Experimental Wavelet Analysis of Rotor-Rub Vibration Signal

Eduardo Rubio, César Chávez-Olivares, Alejandro Cervantes-Herrera

Abstract*: A common defective phenomenon in rotating machinery is rotor-casing rub that generates impacts when the rotor rubs against the stator. Vibration sensors and data analysis techniques are commonly used for fault signature extraction and mechanical systems diagnosis. In this paper, an experimental characterization of rotor-rub is made by time-frequency analysis by means of the wavelet transform. A rotor kit, equipped with a variable speed DC motor, an accelerometer and a data acquisition system are used to acquire the mechanical vibration data. Vibration signal in frequency and time-frequency domains are shown for no-rubbing, light, and severe rubbing cases. Results show that FFT is unable to report where in time particular components of rubbing appear. However, the time-frequency analysis is able to give location information in time to differentiate light from severe rubbing, and extract the main spectral components showing a spectrum rich in high frequency components, characteristic of this phenomenon.

***Keywords* : Experimental, rotor-rub, time-frequency analysis, rotating machinery.**

I. INTRODUCTION

Condition based monitoring (CBM) is a process that involves the use of sensors to measure and analyze machine vibrations to establish trends, and predict operating failures. The implementation of adequate maintenance techniques leads to significant savings and improvement of the overall efficiency of industrial plants. This is achieved by applying analysis techniques such as the Fast Fourier Transform (FFT) to the vibration signal [1]. A common problem that faces industrial machinery is the rubbing phenomenon, and occurs because of the contact between the rotor and the stator of a rotational mechanical system. This phenomenon produces a distorted vibration signal and stiffening effects that increase the resonance frequency of the system [2].

Time-frequency analysis of a vibration signal is a classical processing technique for machinery diagnosis, while the wavelet transform is an emerging technique that has gained popularity in recent years. Wavelet analysis has been applied in various fields such as biological, mechanical vibrations, acoustic and ultrasonic signals. It has been mainly used for signal compression and denoising, singularity analysis and feature extraction. For better results, the optimum mother wavelet should be selected [3]. FFT processing gives no information of the spectral components in time, in contrast with the wavelet transform, that provides time-scale information enabling the identification of features that are transient in nature [4].

Time-frequency analysis has been used for fault signature extraction and state classification for rotor fault diagnosis [5]. Customized wavelets have been used to detect faults in mechanical systems. Rolling bearings may degrade and present defects in inner-race, outer-race, rolling elements, or cage, that can be detected effectively with denoising wavelet techniques [6]. Mechanical systems can be found that show non-linear and non-stationary frequency response and wavelets are very useful in analyzing these phenomena as demonstrated in gearboxes [7] and wind turbines [8].

Wavelet techniques have also been applied in the analysis of the rotor-rubbing phenomenon. Reports can be found that use harmonic wavelet transform for cracked rotor sliding bearing systems with rotor-stator rubbing [9], reassigned scalograms to study rubbing impacts for rotor-stator fault diagnosis [10], and wavelet transform for detection of single-point rub in aeroderivative gas turbines [11].

II. EXPERIMENTAL METHODOLOGY

The experimental platform for rubbing experiments is shown in Fig. 1. It consisted of a speed controlled DC motor, coupled to a shaft supported by ball bearings, a drilled disk with bolts to simulate unbalancing forces, and an adjustable friction mechanism. An accelerometer sensor was mounted on the bearing casing next to the motor, and a data acquisition system was used to measure data with a sampling frequency of 10kHz.

Signals were processed with Daubechies 4 discrete wavelet transform. The algorithm is based on a multiresolution process that decompose the signal into frequency sub-bands, by low-pass and high-pass filtering applied to the time-domain signal, according to Fig 2.

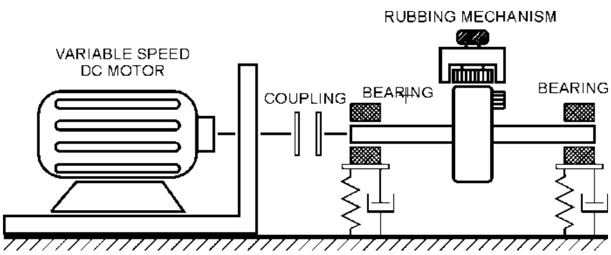

Fig. 1.Experimental set-up.

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* Correspondence Author

Eduardo Rubio, Centro de Ciencias de la Ingeniería, Universidad Autónoma de Aguascalientes, Aguascalientes, Ags., Mexico.

Alejandro Cervantes-Herrera, Centro de Ciencias de la Ingeniería, Universidad Autónoma de Aguascalientes, Aguascalientes, Ags., Mexico.

Chávez-Olivares, Centro de Ciencias de la Ingeniería, Universidad Autónoma de Aguascalientes, Aguascalientes, Ags., Mexico.

The wavelet scale function was defined as,

$$A_i = H_0 S_{2i} + H_1 S_{2i+1} + H_2 S_{2i+2} + H_3 S_{2i+3}$$

for scaled coefficients,

$$H_0 = \frac{1+\sqrt{3}}{4\sqrt{2}}$$

$$H_1 = \frac{3+\sqrt{3}}{4\sqrt{2}}$$

$$H_2 = \frac{3-\sqrt{3}}{4\sqrt{2}}$$

$$H_3 = \frac{1-\sqrt{3}}{4\sqrt{2}}$$

And the wavelet function defined as,

$$C_i = G_0 S_{2i} + G_1 S_{2i+1} + G_2 S_{2i+2} + G_3 S_{2i+3}$$

for wavelet coefficients,

$$G_0 = H_3$$

$$G_1 = -H_2$$

$$G_2 = H_1$$

$$G_3 = -H_0$$

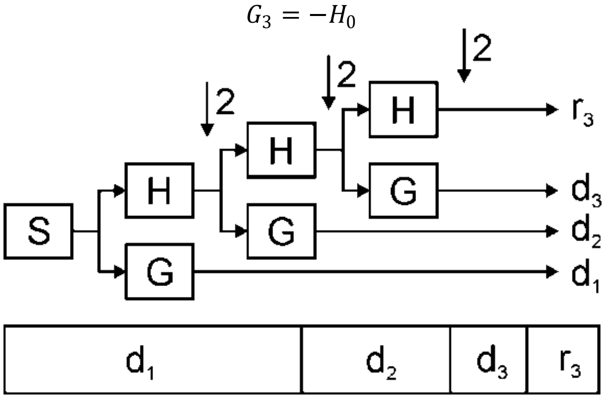

Fig. 2. Wavelet sub-band coding by cascade filtering of the signal.

III. ANALYSIS AND DISCUSSION OF RESULTS

The vibration acceleration signal in time-domain for the rub-free and rubbing rotor are shown in Figs. 3 and 4 respectively. Two intensities of rotor-stator contact friction can be appreciated. From 0-1.5s the systems was subjected to light rub, while for 1.5 to 3.3s a more severe friction was established. Rubbing reflects the characteristic impulse train in the casing acceleration signal. These sharp peaks perturb the system and produce oscillations containing the system vibration modes.

Plot in Fig. 5 corresponds to the spectral components of the time domain signals. For the rub-free case, vibrations are small and contained in the lower portion of the spectrum, with main frequency components located at the natural and harmonic frequencies of the spectrum, below 500 Hz, as it can be noted in the inset plot.

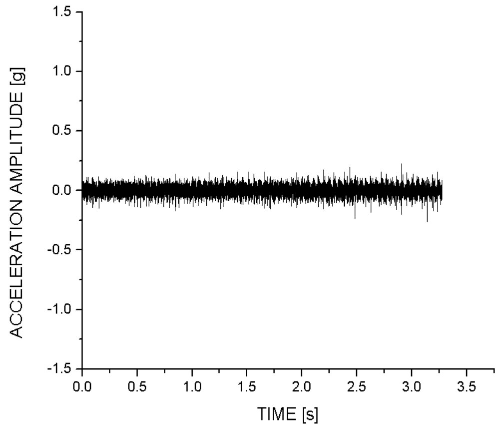

Fig. 3. Rotor friction-free acceleration vibrations signal.

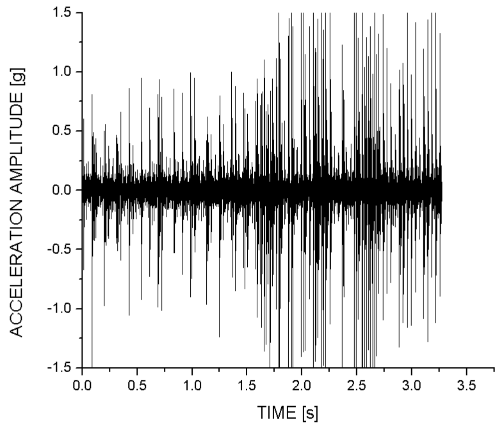

Fig. 4. Acceleration vibrations signal with rotor-stator friction.

When friction between the rotor and the stator exists, a spectrum rich in high frequency components arises. As expected, FFT offers information on the frequency content of the signal, but it does not make a distinction between the light and severe rubbing sections showed in the time-domain signal.

The results obtained by processing the vibration signal with the wavelet transform are shown in Figs. 6-7. These plots show six levels of decomposition of the signal. Each level represents the amplitude of the vibrations signal for a particular frequency sub-band. The components of higher frequency are contained in sub-band d_1 and lower frequency components are extracted in sub-band d_6.

In concordance with the power spectrum of the rotor with rubbing, wavelet coefficients amplitude is higher for sub-bands d1, d2 and d3, that extract the higher frequency components of the signal. Additionally, the wavelet transform provides the temporal information that enables the characterization of the rubbing severity. In this sense, sub-band d2 offers the highest wavelet coefficient values to appreciate the difference between light and severe rubbing.

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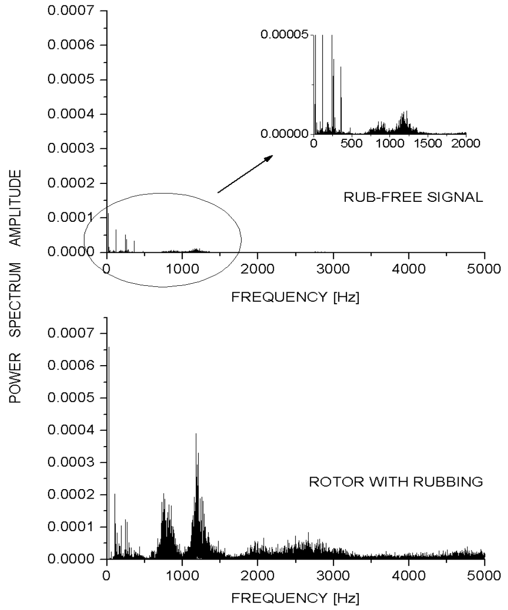

Fig. 5. Signal spectral components of the rotor system.

IV. CONCLUSION

FFT is able to analyze the components of a stationary signal, but fails to detect transient phenomena. The wavelet transform allows the analysis of complex machinery vibrations information that are transient and non-linear in nature. Rotor-rubbing is a particular case of this phenomenon, and has been studied with the discrete wavelet transform. Higher wavelet coefficient values in the first levels of decomposition show that the rubbing signal spectrum is rich in high frequency components. Additionally, the translation property of the wavelet analysis permits the extraction of temporal information, and gives location of transient signals in time. This permitted the extraction and differentiation of light from severe rubbing in the acceleration vibration signal.

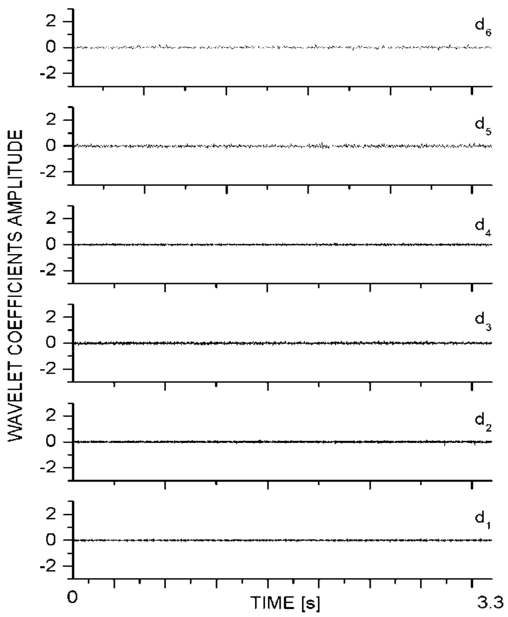

Fig. 6. Wavelet coefficients for 6 sub-band coding of the rub-free vibration signal.

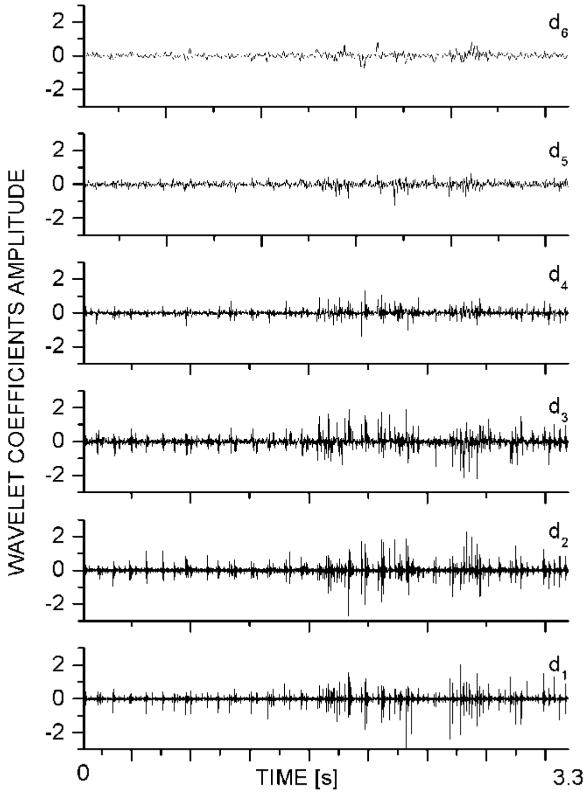

Fig. 7. Wavelet coefficients for 6 sub-band coding for the rotor with rubbing.

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AUTHORS PROFILE

Eduardo Rubio received his Ph.D. and M.S. degrees in Energy from the Universidad Nacional Autónoma de México (UNAM) in 2002 and 1996 respectively, and Engineering degree in Communications and Electronics from the Instituto Politécnico Nacional (IPN) in 1990. Currently, he is a research professor at the Universidad Autónoma de Aguascalientes (UAA). His current interests include basic research in solar thermal systems, and technology research for industry

César Chávez-Olivares received the B.E. degree in Electronics Engineering from the Universidad Autónoma de Aguascalientes in 2006, and the M.Eng. and Ph.D. degrees in Electrical Engineering from the Universidad Autónoma de San Luis Potosí in 2009 and 2014 respectively. He was a CONACyT Research Fellow at Instituto Tecnológico de Aguascalientes from 2014 to 2015. In 2015 he joined the Center of Engineering Sciences at Universidad Autónoma de Aguascalientes, where is currently a Professor and Researcher. His research interests include vision systems, modeling, identification, and control of robot manipulators.

Alejandro Cervantes-Herrera received the B. Eng. degree in Electronics from the Instituto Tecnológico de Aguascalientes, and the M.Sc. and Ph.D. degrees in Sciences from CINVESTAV Guadalajara in years 2008 and 2012 respectively. He has been a researcher professor at the Universidad Autónoma de Aguascalientes since 2014 in the Robotics area. His current research interests include hybrid systems and multi-agent systems control.