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Prediction of failures in rotating machines by vibration spectral analysis

Pedro Fernando Poveda[1], Roberto Navarro de Mesquita [2]
[1]*pedro.poveda@usp.br*
[2]*rnavarro@ipen.br*

1. Introduction

Predictive maintenance through monitoring and fault diagnosis has become an important research field that spreads worldwide inserted in Industry 4.0 concepts. These include, physical and virtual models able to online replication and simulation of physical plants in real time.
According to Mobley [1], maintenance represents an important part of the total operating costs of all manufacturing or production plants, reaching up to 60% of the total cost. Inadequate maintenance management directly affects the competitiveness and viability of these plants. The dominant reason for this ineffective management is the lack of available data to quantify the real need for repair or maintenance of machinery, equipment and systems. Maintenance strategies can be:
a) Corrective, where the maintenance action (replacement, repair, adjustment, etc.) is only implemented when operation is somehow impaired;
b) Preventive, which is mainly time-driven, where maintenance tasks are based on elapsed time or hours of operation. Figure 1 illustrates an example of the statistical behavior of a machine's life. The average time to failure indicates that new machines haves a higher failure probability at operation starting. After the initial period, this probability is relatively low during normal service life. Failure probability increases as time elapses [1];

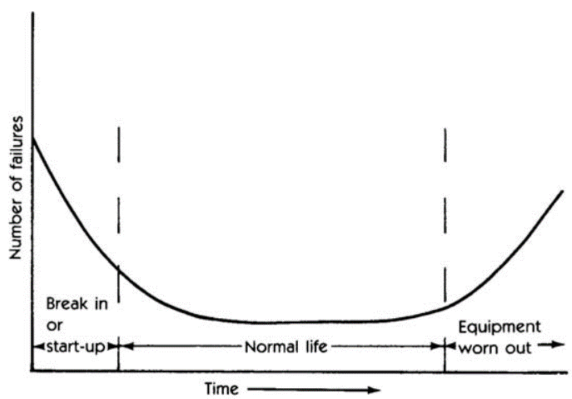

Figure 1 - Statistical curve showing machine and component failures over time [1]

c) Predictive maintenance involves regularly monitoring operating conditions of machines and process systems, using measured indicators. This monitoring should provide the necessary data to ensure the maximum interval between repairs and minimization of the number and cost of unscheduled interruptions. Typical indicators are vibration, noise, electrical current, heating or lubricating oil analysis. According to Randall [2], the most efficient ways to diagnose and monitor failures in rotating machinery is frequency spectrum vibration analysis. Even initial and discrete failures can be identified and indicate the need for future stoppages for corrective maintenance. Vibration frequency analysis captures characteristic frequencies associated with each component that are submitted to cyclical movements. These predictive maintenance principles have been researched to be applied to powered nuclear reactors [3]. This work describes the development of a methodology to predict failures based on vibration spectral analysis.

2. Methodology

The methodology is based on concomitant computational and experimental of simulations performed on a multifunctional plant, specifically built for this purpose (shown in Figure 2). This plant was conceived to obtain vibration data and future research involving other indicators, such as electrical current, yield, oscillations, etc.

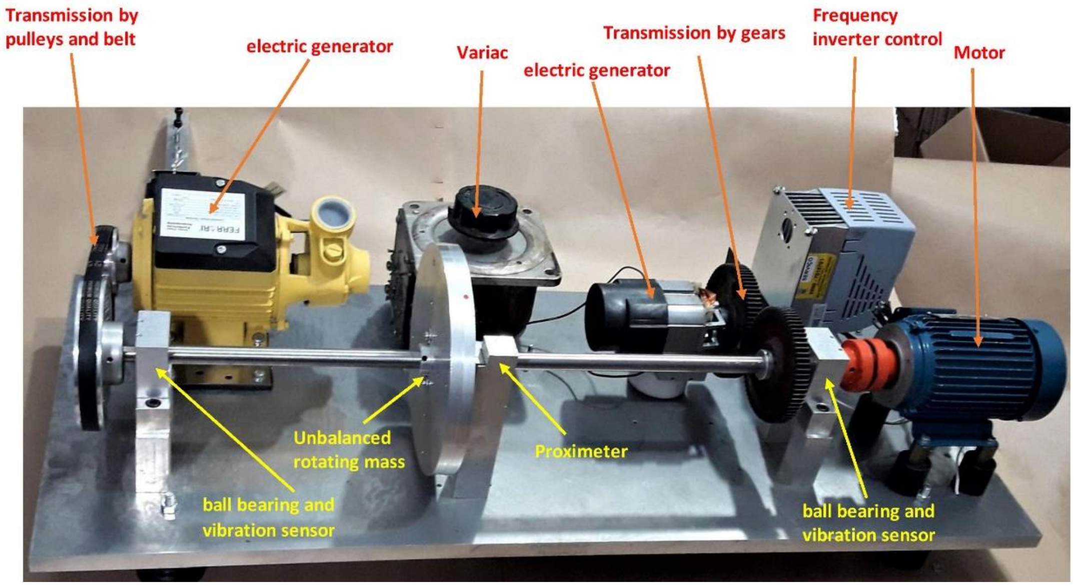

Figure 2 - Multifunctional plant constructed

The built plant has many advantages when compared to similar commercial equipment. It is more robust and, therefore, less susceptible to unknown spurious vibrations. It also allows controlled signal superposition enabling much precise and reliable performance evaluation of simultaneous failures and anomalies of components. Simultaneous failures are a very common situation in spectral analysis monitoring and diagnostics applications in the real world.

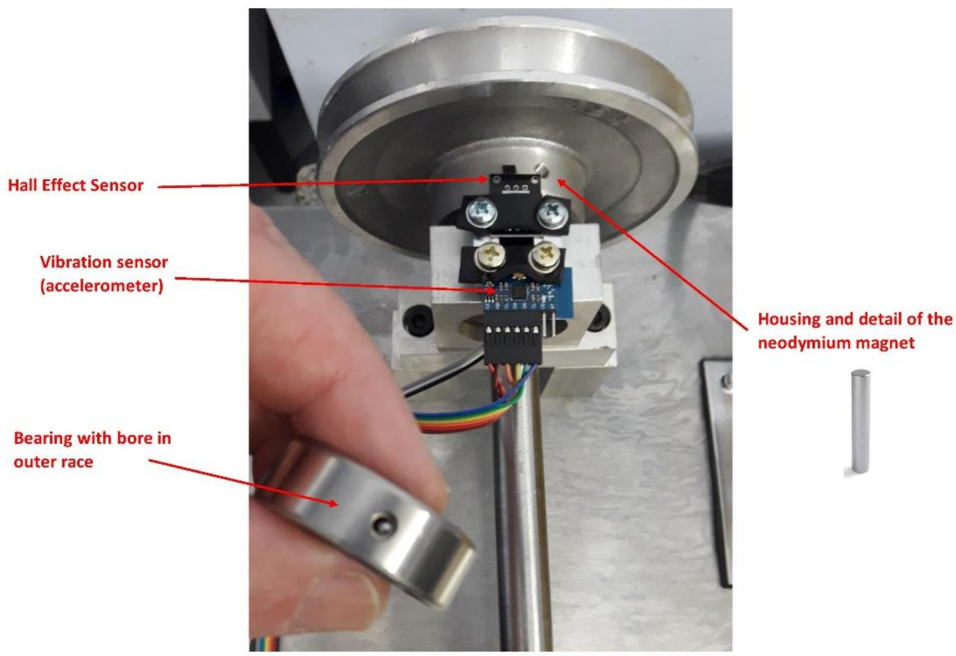

Figure 3 - Vibration and hall effect sensors mounted and bearing with hole (for failure simulation) in the outer race

Figure 3 shows sensors mounted near the bearing. It also shows the hole in the aluminum pulley to house a Neodymium magnet to produce a corresponding magnetic field for each shaft rotation and a consequent hall-effect sensor excitation. A hole was drilled in its outer bearing race simulating a failed bearing.

Signal acquisition from vibration sensors (accelerometers) and hall-effect sensors was done using an Arduino Uno board (with ATMega328P processor). Signal processing was performed using Simulink toolbox from MATLAB connected Arduino board via USB cable according to CTMS [4].

3. Results and Discussion

Obtained signals were processed using Hilbert and Inverse Fourier Transforms implemented through developed algorithms in Matlab analyze the spectrum in the range of the bearing's natural frequency, calculated by Equation 1 [2].

$$fn = \frac{nf}{2}\left(1 - \left(\frac{d}{D}\cos\alpha\right)\right) \quad (1)$$

Where: f_n is the natural frequency of the bearing balls in Hz; f is the rotation frequency in Hz; n is the number of the bearing balls; D is the bearing's primitive diameter in mm; d is the diameter of the bearing balls; α is the contact angle (for radial bearings = 0°).

The results for the faulty bearing (where the hole in the outer ring was drilled) are shown in Figure 5.

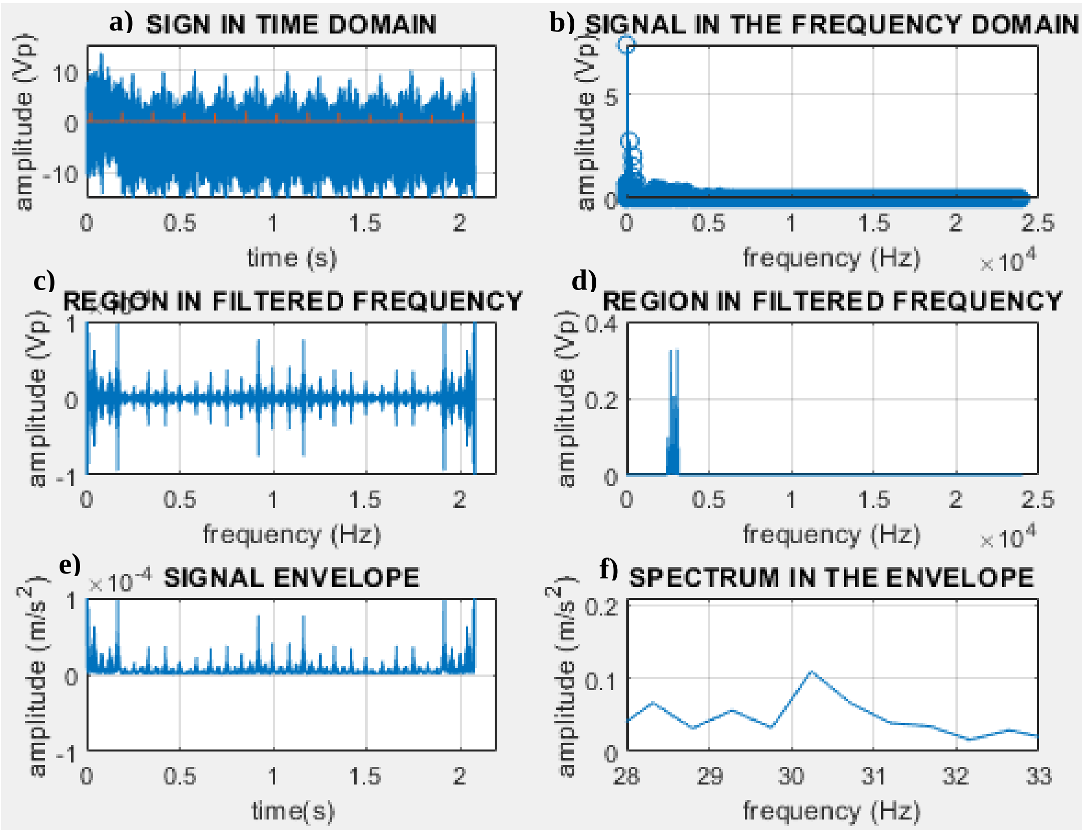

Figure 4 - Results obtained for flawless bearing

Both figures refer: a) to obtained signals (in peak voltage) in time domain, describing vibration sensors over time; b) positive signals in frequency domain (peak voltage) in frequency domain after Inverse Fourier Transform in the frequency range; c) and d) signals (peak voltage) in the frequency range where analysis is performed; e) presents the signal envelope (m/s2) after Hilbert Transform in the frequency domain, which consists of the analysis of characteristic vibration peaks in frequency ranges close to the natural frequency of the component.

Comparing the obtained graphs for both situations, it can be observed that:

• It is not possible to distinguish significant differences between faultless and faulty bearings through time-domain vibration amplitude graphs. In the other hand;

• The differences between both bearing spectra are clearly seen in frequency domain graphs. These differences are much more clearly seen when "Envelope Spectrum" technique was applied, shown in the last line of each figure.

This technique proved to be adequate to locate defects. A clear vibration amplitude increase can be observed in the 30 Hz region. The central peak, flanked by two smaller peaks, is characteristic of a bearing failure as described by Randall [2]. As the failure criticality increases, the central peak becomes more pronounced in relation to the others. This fact enables not only its identification, but also, the estimate of criticality level and evaluation of failure propagation speed. This may imply changing operating time up to the necessity of stopping the machine or plant to replace the defective component.

However, to obtain satisfactory results, it is necessary to know the physical and functional characteristics of each component. Specific natural frequency obtainment and, consequently, the ability to "close the envelope" in the corresponding region of the spectrum are conditions to this task. In this experiment, a theoretical natural frequency of 29.34 Hz was obtained for the bearing used through Equation 1. From the obtained graph, the vibration peak was near 30.3 Hz. This difference may be due to several factors such as: angular velocity fluctuation of the shaft, slippage and inertia in the dynamic propagation of vibrations.

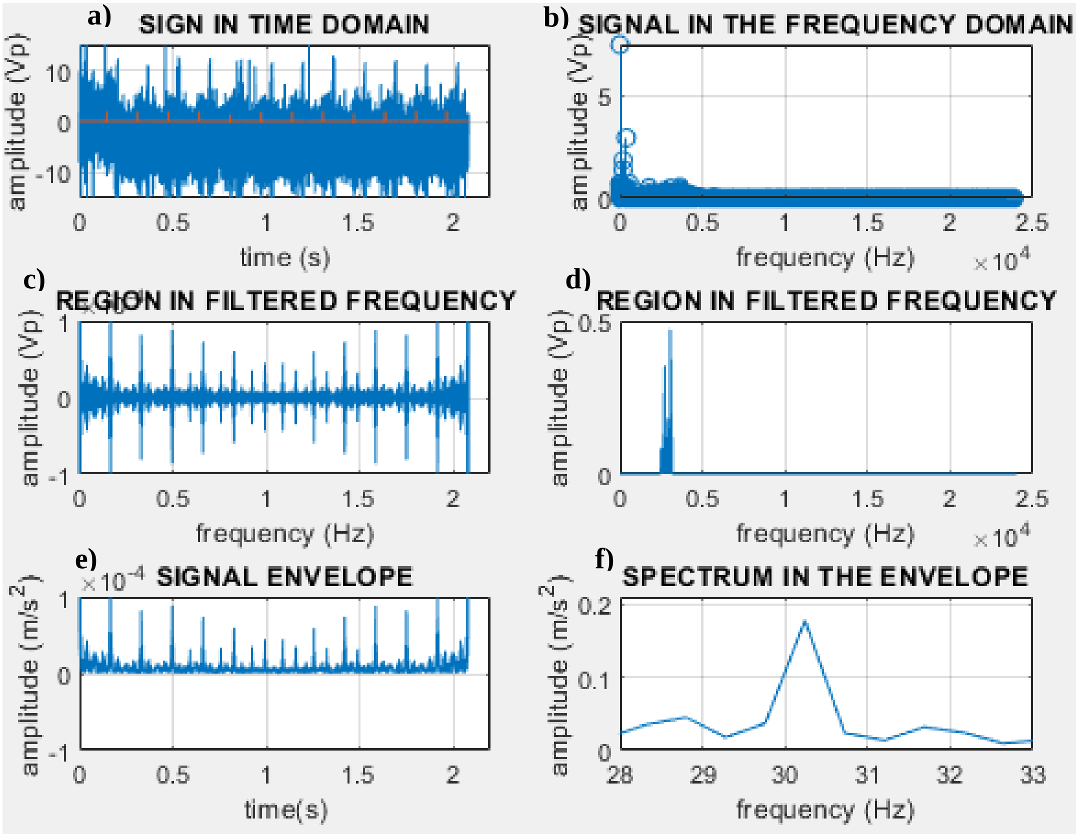

Figure 5 - Results obtained with defective bearing

4. Conclusions

The used techniques proved to be adequate for predicting failures in rotating machinery components. However, the search and identification of characteristic signals was performed in a non-automated way. A larger database of these failures must be obtained. The natural frequency calculation of the component to be monitored and the search for the spectrum close to this frequency region was manually evaluated and is currently being done by analysts. For efficient application in industrial processes, especially in nuclear plants, automation routines must be introduced to obtain independence from human intervention, and this is the final objective of our research.

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