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AN ANALYSIS OF THE ROTATING MACHINES TRANSIENT VIBRATION USING THE SHORT TIME FOURIER TRANSFORM

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Abstract. *Identification of faults and structural ressonances in rotating machines is usually carried out using traditional techniques based on the vibration signals spectral analysis. In this case, the vibration signals are measured from machine working with constant rotation. During the start-up from rotating machines are generated transient vibration components which may not be detected by using the Conventional Fourier Analysis. In this sense, the objective of this work is to use time-frequency distributions for the identification of the vibration signals transient features from machines with non-constant speed. It was used the Short Time Fourier Transform (STFT) as a time-frequency distribution, in order to detect the vibration components of rotating machines operating in non-stationary conditions. The vibration signals have been measured from a rotor during its start-up. They have been acquired using the Labview® software and, subsequently, they have been processed and studied in the Matlab® software.*

Keywords: *identification, signal analysis, time-frequency distribution, transient vibration.*

1. INTRODUCTION

The presence of vibrations in rotating machines usually cause undesirable effects, such as, fatigue, noisy operation and a reduction of rotor life (Abreu, 1998). This problem is more significant during the start-up from rotating machine or when it operates close to resonances, named as critical frequencies. Therefore, the identification of the resonances and vibration modes is an important step to be considered in the rotor design. The calculation of Frequency Response Function (FRF) by using Experimental Modal Analysis is one of methods which may be used for the identification of resonances of the rotor (Ewins, 1984). Another approach would be the construction of a finite elements model and the computational simulation of the rotor vibration modes (Abreu, 1998).

A practical method which may also be used to identify the critical frequencies of a rotor is to measure the vibration signals during its start-up (Meng and Qu, 1991; Lee et al., 2001). From a theoretical point of view, the rotor rotation frequency linearly changes with respect to the time until the stationary steady condition. Thus, when the rotation frequency from rotor is close to resonance the amplitude vibration increases. The Fast Fourier Transform (FFT) algorithm is one of most widely used signal analysis tools for the separation of the frequencies components of the rotor vibration signal. However, the main drawback of the FFT algorithm is that it assumes signal frequencies do not change with the time (Cohen, 1995; Lee et al., 2001). In this way, the transient vibration components from rotor are difficult of identifying by using FFT algorithm, particularly, if it operates in non-constant rotation. In this case, it is recommended the use of time-frequency distributions for the detecting the vibration components generated by the resonances and the variation of the frequency with the time during the start-up (Guimarães, 2000; Lee et al., 2001).

It will be used, in this work, the Short Time Fourier Transform (STFT) as a time-frequency representation in order to detect the critical frequencies and the noise generated by the vibration of the rotor during its start-up. After the time domain signal processing by using the STFT, it will be generated a map of the signal energy distribution in both time and frequency domains. Hence, the rotor vibration components will be detected according to pattern features displayed in time-frequency map. In the following, it will be defined the Short Time Fourier Transform and the experimental procedure used in the measurement of the rotor vibration signals. Subsequently, it will be discussed the obtained results, the conclusions and the effectiveness of the STFT as a rotor vibration signal analysis tool.

2. SHORT TIME FOURIER TRANSFORM

2.1. Definition

The idea of the Fourier Transform (FT) is to decompose the time domain signal, x(t), in its frequency components. For this purpose, the FT compares x(t) with harmonics functions in order to extract the phase and amplitude information of the each signal component in the frequency domain. In the FT, the harmonics used as base functions to compare x(t) have a infinite time duration. Therefore, the signal in the frequency domain, X(f) has obtained by the application of FT to the x(t) only indicates which frequencies existed during the total duration of x(t) (Cohen, 1995):

$$X(f) = \int_0^{\infty} x(t) e^{-j2\pi ft} dt \quad (1)$$

where j is a pure imaginary and f represents the frequency in Hz. The frequency energy density or spectrum, $X^2(f)$, does not give no indication of when the frequencies components existed and neither the time duration of signal spectral contents. Hence, if the vibration signal is measured with the rotor by working in changing rotation the spectrum, $X^2(f)$, only will indicate the average frequencies that occur in the time duration of x(t) (Cohen, 1995).

A simple way of identifying when and how the frequencies components from signal are changing with respect to the time is to break up x(t) into small time segments and to apply the FT in each time segment (Cohen, 1995). This concept is used in the definition of the Short Time Fourier Transform (STFT):

$$STFT(t, f) = \int_0^{\infty} x(\tau) h(\tau - t) e^{-j2\pi f\tau} dt \quad (2)$$

where h(τ-t) represents a window function used to break up the signal, x(t), into segments of finite time duration. Thus, when x(τ) is multiplied by h(τ-t), the idea is to observe only a piece of x(t) has limited by the time duration of window h(τ-t). This procedure is applied to each point of discrete signal in the time domain. Subsequently, the FT is applied to each segment of x(τ), x(τ)h(τ-t), by considering that the signal is stationary into the window function.

2.2. Selection of the Window Function and the Time Duration

The choice of the window function time duration, σ_t, is the main problem of the STFT. Theoretically, it is impossible to extract any signal component that has simultaneously, short time duration, σ_t, and a narrowband, σ_f, by using a time-frequency distribution. In the practice, there is always a tradeoff between σ_t e σ_f has defined by the uncertainty principle (Cohen, 1995):

$$\sigma_t \sigma_f \geq \frac{1}{2} \quad (3)$$

that is, the larger is σ_f, the smaller is the σ_t and vice-versa. For example, in the FT, the harmonics functions used to decompose x(t) have infinite time duration. Hence, in the FT, any time information of the signal components is missed since σ_t will tend to the infinite and σ_f will tend to zero according to equation (3). In the STFT, the selection of window time duration, σ_t, depends on the nature of the signal to be studied. In the case of rotor by operating in changeable rotation, the rotation frequency slowly changes with respect to the time during the start-up. Therefore, in this work, it will be chosen a window with long time duration and frequency narrowband. Consequently, the STFT to be applied in the rotor vibration signals will have a long time resolution and a small frequency resolution.

The window function shape, h(τ-t), should also be chosen for the STFT computation. There are many windows to be selected for the extraction of the signal transient components. It will be used, in this work, a Gaussian window in the processing of the STFT since the product between σ_t and σ_f is minimized for this type of window (Wang and McFadden, 1995; Cohen, 1995). Furthermore, the Gaussian window avoids the presence of unwanted ripples in the time-frequency energy distribution.

3. EXPERIMENTAL AND NUMERICAL PROCEDURE

The rotor to be studied in this work is driven by an electrical motor. The rotor vibration signals in the time domain were measured by using an accelerometer placed on the motor case. The Table 1 describes the parameters values used in the acquisition of the rotor vibration data. The accelerometer from 4214 model Bruel & Kjaer manufacturer used in this work has an integrated signal pre-amplifier for increasing the output signal gain. The output signals from accelerometer were connected to the data acquisition board from National Instruments manufacturer. During the processing in the data acquisition board, the signals were filtered using an anti-aliasing filter in order to avoid the presence the frequency components larger than half of acquisition frequency. The Labview® software was used for saving the vibration signals in the time domain in a format of text file. The Figure 1 illustrates the electrical motor case and the rotor foundation used in this study. The rotor has 2 disks placed on the left and right ends

After the acquisition of the signals in the time domain using the instrumentation above described, they have been processed in the time-frequency and frequency domains by using the Matlab® software. The FFT and STFT algorithms have been applied directly to the vibration signals without any previous treatment. The spectrum of rotor vibration has been obtained by the application of the function fft available in the Matlab® software to the signals in the time domain. For the processing of the STFT, it was used the spectrogram function available in the Matlab® software and a Gaussian window has applied to the rotor vibration data in the time domain. In order to decrease the processing time of the STFT, the Spectrograms to be shown in this work have been obtained by the application of the non-overlapping Gaussian window to some points from rotor vibration signals.

Figure 1 – Rotor with 2 disks used in the study of this work.

Table 1 – Parameters values used in the acquisition of the vibration signals measured in the rotor.

Sampling Frequency [Hz]	Number of Points	Acquisition Time [s]	Sensitivity of accelerometer [$m/s^2/mV$]
25000	50000	2	1.05

4. RESULTS AND DISCUSSION

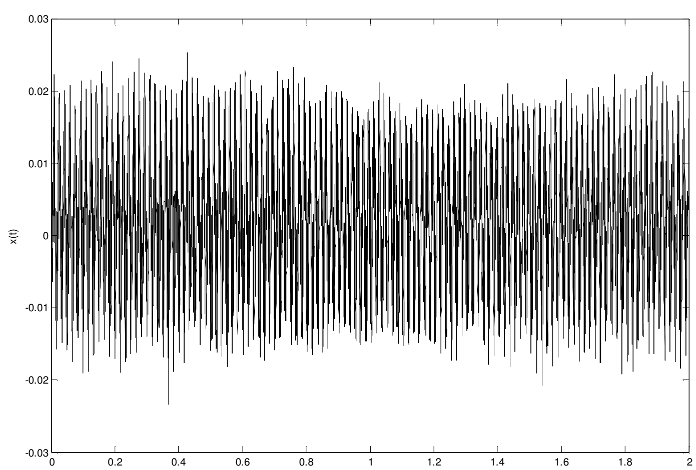

Figure 2 – Vibration signal in the time domain measured in the rotor by operating in stationary steady.

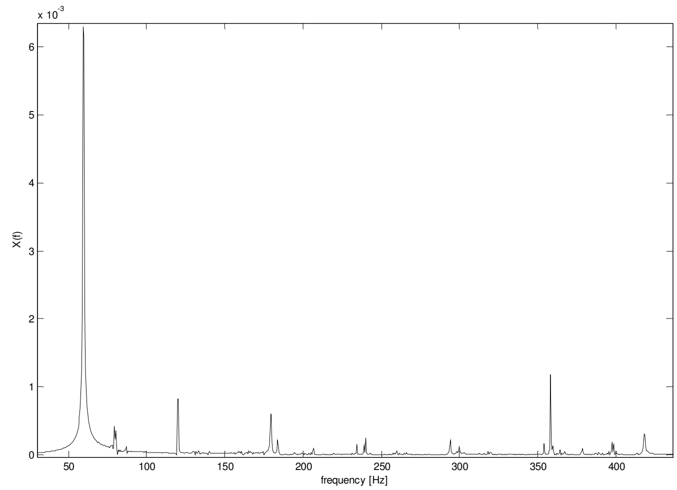

Figure 3 – Vibration Signal in the frequency domain measured in the rotor by operating in stationary steady.

The Figures 2 and 3 illustrate the vibration signals measured in rotor by working in stationary steady. In this case, the rotor rotation frequency is 3540 rpm or 59 Hz. The rotor vibration signal in the time domain was measured with a sampling frequency of 25000 Hz. It is interesting to note that the rotor vibration signal has shown in the Figure 2 has an amplitude modulation. This modulation may have been caused by a misalignment from shaft or by the unbalanced rotor. The frequency spectrum has shown in the Figure 3 has the frequency component of 59 Hz and several harmonics caused by the different modes of rotor vibration. However, it can be seen that the frequency of 59 Hz is the main vibration component caused by the rotor rotation in stationary steady.

The rotor vibration signal measured during the start-up is illustrated in the Figure 4. The increase of the vibration amplitude have shown in the Figure 4 is caused by the increase of centrifuge force due to the rotor acceleration. The vibration signal in the time domain illustrates a transient frequency component between 1.2s and 1.8s approximately. This component was caused by the passing of the rotation frequency around one of the rotor critical speed. The FT of this signal illustrates a frequency component equals to the 17 Hz, which was caused by the rotor foundation vibration, as can be seen in the Figure 5. This natural frequency was also identified by using modal analysis of rotor foundation. Nevertheless, since the vibration is transient, the signal spectrum does not yield a reliable indication of the critical frequency value from rotor.

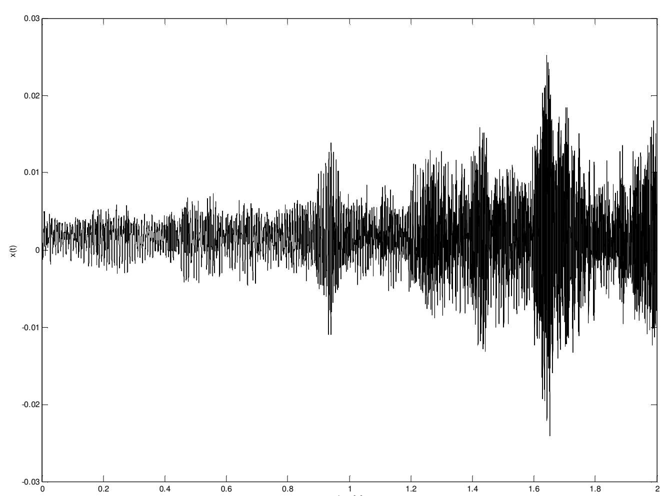

Figure 4 – Rotor vibration signal measured in transient steady.

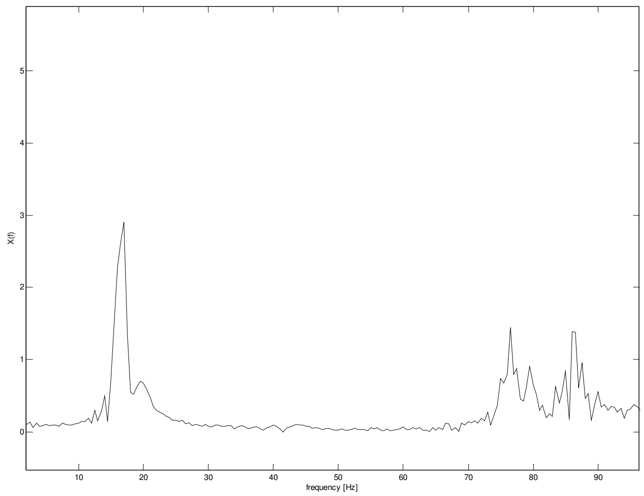

Figure 5 – FT of the rotor vibration signal by operating in transient steady.

The time-frequency energy distribution of rotor transient vibration by using the STFT is shown in the Figure 6. The lines represent the contours of each signal component in the time-frequency domain. For the processing of the STFT, it was used a non-overlapping Gaussian window with 6000 points which corresponds to a time duration, σ_t, equals to the 0.24s, approximately. The choice of this time duration was based on the trial-and error, after some simulations of STFT. By using the STFT, it is possible to observe when the transient vibration components occurred and how these components are changing with the time. For example, it can be seen that one of the signal energy peaks occurs in about 1.65s and 32 Hz. It is believed that this frequency value represents one of the critical frequencies from rotor.

Another interesting analysis which can also be extracted from this diagram is the behaviour of rotor rotation frequency with the time. From the time-frequency map, it is observed that the frequencies of two signal components are changing of a linear approximately manner with respect to the time until the frequency of 59 Hz which is rotor rotation in stationary steady. This linear variation was caused by the rotor rotation acceleration during its start-up. There are still two signal components with constant frequencies along the time. These two frequencies, 10 Hz and 21 Hz probably represent two of the natural frequencies of the electrical motor case.

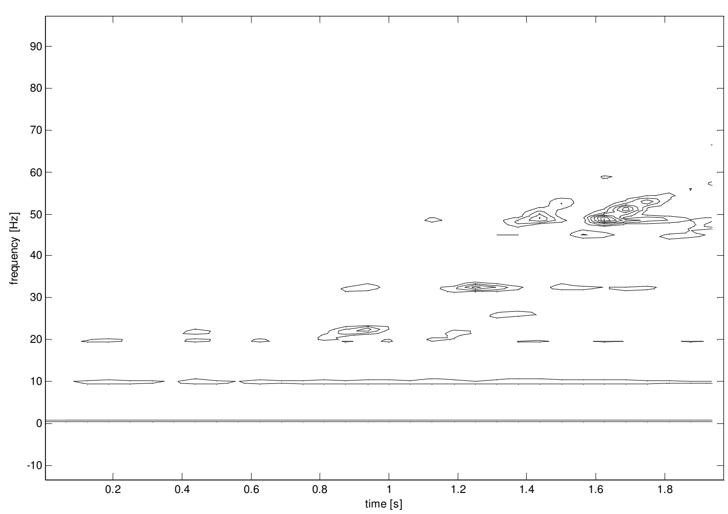

Figure 6 – STFT of rotor vibration during the start-up.

The Figure 7 illustrates the transient vibration from rotor after to turn-off the electrical motor. In this case, the time-frequency map displays a line slightly declined, since the rotor rotation decreases with the time until stopping. After to turn-off the electrical motor, the rotor stopping time is slower than its start-up. Although the vibration signal in the time domain is not illustrated, it can be seen that in about 0.05s and 32 Hz, the amplitude of time-frequency energy distribution is maximum. Therefore, it is expected that the frequency component of 32 Hz represents one of the rotor critical frequencies, since it occurred in the forward and backward analysis of the rotor.

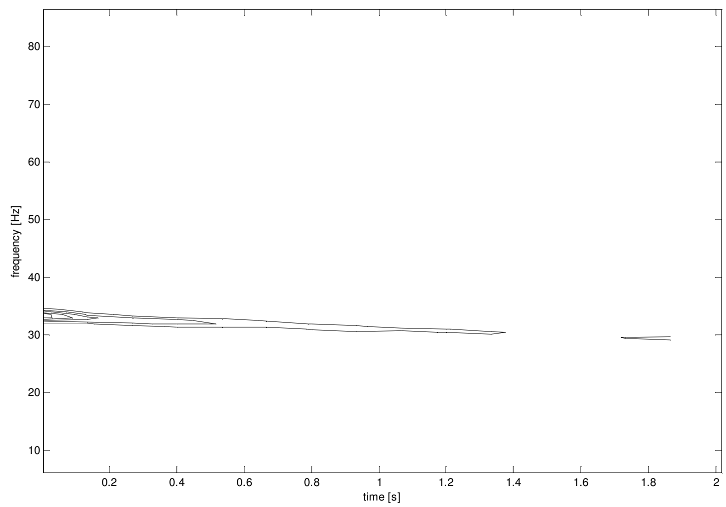

Figure 7 – STFT of vibration signal measured after to turn off the motor.

5. CONCLUSIONS

In this work, it was studied the transient behaviour caused by the vibration of a rotor during its start-up and stopping using the STFT. The time-frequency maps provided by the STFT shown the vibration signal energy has maximum value in the frequency of 32 Hz in the forward and backward analysis from rotor. This frequency component of 32 Hz should be one of the rotor critical rotation frequencies. However, the procedure used in this work is not totally reliable since the rotor vibration signals used in this work may be masked by the motor case vibration and by the foundation vibration. Hence, it is necessary the use of others modal analysis methodologies in order to validate the rotor critical frequency value has obtained in this work. By using the time-frequency map, it was also possible to identify the linear variation of rotor rotation frequency with the time. The slow variation of the rotation frequency was identified during the rotor stopping.

Since the rotor has a small acceleration in the start-up and after to turn-off the electrical motor, it was necessary to select a window function with long time duration in order to produce a time-frequency distribution with a small frequency resolution. The choice of time duration from window function used in the STFT was based in trial and error. In the future, it will be used others time-frequency distributions, such as the Wigner Distribution and the Continuous Wavelet Transform in order to extract the transient features of the rotor vibration signal.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Abreu, G. L. C. M., **Controle Ativo de Vibrações Laterais em Rotores Flexíveis Usando Atuadores Magnéticos**. Dissertação de Mestrado, Universidade Federal de Uberlândia, Uberlândia, Brasil, 1998.

Ewins, D. J., **Modal Testing: Theory and Practice**. Ed. Academic Press, 1984.

Meng, Q., Qu, L., **Rotating Machinery Fault Diagnosis Using the Wigner Distribution,** Mechanical Systems and Signal Processing, Vol. 3, pp. 155 – 166, 1991.

Lee, S. U., Robb, D., Besant, C., **The Directional Choi-Williams Distribution for the Analysis of Rotor-Vibration Signals**, Mechanical Systems and Signal Processing, Vol. 15(4), pp. 789 – 811, 2001.

Cohen, L., **Time-Frequency Analysis**. Ed. Englewood Cliffs, Prentice-Hall, 1995.

Guimarães, T. A., **Análise Tempo-Frequência de Sinais de Vibração Aplicada à Detecção de Falhas em Caixas de Câmbio**, 95 p., Dissertação de mestrado, Universidade Federal de Uberlândia, Uberlândia, Brasil, 2000.

Wang, W. J., McFadden, P. D., **Early Detection of Gear Failure by Vibration Analysis – I. Calculation of the Time-Frequency Distribution**, Mechanical Systems and Signal Processing, Vol. 7, pp.193 – 203, 1993.

8. RESPONSIBILITY NOTICE

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