ANALYSIS OF ROTOR DYNAMICS DEFECTS USING VIBRATION BASED MONITORING

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Abstract. *The monitoring of industrial processes and equipments is an essential part of maintenance, being directly related to more competitive manufacturing. Vibration based monitoring is a non-destructive sensing for the purpose of detecting changes, which may indicate faults related to damage or degradation. The detection methodology is based on pattern recognition applied either to time domain or to frequency domain. The vibration signature of equipment can provide a variety of information on many components and structures such as gear meshing frequencies, bearings, structural resonances, and even electrical faults. This contribution analyzes signals of a rotor dynamics experimental apparatus, simulating four situations: 1 – New machine; 2 – New machine, unbalanced; 3 – Middle age machine; 4 – Machine with severe problem. Basically, each of these conditions are characterized by an unbalanced mass and also different gaps on ball bearing. Vibration based monitoring is applied to these situations, establishing proper signatures in frequency and time domain. Moreover, Lyapunov exponents are employed in order to evaluate chaotic characteristics of the signals. Results show evidences of the increase of complexity in signals of machines with problems.*

Keywords*: Vibration, Rotor dynamics, Nonlinear dynamics, Monitoring, Lyapunov exponents,Chaos.*

1. Introduction

Maintenance is associated with several researches dedicated to cost reductions in different kinds of industries. There are different maintenance managements that depend on the types of equipments and also their importance on some industrial process. The monitoring of industrial processes and equipments is an essential part of maintenance, being directly related to more competitive manufacturing. Effective monitoring can support cost reduction and efficiency improvement strategies (Bansal *et al.*, 2004).

There are different variables that can be monitored being related to thermal characteristics or dimensional properties. However, vibration based technology has been largely employed in different situations. In general, vibration based monitoring is a non-destructive sensing for the purpose of detecting changes, which may indicate faults related to damage or degradation. The detection methodology is based on pattern recognition applied either to time domain or to frequency domain. The vibration signature of equipment can provide a variety of information on many components and structures such as gear meshing frequencies, bearings, structural resonances, and even electrical faults.

The frequency domain analysis is more attractive because it can give more detailed information about the status of the machine. Nevertheless, the time domain analysis can give qualitative information about the equipment condition and, the vibration amplitude can give an indication of the severity of the problem.

Vibration based technology has been largely employed in the monitoring of rotating machinery. In this particular field, faults can be categorized as mechanical or electrical types. Rolling element bearings are widely used in industry and many problems associated with machineries are due to bearing failures. Therefore, the improvement of rotor machines performance passes to the evaluation of bearing status. Detection systems can reduce maintenance costs, avoid catastrophic failures and increase machine availability.

Literature reports researches in order to perform monitoring and fault identification in different engineering problems. Carden & Fanning (2004) present a review on vibration based monitoring giving special attention on structural engineering applications. Wiedenbrug *et al.* (2002) treats the monitoring of induction motors, discussing their signatures for different operational situations. Dron *et al.* (2001, 1998) employs autoregressive spectrum analysis methods for setting up a conditional maintenance program via vibration analysis on ball bearings. Kazzaz & Singh (2003) treats different signal process techniques for monitoring an electrical machine.

Modern techniques are growing in the field of vibration based monitoring. As examples, one could mention the use of fuzzy logic (Liu *et al.*, 1996) and wavelet transform (Singh & Ahamed, 2004). Pend & Kessissoglou (2003) discuss fault diagnosis of machinery comparing vibration signature with particle analysis. The use of nonlinear tools, usually applied to nonlinear dynamics analysis, seems to be interesting, since chaotic behavior is identified in different situations (Mevel & Guyader, 1993; Tiwari *et al.*, 2000)

This contribution analyzes signals of a rotor dynamics experimental apparatus, simulating four situations: *1 – New machine*; *2 – New machine, unbalanced*; *3 – Middle age machine*; *4 – Machine with severe problem*. Basically, each of these conditions is characterized by unbalanced mass and also different gaps on ball bearings. Vibration based monitoring is applied to these situations, establishing proper signatures in frequency and time domain. Moreover, in order to use nonlinear tools to identify signature characteristics, Lyapunov exponents are employed to evaluate the presence of chaos in the signals.

2. Experimental apparatus

This contribution focus on the experimental apparatus that represents a horizontal Jeffcott rotor supported on ball bearings NSK 608Z. The rotor system is excited by an electric motor WEG NBR 7094, 220V (0.25kW, 3390rpm, 60Hz). Figure 1 shows apparatus photographs. Basically, the set up has the following geometrical characteristics related to the axis: length (L = 54 x 10^{-3} m), major diameter (D = 12mm), minor diameter (D_1= 8mm). Moreover, the disk has the following characteristics: internal radius (R_1 = 6mm), external radius (R_2 = 55mm), width (h = 15mm).

The apparatus is instrumented with the aid of displacement sensor BAW 018-PF-1K-03 BALLUFF. Moreover, accelerometers SN 353M197 ICP are positioned on the ball bearing in order to take measurements in the vertical and horizontal directions. Signals are analyzed with the aid of dynamic signal analyzer HP 35665A and also an oscilloscope HP 54603B.

Figure 1. Experimental apparatus.

In order to analyze some typical signatures related to rotor dynamics system, four different situations are treated:

Situation 1 – New machine: New ball bearings are considered and the system is previously balanced.
Situation 2 – New machine, unbalanced: New ball bearings are considered, however an unbalanced mass of 5,63g is positioned to a distance of 48mm;
Situation 3 – Middle age machine: This situation introduces a typical defect related to ball bearing gap. Ball bearings with 0.076 mm gap and unbalanced mass are considered.
Situation 4 – Machine with severe problem: Now, one tries to introduce severe defects related to great ball bearing gap. Ball bearings with 0.3 mm gap and unbalanced mass are considered.

Natural frequencies of the rotor system are experimentally analyzed taking the measurement of accelerometer positioned in the rotor system disk. The excitation is provided by an impact hammer. An FFT analysis presents peaks at 46 Hz, 300 Hz and 700 Hz. These peaks are related to the natural frequencies of the rotor system.

Other characteristic frequencies can be evaluated by analytical argue (Eisenmmam & Eisenmmam Jr, 1997). In general, it is important to highlight the following frequency values: outer ring raceway - 120 Hz, inner ring raceway - 194 Hz, ball defect - 91 Hz, cage - 17 Hz, rolling elements - 833 Hz.

The rotor system is analyzed in rotor angular speed 2700rpm (45Hz), which is close to a natural frequency of the system. Signals signatures are analyzed considering time and frequency domain analysis and also nonlinear tools, where Lyapunov exponents are used with this aim. Although the system probably has spatiotemporal characteristics, the algorithm due to Kantz (1994) is employed to estimate the maximum Lyapunov exponent. The state space reconstruction is used in order to construct a vector time series from a scalar signal, measured from the experimental set up. The basic idea of the state space reconstruction is that a signal contains information about unobserved state variables that can be used to predict the present state. The reconstructed space is equivalent to the original dynamics from a topological point of view. Here, the method of delay coordinates is employed to perform state space reconstruction. The mutual information method is employed to estimate the time delay, τ, while the determination of embedding dimension, D_e, is done with the aid of the false nearest neighbors method (Franca & Savi, 2001).

3. New Machine

A new machine situation is now analyzed. At first, time domain analysis is considered. Figure 2 shows the time history of electric signal obtained in vertical and horizontal directions with displacement sensors. Notice that vertical direction has greater amplitudes. The beating aspect of the vertical signal is a high frequency (892Hz) modulated with a low frequency (83Hz). Figure 3 shows a close orbit, typical of periodic motions.

Frequency domain analysis is performed for the accelerometer signals. With this aim, FFT is considered for the vertical and horizontal signals (Figure 4). Notice that resonance conditions influences the response since one has great amplitude near the natural frequency. Moreover, it is noticeable other characteristic system frequencies as 300Hz (system frequency) and 890 Hz (rolling elements frequency).

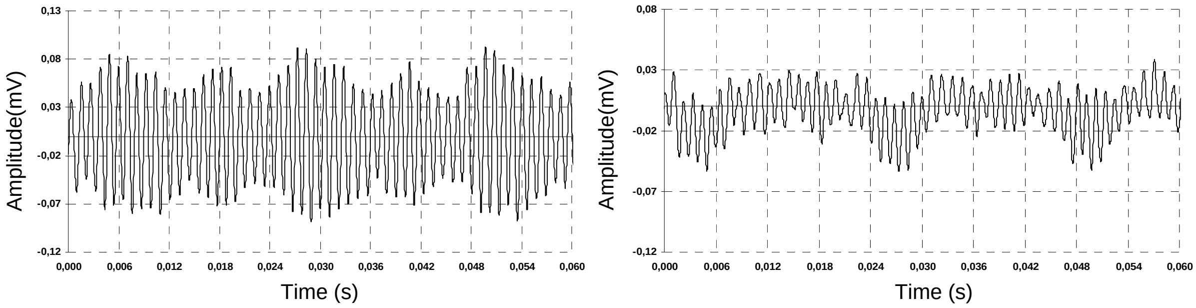

Figure 2. Time history, vertical and horizontal directions.

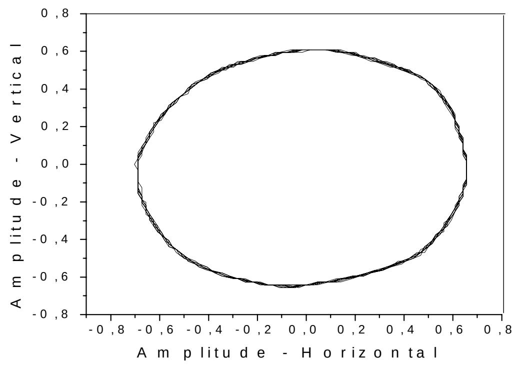

Figure 3. Orbit.

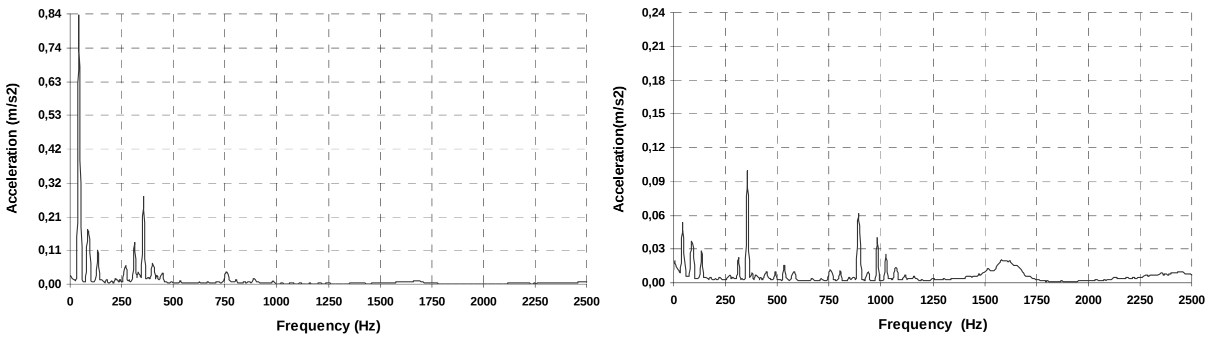

Figure 4. FFT, vertical and horizontal directions.

At this point, Lyapunov exponents are employed in order to obtain more details about the signal signature. Figure 5 shows the determination of delay parameters and also the maximum Lyapunov exponent. From the two first pictures it is possible to conclude that delay parameter is $\tau = 10\Delta t$ and the embedding dimension is $D_e = 3$. These values are used in the estimation of Lyapunov exponents. Although this is difficult to obtain conclusions from experimental data, it should be pointed out the horizontal characteristic of the curve, which is associated with a null exponent, related to a periodic motion.

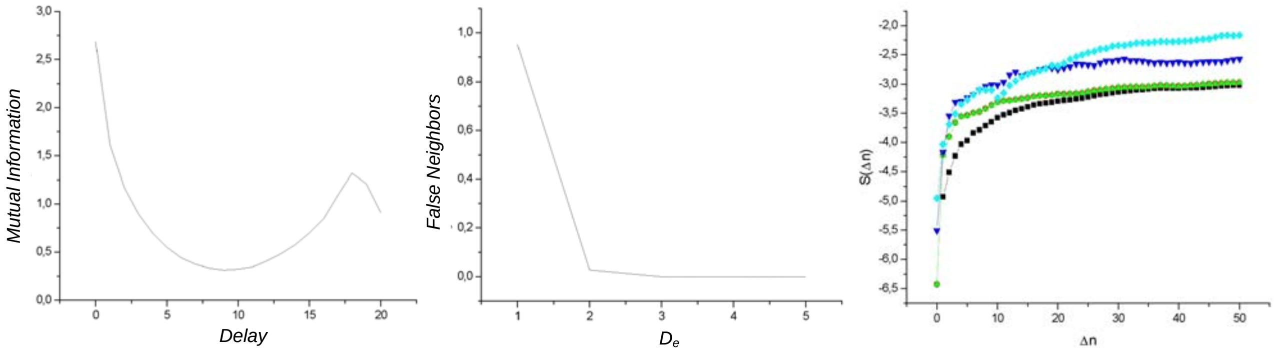

Figure 5. Evaluation of delay parameters and Lyapunov exponent.

4. New Machine with Unbalanced Mass

At this point, it is analyzed a situation which simulates a new machine with unbalanced mass. Time domain analysis shows a change on the time series form due to different harmonics (Figure 6). The orbit remains presenting a closed curve (Figure 7). Frequency domain analysis (Figure 8) shows a great increase in amplitudes when compared to situation 1, balanced system. Notice that amplitudes pass from 0.84 m/s^2 to 2.1 m/s^2. Besides, it is clear that vertical direction is more influenced than horizontal one. It should be pointed out that unbalanced mass has greater influence in the rotation frequency and also in the two first harmonics.

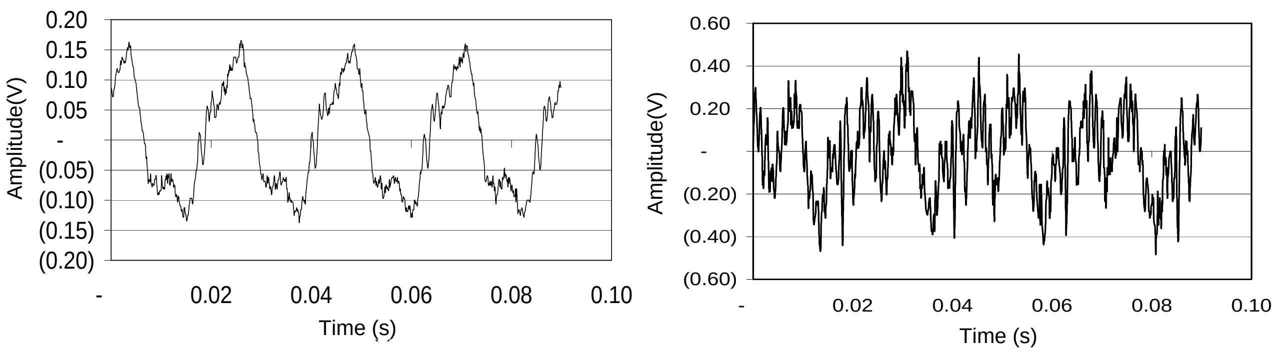

Figure 6. Time history, vertical and horizontal directions.

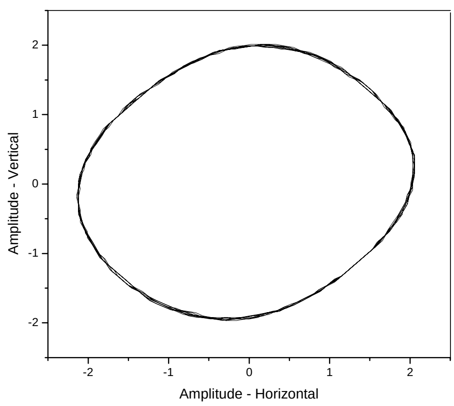

Figure 7. Orbit.

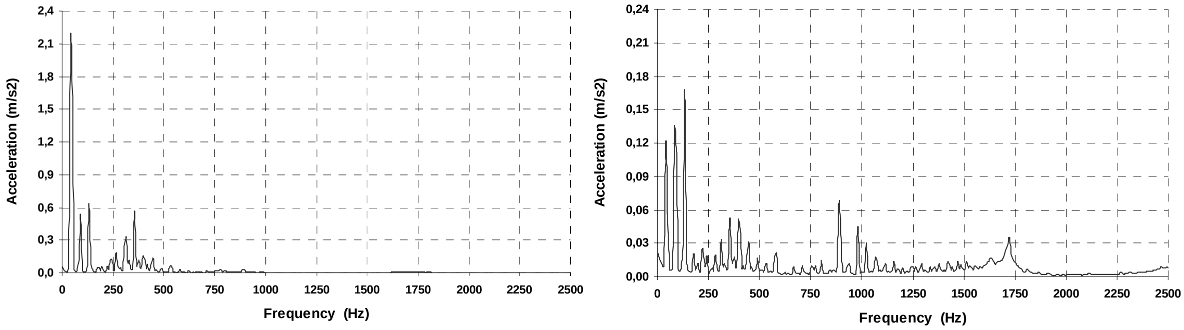

Figure 8. FFT, vertical and horizontal directions.

The signature of Lyapunov exponents is now focused on. The first two pictures of Figure 9 shows the determination of delay parameters, furnishing $\tau = 10\Delta t$ and the embedding dimension is $D_e = 3$. These values are used in the estimation of Lyapunov exponents. Again, it should be pointed out the horizontal characteristic of the curve, which is associated with a null exponent, related to a periodic motion.

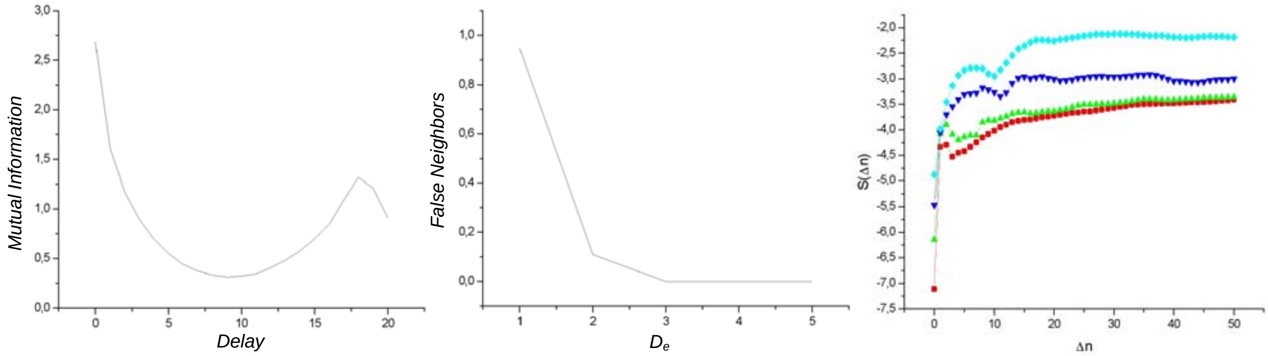

Figure 9. Evaluation of delay parameters and Lyapunov exponent.

5. Middle Age Machine with Unbalanced Mass

A middle age machine is now treated considering ball bearings with a 0.076 mm gap and also an unbalanced mass. Time domain analysis shows signals with irregular characteristics (Figure 10-11). Since the orbit remains a closed curve, it is possible to say that this behavior is related to vibration superposition. Frequency domain analysis (Figure 12) shows the increase of amplitudes, especially in horizontal direction. Besides, horizontal direction FFT shows different spectrum, presenting peaks at different frequency values. This FFT also presents a continuous spectrum over a limited range. Therefore, the energy is spread over a wider bandwidth. This is a well-known characteristic of chaotic behavior and it indicates a complex response of the rotor system. Vance (1988) argues that a combination of different bearing components tends to cause this increase.

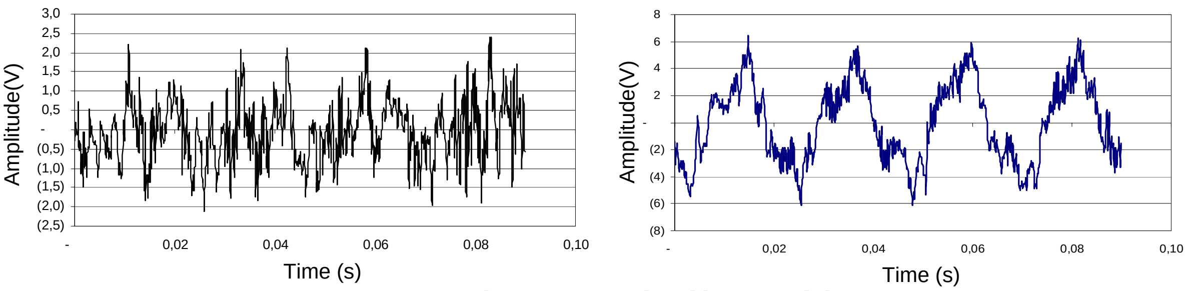

Figure 10. Time history, vertical and horizontal directions.

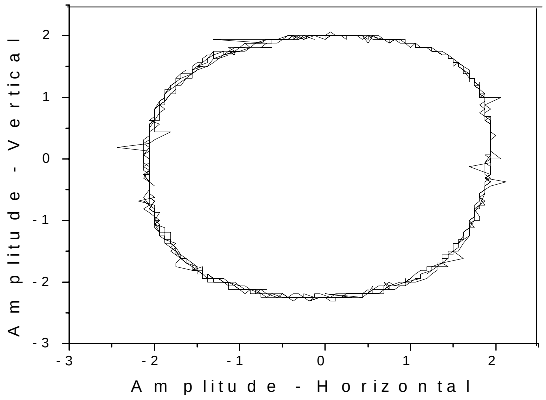

Figure 11. Orbit.

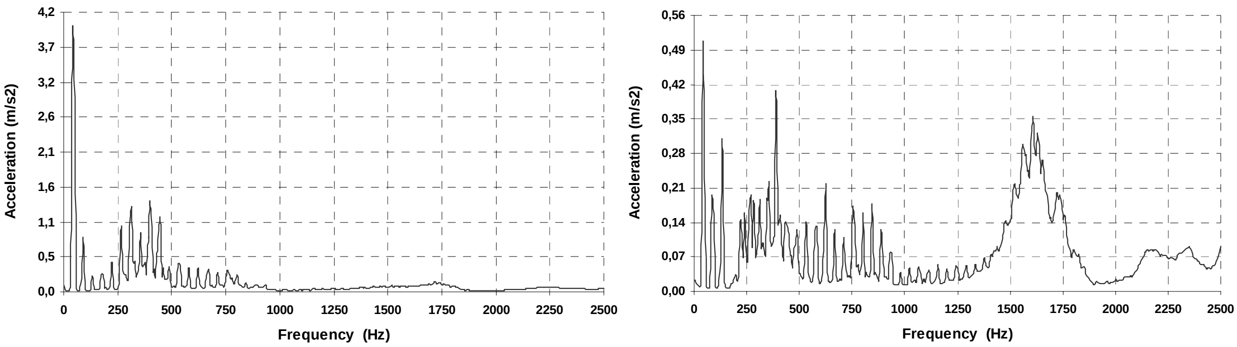

Figure 12. FFT, vertical and horizontal directions.

The analysis of Lyapunov exponents is now performed. The first two pictures of Figure 13 shows the determination of delay parameters, furnishing $\tau = 10\Delta t$ and the embedding dimension is $D_e = 5$. The increase of the embedding dimension is related to the increase on the signal complexity. Lyapunov exponents also show a different behavior where there is not a horizontal curve clearly defined.

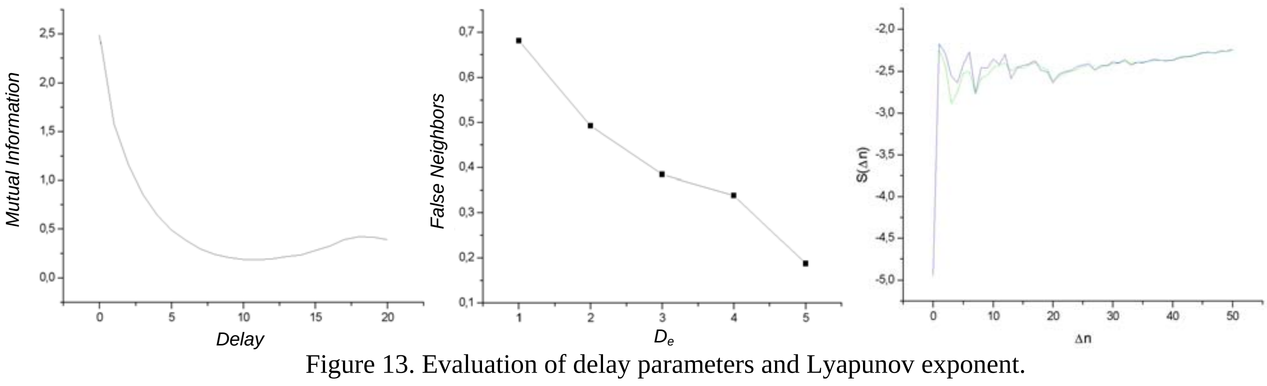

Figure 13. Evaluation of delay parameters and Lyapunov exponent.

6. Machine with Severe Problem and Unbalanced Mass

Now, a machine with severe problems is simulated considering ball bearings with a great gap (0.3 mm) and also an unbalanced mass. Time domain analysis remains showing signals with irregular characteristics (Figure 14-15). This characteristic is more pronounced than the previous situation since the orbit it is not a closed curve anymore. Frequency domain analysis (Figure 16) also shows the increase of complexity of the response. Again, FFT presents a continuous spectrum over a limited range. Although it is not possible to assure that this response is related to chaos, it presents some chaotic-like characteristic. Literature related to vibration based monitoring usually associates this kind of behavior to random noise.

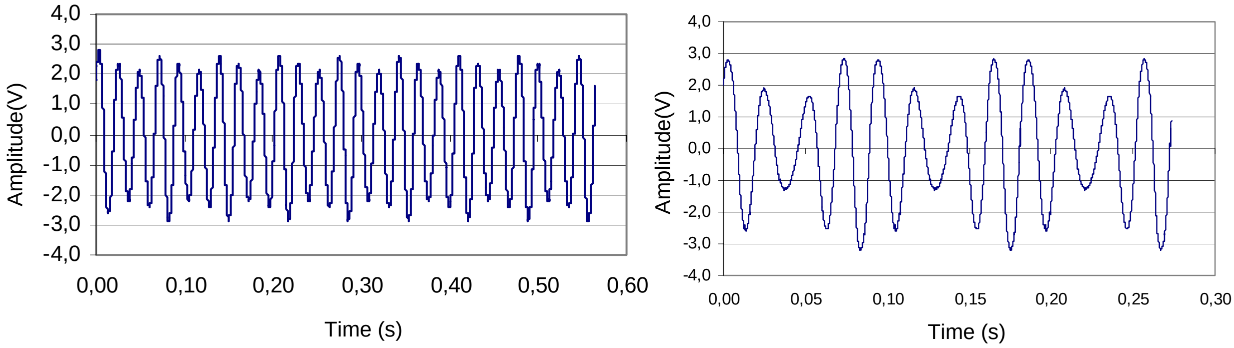

Figure 14. Time history, vertical and horizontal directions.

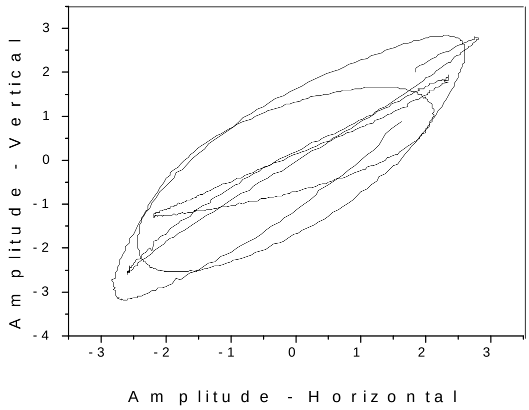

Figure 15. Orbit.

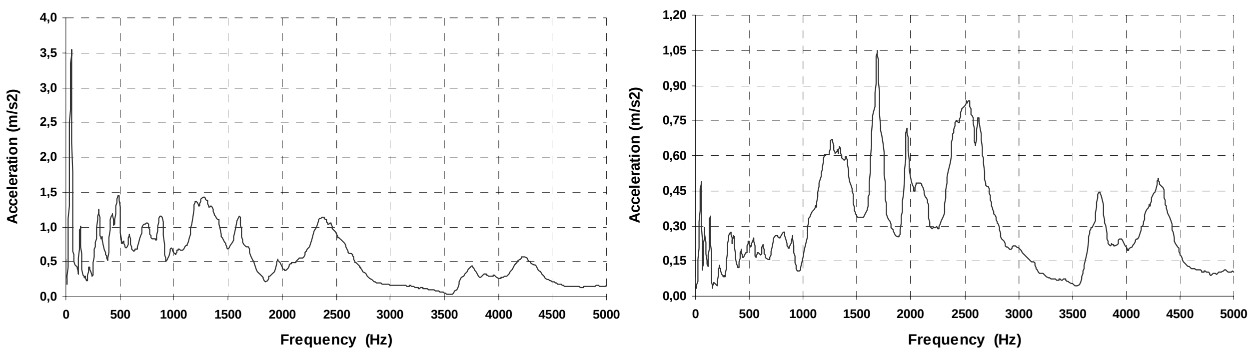

Figure 16. FFT, vertical and horizontal directions.

Lyapunov exponents are now employed in order to obtain more details about the signal signature. The first two pictures of Figure 17 shows the determination of delay parameters, furnishing $\tau = 25\Delta t$ and the embedding dimension is $D_e = 2$. Now, it is noticeable the flat characteristic of the mutual information curve and the decrease of the embedding dimension. Lyapunov exponents now show a positive slope indicating the chaotic characteristic of the signal.

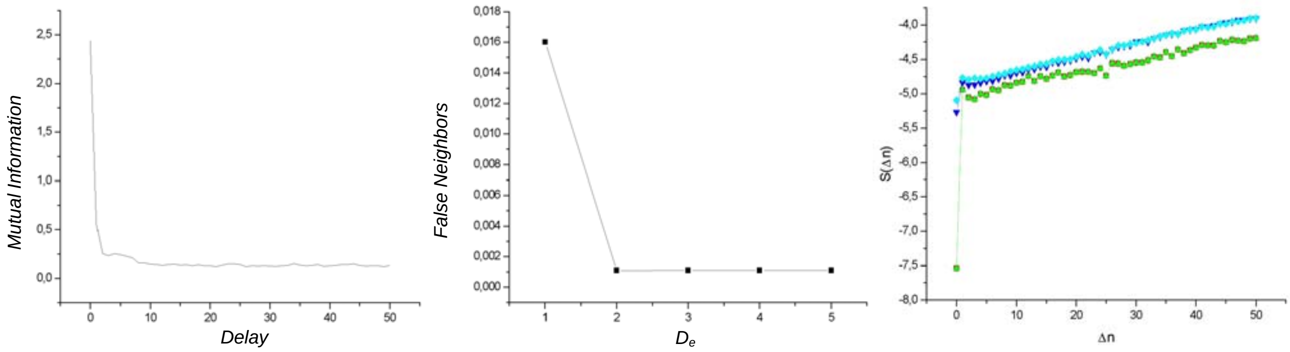

Figure 17. Evaluation of delay parameters and Lyapunov exponent.

5. Conclusions

This contribution analyzes signals of a rotor dynamics experimental apparatus, simulating four situations: 1 – New machine; 2 – New machine, unbalanced; 3 – Middle age machine; 4 – Machine with severe problem. Each of these conditions is characterized by an unbalanced mass and also different gaps on ball bearing. Vibration based monitoring of these situations show evidences of the increase of complexity in signals of machines with problems. The analysis of Lyapunov exponents indicates the chaotic characteristics of the signal of the machine with severe problems.

6. Acknowledgements

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