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DETECTION AND ANALYSIS OF THE VIBRATION SIGNALS PRODUCED BY THE CAVITATION IN CENTRIFUGAL PUMPS

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Abstract. *The cavitation phenomena cause noise, vibration and instability in centrifugal pumps. Furthermore, the cavitation usually generates wear and material erosion of the rotor blades which decreases the hydraulic performance and the pump life. In this work, it will be studied the vibration components produced by the centrifugal pumps cavitation using the signal processing and statistical analysis. In order to detect the vibration components caused by the cavitation phenomena, it was applied the Fourier Transform and Continuous Wavelet Transform to the vibration signals in the time domain experimentally measured in the centrifugal pump. By using the signal analysis in the frequency and time-scale domain, it was possible to identify and analyze some features of the vibration caused by the pump cavitation.*

Keywords: *cavitation, centrifugal pumps, vibration signals, time-frequency analysis*

1. INTRODUCTION

Cavitation phenomena in centrifugal pumps generate instability and decrease their hydraulic performance. The cavitation also causes others undesired effects in centrifugal pumps, such as, pitting, material erosion of the rotor blades, vibration and noise (Cudina, 2003; Sakthivel, 2010). During the cavitation process, the fluid starts to flash and vaporization occurs. In this way, the pump walls and the rotor blades are bombarded by the bubbles due to the vaporization. This process of the bombardment of the bubbles on the pump components produces random vibrations with frequencies to be determined in the spectrum of measured signals. Hence, the application of the signal analysis techniques in the diagnosis of cavitation in pumps is an important tool to be used in the correction of their ideal operation range.

In the condition monitoring of the pumps, it is usually used vibration signals or acoustic signals in order to detect the cavitation phenomena. For example, Cudina (2003) used acoustic signals to identify the beginning of cavitation of centrifugal pumps of a nuclear power plant. By using the spectral analysis, Cudina (2003) has applied the Fourier Transform to the vibration signals measured in the centrifugal pumps with microphones to detect the frequency tone produced by the cavitation. Sakthivel et al. (2010) have developed a pump faults classification system using the measured vibration signals with accelerometers and the logic fuzzy for the automatic identification of the cavitation, bearing fault, seal and impeller faults. In this system, the classification fuzzy rules and membership functions were created using the statistical parameters extracted from vibration signals.

In this work, it will be studied the transient vibration signals caused by the cavitation in centrifugal pumps of the water treatment plant using Wavelet Transform technique. The main objective is to purpose a methodology and a signal processing tool in order to detect the random patterns produced by the cavitation phenomena in centrifugal pumps. After measuring of the centrifugal pump vibration without and with cavitation, the signals in the time domain will be processed to the time-scale domain using the Continuous Wavelet Transform (CWT). Subsequently, the random vibration energy density will be obtained using the statistical parameters, such as, mean and standard deviation (Cohen, 1995). By using this methodology, it is possible to separate the vibration signals components caused by the cavitation from the noise spectra and to detect the presence of this undesired vibration source in centrifugal pumps.

2. CAVITATION IN CENTRIFUGAL PUMPS

2.1 Description of the phenomena

A centrifugal pump is a hydraulic machine that transforms work from drive motor into the mechanical energy of the flowing liquid. The main components of a centrifugal pump are the rotor shaft, the blades, the pump wall and the bearings. In hydraulic systems, cavitation naturally occurs due to the acceleration of the fluid caused by the transformation of the rotor blades work in fluid kinetic energy. According to the mechanic energy conservation principle, when the liquid is accelerated its pressure diminished. Since the absolute static pressure of fluid is lower the saturated vapour pressure in some points of the flow, at the prevailing temperature conditions, the fluid starts to flash and vaporization occurs (Cudina, 2003). Because of this, bubbles are caught up by the flowing liquid which causes the collapse of these on the rotor blades and on the centrifugal pump wall. Usually, the collapse time of the bubbles implosion is very small (approximately 0,003 s) which increases the bubbles impact pressure on the centrifugal pump components.

Figure 1. Damage of the centrifugal pump rotor caused by the cavitation.

In practice, the cavitation could be interpreted as the bombardment of the bubbles on the rotor blades and centrifugal pump walls. Figure 1 illustrates an example of the damages caused by the cavitation phenomena in rotor blades of a centrifugal pump. Since the bombardment frequency of the bubbles and its intensity (amplitude) is not defined, it is difficult to predict analytically the features of the vibration signals produced by the cavitation in centrifugal pumps.

2.2 Characteristics of the vibration signals measured in centrifugal pumps

In a general way, each pump component generates a vibration signal component with a determined frequency. For example, the vibration frequency of the rotor shaft is the rotation frequency of the centrifugal pump working. The vibration signals components produced by the rotor blades have a frequency which is obtained by multiplying the number of blades by the rotational frequency of the rotor shaft. On the other hand, the vibration caused by the rolling bearings from rotor is similar to the vibration of a single-degree-of-freedom mechanical system which excites the high frequencies range of the spectra. All these vibration components abovementioned are deterministic and could be easily detected by analyzing the frequency spectrum of the measured signals in the centrifugal pumps (Sakthivel et al, 2010).

Identification of the vibration frequencies caused by the cavitation in centrifugal pumps is more difficult by using the signal frequency spectrum. For the cavitation, the frequency of the bombardment of the bubbles on the rotor blades which has the character water hammer blows could be not determined analytically (Cudina, 2003). Thus, it is easier to detect the frequency range of vibration produced by the cavitation due to the random nature of these signals. For the velocity signals, the frequency range of the cavitation vibration is placed on low frequency range of the spectrum. In the case of the acceleration signals, the cavitation excites the high frequencies range of the measured vibration signals. In this work, it will be used the Continuous Wavelet Transform and statistical techniques in order to extract the energy density of these random vibration components.

3. TOOLS FOR THE VIBRATION SIGNALS ANALYSIS MEASURED IN THE CENTRIFUGAL PUMP

3.1 Continuous Wavelet Transform

The Fourier Transform (TF) and the Continuous Wavelet Transform (CWT) could be defined using the correlation concept of the signal. In the traditional spectral analysis, the vibration signal in the time domain is compared with harmonic functions. In this way, by using the Fourier Transform (TF), the vibration signal could be decomposed in the individual frequency components. Although the FT is a powerful tool in the signal processing context, its main disadvantage is that the transient vibration signals caused by the cavitation in pumps could not be easily extracted by the conventional spectral analysis. Since that the window in the time domain used in the FT has infinity duration, it is not possible to extract neither when the transient component has occurred and nor its duration in the time-frequency plane (Cohen, 1995). In this case, appropriate techniques of the non-stationary signal analysis should be used for this purpose.

In the CWT, a correlation between the vibration signal, x(τ) and functions previously chosen by the signal analyst, known as mother wavelet, is computed during its processing In this work, it will be applied the Continuous Wavelet Transform (CWT) to the vibration signals measured in the centrifugal pumps with and without cavitation. The main advantage of the CWT when compared the Short Time Fourier Transform (STFT) is the multiresolution analysis used in the decomposition of the vibration signal. For the vibration components with high frequency is used a mother wavelet with short duration; otherwise, for the signal components with low frequency, the mother wavelet used in the analysis has long time duration. The CWT to be used in this work is defined by (Heneghan et al., 1994):

$$CWT(t,a) = \frac{1}{\sqrt{|a|}} \int_{0}^{\infty} x(\tau)\psi^*(t-\tau)d\tau \tag{1}$$

where ψ is the mother wavelet which is compared with signal in the time domain, $x(t)$, a is a scale factor used in the dilation of $\psi(t)$ and τ is the delay time used in the convolution integral from CWT. In practice, there exist different types of mother wavelet that can be used in the correlation with $x(t)$. In this work, it will be used the Morlet Wavelet for the extraction of the features of transient vibration produced by cavitation in centrifugal pumps. Indeed, the Morlet Wavelet is a amplitude modulated harmonic function with a Gaussian envelope. For the Morlet Wavelet, the central frequency of the band of $\psi(t)$ can be easily associated with the scale factor used in its dilation.

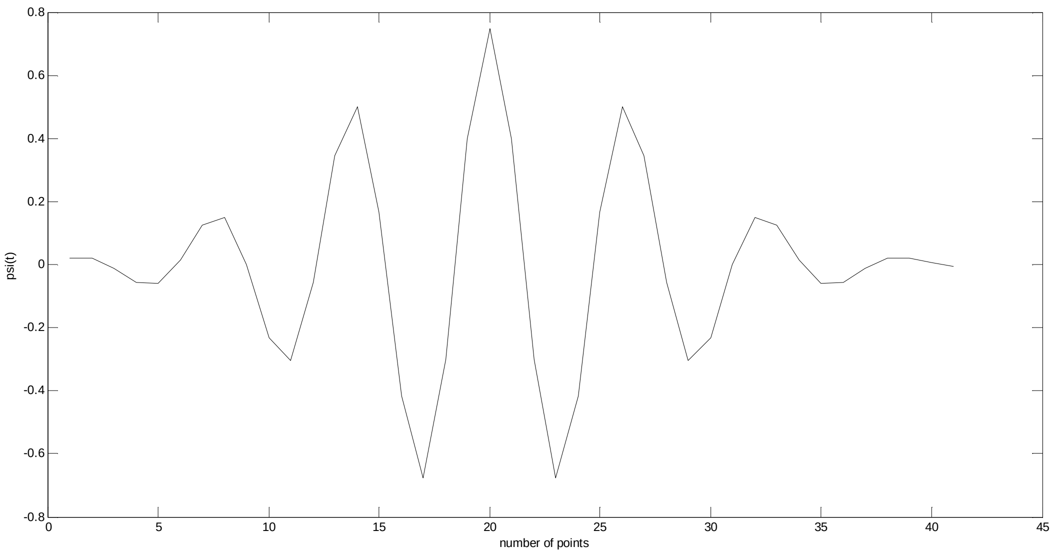

Figure 2. Morlet wavelet to be used in the analysis of the vibration signals measured in the centrifugal pump.

Figure 2 shows the Morlet wavelet used in the CWT of the vibration signals to be measured in the centrifugal pumps. The relation between the scale and frequency, f, of Morlet wavelet family correlated with the vibration signals is described by Eq. (2) (Heneghan et al., 1994):

$$a = V \log_2 \left(\frac{k_\psi}{f} \right) \tag{2}$$

where the parameter V represents the scale division in octaves and the k_ψ a constant to be determined. In this work, this equation will be used in order to estimate the frequencies of the transient vibration components due to the pump cavitation. By using Eq. (2), it can be seen that the larger is the scale factor, the lower is the frequency of the components of signal, that is, the larger is the dilation of the mother wavelet.

3.2 Estimation of the Duration of the Transient Vibration Components Caused by the Pump Cavitation

The duration of the transient components of the vibration signal measured in the centrifugal pump can be estimated by using the standard deviation concept in the time domain. A simple way of calculation this parameter is to use the energy density of the signal per unit time or instantaneous power, $|x(t)|^2$. However, as the average process is applied to the vibration in the time domain, this parameter represents only the global mean duration of the whole signal. By using this concept, the global mean time and global mean duration of the signal are defined respectively by (Cohen, 1995):

$$< t >= \frac{1}{|x(t)|^2} \int t |x(t)|^2 \, dt \tag{3}$$

$$\sigma_t^2 = \frac{1}{|x(t)|^2} \int \left(t - \langle t \rangle\right)^2 |x(t)|^2 \, dt \tag{4}$$

Unfortunately, the mean duration of the transient vibration components caused by the cavitation could not be estimated using the Eq. (4). Since the standard deviation has defined in the Eq. (4) is the global spread of signal in the time domain, this parameter would could not represent the duration of the vibration components due the cavitation. Nevertheless, it is possible to extract several parameters to be used in the study of the pump cavitation, as for example, the average duration of the transient vibration components or the frequency band excited by these components by using the CWT given in the Eq. (1) (Cohen, 1995; Loughlin et al., 2000). These quantities are known as local averages (Cohen, 1995). In this work, it will be estimated the conditional mean duration, $\sigma^2_{t|\omega}$, of the transient vibration components caused by the cavitation according to the equation (3) (Cohen, 1995):

$$\sigma_{t|\omega}^2 = \frac{1}{P(\omega)} \int \left(t - \langle t \rangle_\omega\right)^2 P(t,\omega) dt \tag{3}$$

such that P(ω) represents the signal magnitude in the frequency domain, ω, and P(t,ω) is the joint time-frequency probability density function. The parameter <t> is the conditional average time of the transient components given by (Cohen, 1995)

$$< t >_\omega = \frac{1}{P(\omega)} \int t P(t,\omega) dt \tag{4}$$

that is, the local mean time of the vibration signal calculated for the selected frequency, ω. In this work, the joint time-frequency probability density function to be used in the calculation of the mean duration of the transient components will be the CWT has defined by the Eq. (1). This parameter may be correlated to the vibration caused by the collapse time of the bubbles generated by the cavitation.

4. MEASURING AND PROCESSING OF THE VIBRATION SIGNALS

Figure 3. Image of the centrifugal pump case used in the analysis of the cavitation.

For the measuring of vibration data, it was used 3 (three) accelerometers have mounted on the cube faces with $1cm^3$ of volume. Hence, these 3 accelerometers measured the acceleration vibration signals simultaneously in axes x, y and z. Figure 3 illustrates the centrifugal pump used for the measuring and analysis of vibration signals with and without cavitation. During the measuring, the 3 three accelerometers were placed on the pump case as close as possible from the rolling bearings. In order to study the sensitivity of the vibration signals to the pump cavitation, for each measuring, the 3 accelerometers were positioned in each axes, x, y and z.

The vibration signals were measured by using 3 model accelerometers from PCI manufacturer. Table 1 describes the parameters values used for measuring the vibration data in the time domain. It is not necessary to use a signal conditioning unit since this accelerometer has an integrated signal pre-amplifier for increasing the output signal gain. The signals measured from centrifugal pump without and with cavitation were directly connected to a data acquisition board from National Instruments manufacturer. Subsequently, the software Matlab® 2009 with a toolbox integrated to the software Labview® was used to save the data file in a txt format.

Table 1. Parameters values used in the acquisition of vibration signals by considering the pump with and without cavitation.

Sampling Frequency	**Number of Points**	**Acquisition Time**	**Sensitivity of Accelerometer**
25600Hz	100000	3.9 s	$1.05mV/m/s^2$

After the vibration data aquisition, the signals in the time domain were processed to the frequency domain by using the FFT (Fast Fourier Transform) algorithm available in the Matlab® R2009 software. This spectral analysis was necessary in order to identify which is high frequency range of the stochastic vibration componentes produced by the pump cavitation. Subsequently, the time-scale matrix provided by the CWT was obtained by using the Eq. (1). This matrix was transformed in a vector by using the rms value given by Eq. (3). Equations (1) and (2) were implemented to analyse the vibration signals via Matlab® R2009 software.

5. ANALYSIS OF THE RESULTS

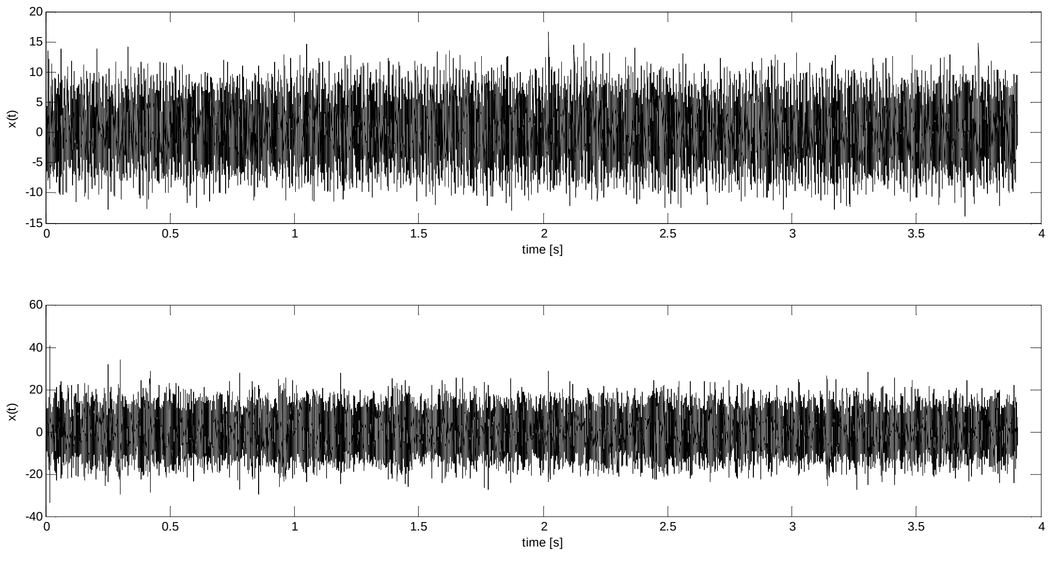

Figure 4. Vibration signals in the time domain measured in the centrifugal pump without and with cavitation.

The figure 4 illustrates the vibration signals in the time domain measured in the centrifugal pump with and without cavitation. The acquisition parameters used in the measuring of the signals are described in the Tab. 1. The signal in the time domain shown in the upper figure represents the pump vibration with cavitation and the vibration has illustrated in the bottom figure is the condition without cavitation. It is interesting to note that the amplitude vibration of the signal measured in the pump with cavitation is larger than the amplitude vibration of pump without cavitation. For the pump without defects, the average amplitude is about 8 mV. Otherwise, the amplitude of the vibration signal with cavitation is approximately 15 mV. Both signals illustrated in the Fig. 1 were measured with the accelerometer has positioned in the z axle.

The frequency spectrum of the vibration signals measured in the centrifugal pump with and without cavitation is shown in the Fig. 5. For the pump by operating in normal conditions, the amplitude of the vibration signal in the frequency domain is small when compared to the spectra of the pump vibration with cavitation. In the case of the vibration signal measured in the centrifugal pump with cavitation, it can be seen the presence of the several components in the band of the frequency of about 1800 Hz to 3500 Hz. Because the vibration signal measured in the pump is acceleration, it was expected that the presence of these vibration components in band of high frequency caused by the cavitation phenomena. In the range of low and medium frequencies, it can be observed the signal components in the frequencies of 78 Hz, 156 Hz, 234 Hz, etc. The signal amplitude in the frequency of 78 Hz (4860 rpm) is produced by the vibration of pump by working in the rotation frequency. The harmonic frequency of 1232 Hz has observed in the both frequency spectrum (without and with cavitation) was probably generated by the rotation frequency of pump multiplied by the number of blades from rotor.

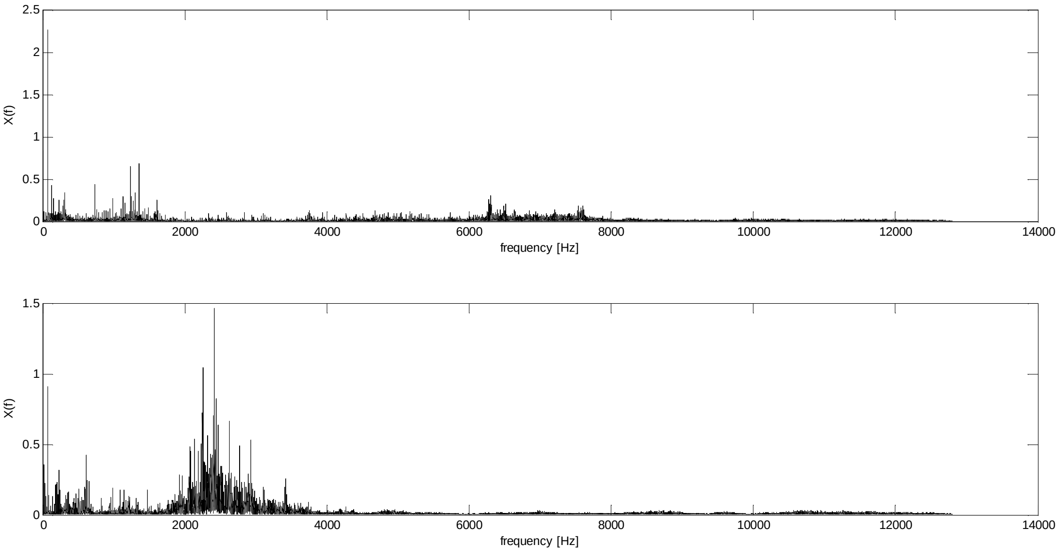

Figure 5. Vibration signals in the frequency domain measured in the centrifugal pump without and with cavitation.

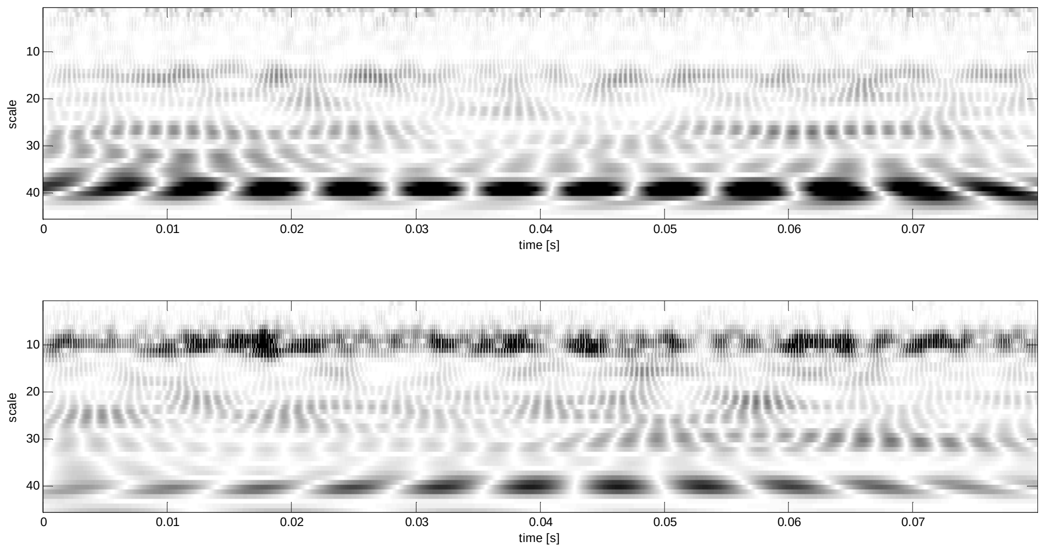

Figure 6. CWT of the vibration signals measured in the centrifugal pumps without and with cavitation.

After the signal analysis in the frequency domain, the vibration signals measured in the pump were processed for the wavelet domain, as can be seen in Fig. 6. For the vibration processing using the Continuous Wavelet Transform has defined in the equation (1), it was considered 2048 samples of the signal in the time domain. In the case of the pump without cavitation, the vibration signal in the wavelet domain (scalogram) displays a constant signal component in the scale of 40 (75 Hz). Furthermore, it can be also seen several components of the vibration in the range of scales of 12 to 17 (region of low frequencies). These components were generated by the pump vibration in its rotation frequency. The scalogram of the vibration signal measured in the pump with cavitation has a constant component in the scale of 7 to 12 (high frequency). This vibration component was produced by the pump by operating with cavitation. Actually, there is several transient vibration components in the scale of as illustrated in the Fig. 6.These transient components with short duration were produced by the vibration of high frequency due to the cavitation.

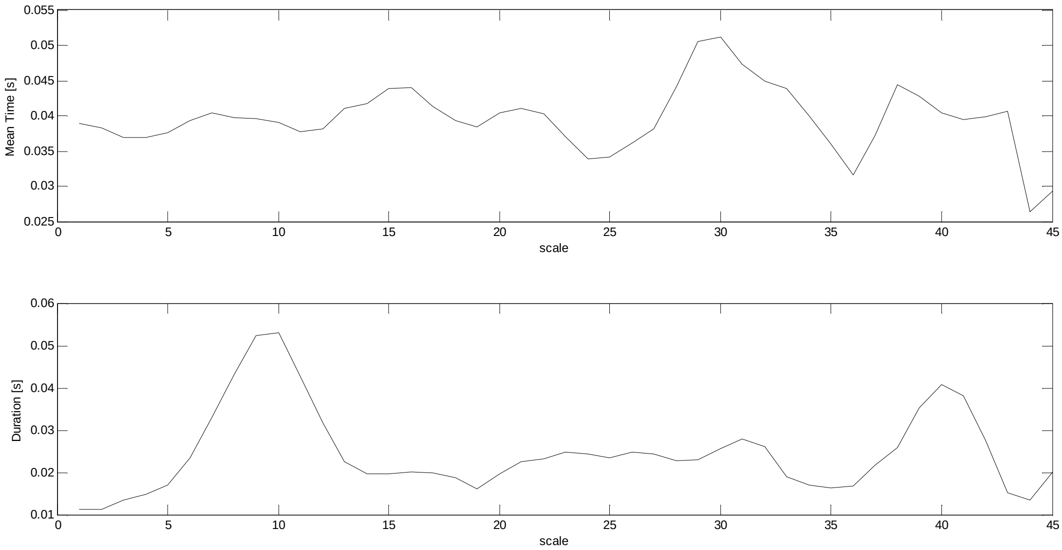

Figure 7. CWT of the vibration signals measured in the centrifugal pumps without and with cavitation.

The figure 7 illustrates the conditional mean time and the conditional standard deviation of the vibration signal measured in the centrifugal pump. It is interesting to note that in the scale of 10, the mean duration of the signal is approximately 0.055s. This value can represent the mean duration of the vibration transient components caused by the cavitation, since these components are concentrated in this scale in scalogram shown in the Fig. 6. In fact, by observing the CWT in the Fig. 6, it can be seen that in the duration of the signal components in this scale is about 0.055. In the scale of 40 (region of low frequency) the local duration of this component is about 0.045 s. The periodicity of this vibration component can be caused by the amplitude modulation phenomena due to the rotation frequency of the pump rotor. From a machinery monitoring point of view, these results can help to detect and monitoring the cavitation phenomena in centrifugal pumps.

6. CONCLUSIONS

In this work, it was used the spectral and wavelet analysis applied to the vibration signals measured in centrifugal pumps in order to detect the cavitation phenomena. First of all, the vibration signals were measured on the pump case by using the accelerometers. In the next step, the vibration signals in the time domain were processed for the frequency and wavelet domains, by using the Fast Fourier Transform and the Continuous Wavelet Transform. The spectral analysis was used in order to detect the frequency band of the vibration signals components produced by the cavitation. On the other hand, the Continuous Wavelet Transform was applied to the vibration data to extract the features of the signal transient components generated by the pump cavitation.

Subsequently, the CWT was used as a joint time-scale probability density function in order to estimate the local mean time and local duration of the transient vibration components caused by the cavitation. These values of these parameters were compared with the transient vibration data have shown in the Scalogram or time-scale map of the CWT. In this context, these parameters could indicate the presence of faults in centrifugal pumps, such as, the cavitation and defects in the shaft of the rotor blades.

7. ACKNOWLEDGEMENTS

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