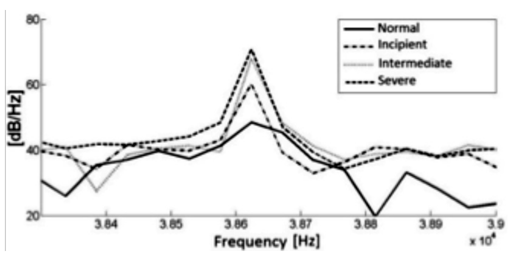

Figure 11. PSD for the three levels of severity in rolling elements.

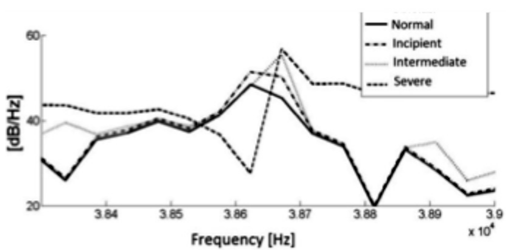

Figure 12. PSD for the three levels of severity in cage.

In Figures (9-12) the tendency of the proposed fault indicators in time domain, Kurtosis and RMS can be observed. In Figures (9-12) N means normal condition, Inc represents incipient, Int is intermediate fault and S stands for severe fault.

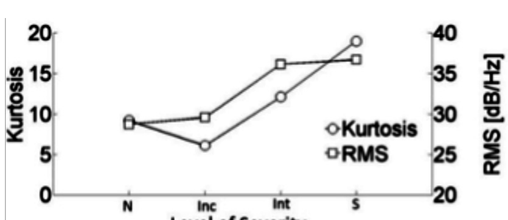

Figure 13. Tendency of Kurtosis and RMS for severity fault in outer race.

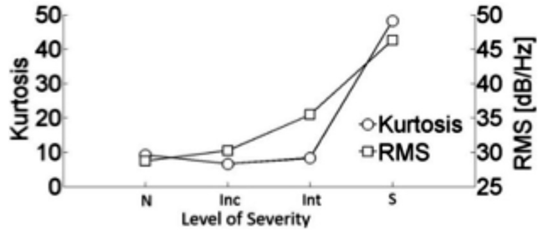

Figure 14. Tendency of Kurtosis and RMS for severity fault in inner race.

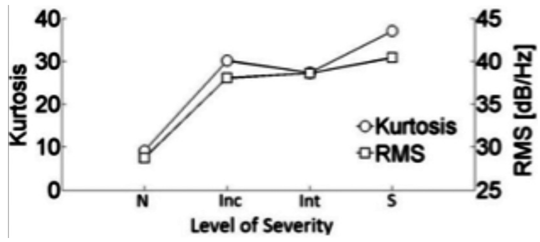

Figure 15. Tendency of Kurtosis and RMS for severity fault in rolling elements.

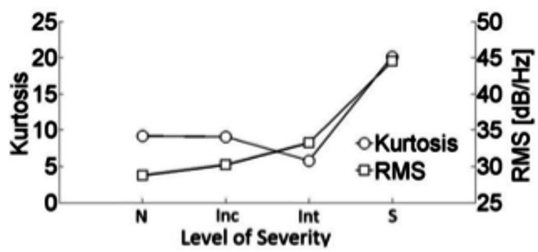

Figure 16. Tendency of Kurtosis and RMS for severity fault in the cage.

RESULTS AND DISCUSSION

Experimental results permit to compare in time and frequency domain the ultrasonic data obtained for each fault scenario studied. In Figures (9-12), it is presented the PSD of the ultrasonic signals for each emulated fault in the suitable bandwidth (38-40 KHz)[2] for the piezoelectric sensor used.

In Figure 9, it can be observed that the ultrasonic signal presents a maximum value in 38.7 kHz and an increase progressive in the amplitude level at this frequency, that is, the magnitude of the spectrum is increased with the fault severity of the fault. The

[2] This frequency range is used by manufacturer's recommendation.

same tendency is reported in Figures (10-12) where the magnitude of the PSD is increasing with the fault severity of the fault.

In the Figure 13 the Kurtosis and RMS value variations for fault condition in the outer race are shown. In this Figure it can be observed that the Kurtosis value increases with the level of severity, even though, in the case of normal condition bearing the Kurtosis value was slightly superior to the value of the incipient fault. On the other hand, the RMS value presented a consistent increase in magnitude in presence of a severer fault condition. In Figures (14-16), it is also observed the inconsistency between the magnitude of Kurtosis and the severity of the fault studied. This reduction of the Kurtosis value can be attributed to an increase of the fault size producing a reduction of the ultrasonic signal peakedness when the rolling elements pass through the notch in each of the faults studied. On the other hand, the RMS value presented an increase in magnitude with the severity of the fault in all the fault scenarios studied.

CONCLUSIONS

Experimental results showed a progressive rise in the PSD magnitude of the ultrasonic signal, in the bandwidth studied, with increasing severity level of the emulated fault. However, the symptom observed does not provide enough information to locate the fault i.e. (inner race, outer race, rolling elements and cage).

In time domain, experiments reveal higher sensitivity of the Kurtosis feature compared to RMS sensitivity in presence of fault condition. Nevertheless, RMS exhibits a consistent behavior i.e. a progressive increase in magnitude with the severity of the fault emulated; contrary to the observed with Kurtosis value. Based on the results it can be concluded that time domain RMS value of the ultrasonic signal is suitable as a fault indicator for bearing monitoring proposed via threshold of the normal condition. Although, it is not possible to locate the fault, the RMS provides a satisfying fault severity estimation comparing the current values with the threshold determined in the normal condition.

FUTURE WORK

A more extended study must be carried out to improve the stage of fault diagnosis (localization and type of fault) using ultrasonic features in time and frequency domain. So, in order to increase the information provided by the system under monitoring, signals such as vibration or infrared thermal images can be fed in a classification scheme to produce not only detection of an abnormal condition but also localization, type of fault and fault severity evaluation.

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