Expert System to Detect Incipient Faults in Rotating Machines Using Fuzzy Logic and Virtual Instrumentation

Renato K. Vanni, Galdenoro Botura Jr, Marilza A. Lemos, Marcio A. Marques, and Luiz C. Rosa

***Abstract*—This paper refers to the design of an expert system that captures a waveform through the use of an accelerometer, processes the signal and converts it to the frequency domain using a Fast Fourier Transformer to then, using artificial intelligence techniques, specifically Fuzzy Reasoning, it determines if there is any failure present in the underlying mode of the equipment, such as imbalance, misalignment or bearing defects.**

***Index Terms*— Expert systems, fault diagnosis, fuzzy logic, rotary machine, virtual instrumentation.**

I. Introduction

About half of all operating costs in the majority of processing and manufacturing plants refer to maintenance costs [1]. That is the main reason for studies to be conducted on activities that can potentially reduce the operating costs. Monitoring the condition of the equipment to diagnose failures or defects is one of the activities that can be referred to as the field of activity in which the parameters, associated to the operation of the equipment, are recorded with the purpose of determining their integrity [2], [3]. Once the integrity can be estimated this information can be for various purposes; for example, planning maintenance stops reducing drastically the risk of unforeseen breakages and the use of corrective maintenance [4].

II. Methodology

This study was conducted in the development environment of virtual instrumentation LabView. The initial step was to define the best equipment for data retrieval best suited for the job – the data collector KOSCAK VK500 E/B with a capacity to collect the samples at intervals of 200ms at a sampling rate of 5kHz. Through a graphical interface (Fig. 1) the user has various information available; such as: the entry signal acquired, sampling time, tolerance for frequency search of the rotation basis, the rotary system, gains at entry, direction of the entry signal rotations (radial or axial) and potency of the equipment analysed.

The captured acceleration signal then goes through an initial processing, where it is conditioned, integrated and transformed to a frequency domain through a Fast Fourier Transform (FFT) or a Discrete Fourier transform (DFT), in case the number of entry samples is different from a power of two (automatically chosen by the LabView System), with the use of a Hanning window signal thus avoiding the "aliasing "effect.

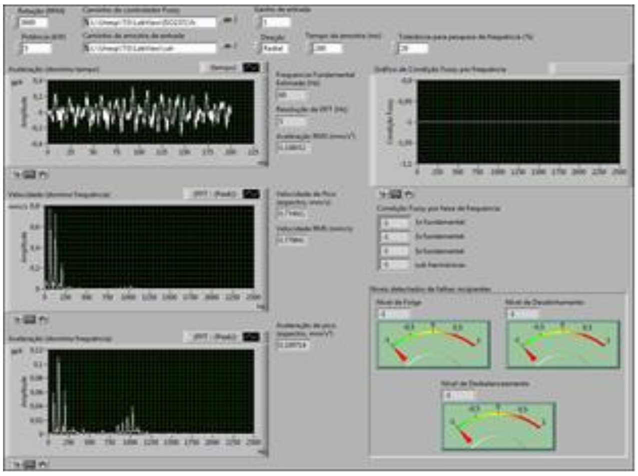

Fig. 1. Graphical interface - front painel

Therefore it uses Mathscript coding to determine the deviation from the fundamental rotational frequency of the equipment supplied by the user. Sometimes the data supplied and entered by the user does not always correspond to the real exact moment the signal was captured, so the rotational system can be, for example, under a heavier load, having impact in its working rotation. The information contained in the velocity spectrum in the frequency domain are processed by an inference system based in fuzzy rules for the determination of the linguistic condition of each identifiable frequency in the spectrum, in accordance to table 1, which indicates the severity of the vibrations according to ISO 2372 [5]. According to the table I, it has the following classes of equipments:

TABLE I: Severity of the Vibrations for The Classes of Machinery

Vibration severity		Machine Classes			
RMS Velocity (mm/s)	Velocity (mm/s)	Class I	Class II	Class III	Class IV
0.28	0.3960	A	A	A	A
0.45	0.6364				
0.71	1.0041				
1.12	1.5839	B			
1.8	2.5456		B		
2.8	3.9598	C		B	
4.5	6.3640		C		B
7.1	10.0409	D		C	
11.2	15.8392		D		C
18	25.4558			D	
28	39.5980				D
45	63.6396				
71	100.4092				

1) *Class I*: Individual parts of motors and machines completely connected to the complete machine in its normal working condition (Production electrical motors

Manuscript received August 3, 2012; revised October 3, 2012.

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of up to 15kW are prime examples of motors in this category).

2) *Class II*: Machines of medium capacity (typical electrical motors with throughput of between 15kW to 75kW) with no special foundation, engines with rigid mounting or machines of up to 300kW on special foundation.
3) *Class III*: Big machines with spinning masses mounted on heavy and rigid foundation, that relatively firm and steady on the direction of the vibration measurements.
4) *Class IV*: Big machinery with spinning masses mounted on foundations that are relatively flexible on the direction of the vibration measurements (for example turbo-generators, especially those with light substructures).

And for the severity:

1) New equipment, initial operation condition, or equipments in optimum conditions.
2) Equipment in good working condition.
3) In permissible working conditions, as long as not for long periods of time.
4) Inadmissible working condition, as the vibration level will cause damage to the equipment.

This controller has the throughput of the machine and the vibration spectrum as its input variables. After processing, a new spectrum is taken as a new exit, but this time with linguistic condition for each of the frequency band. The membership functions used is presented in Fig. 2-5.

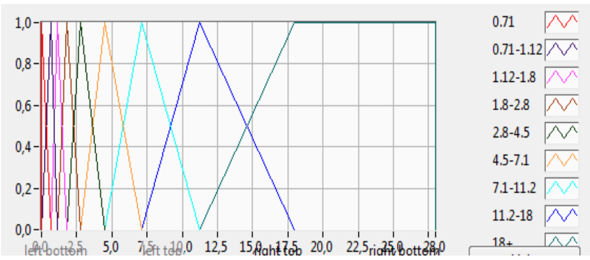

Fig. 2. Levels of vibration

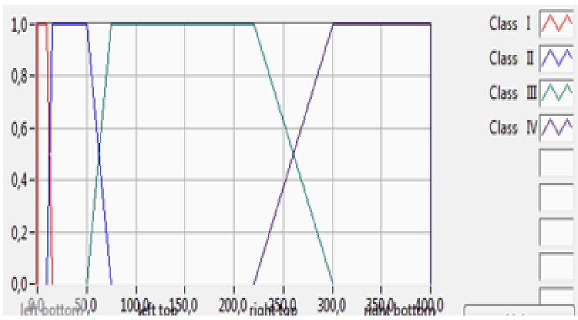

Fig. 3. Power classes

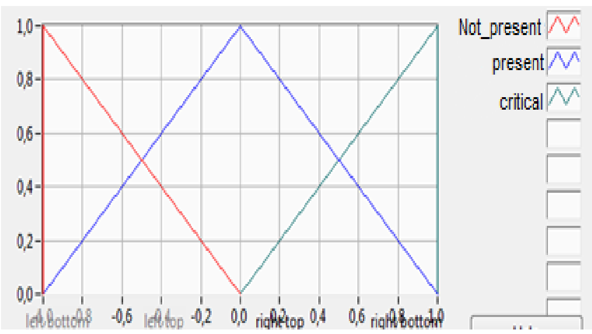

Fig. 4. Final condition

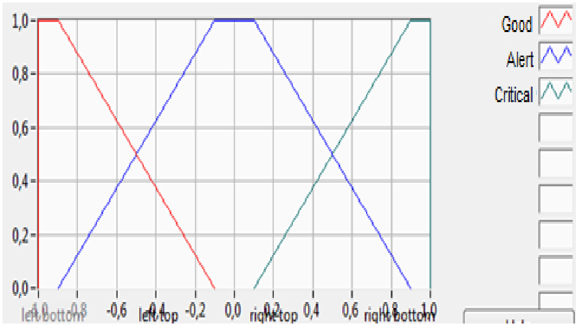

Fig. 5. Vibration level.

The Table of Fuzzy Inference containing the data on the severity of the vibration is described in Tables II-V.

TABLE II: F. UZZY INFERENCE

1st_harm	2nd_harm	3rd_harm	output
Alert	Good	Good	Present
Critical	Good	Good	Critical
Critical	Good	Alert	Critical
Critical	Alert	Good	Critical
Critical	Alert	Alert	Critical

TABLE III: RULES FOR BEARING LOOSENESS

sub_harm	Output
Good	Not_present
Alert	Present
Critical	Critical

TABLE IV: RULES FOR THE UNBALANCING

	Class I	Class II	Class III	Class IV
Up to 1,8	Good	Good	Good	Good
1,8-2,8	Alert	Good	Good	Good
2,8-4,5	Alert	Alert	Good	Good
4,5-7,1	Critical	Alert	Alert	Good
7,1-1,2	Critical	Critical	Alert	Alert
11,2-18	Critical	Critical	Critical	Alert
Over 18	Critical	Critical	Critical	Critical

TABLE V: RULES FOR THE MISALIGNMENT

Good	Critical	Critical
Alert	Good	present
Alert	Alert	present
Alert	Critical	Critical
Critical	Good	Critical
Critical	Alert	Critical
Critical	Critical	Critical
Alert	Alert	Present
Alert	Critical	Critical
Critical	Good	Critical
Critical	Alert	Critical
Critical	Critical	Critical

III. RESULTS

An example of input signals with their respective results is displayed in the Fig. 3. In this test was used the follow configuration: induction motor; cement mill drive system;

power throughput: 1250kW; rotation: 3600rpm; analysis point: anterior motor bearing; sample direction: radial.

As one can notice, no failure mode was detected, which is the correct status as there was not enough vibration for this class of equipment to be classified as having any mode of failure.

As it change the gain input to 10 the results are different. The system shows new values: imbalance level: 1; misalignment level: 0.9810; bearing looseness level: -1. Thus, this time the incipient fault mode of "imbalance" is present.

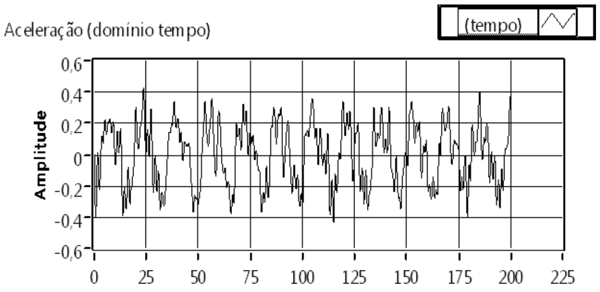

Fig. 6. Acceleration graph (input signal) time domain

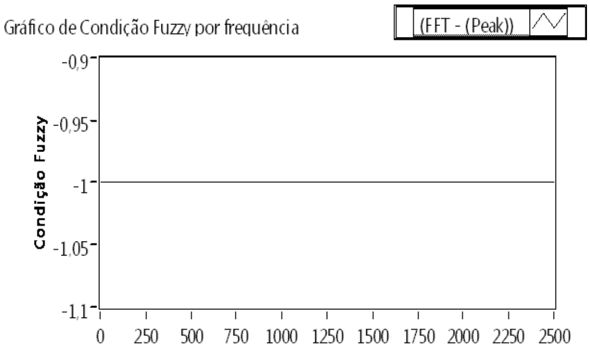

Fig. 7. Fuzzy condition for each frequency value

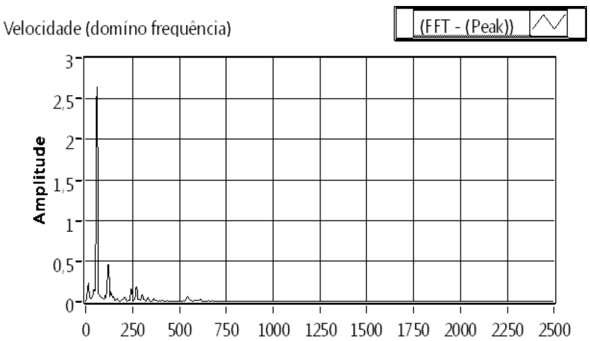

Fig. 8. Velocity spectrum – frequency domain

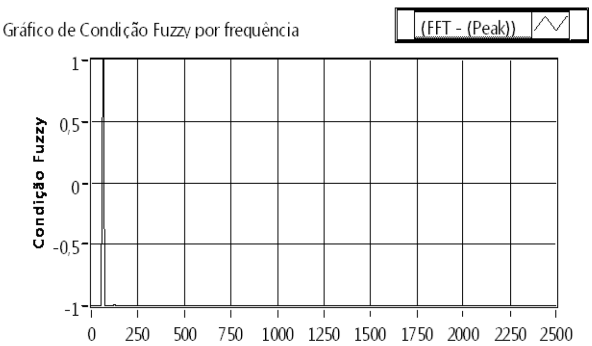

Fig. 9. Fuzzy condition graph- gain 10

IV. Discussions and Conclusions

The system was efficient in detecting incipient faults, indicating that their levels of presence in the data analysed means a good degree of confidence. An observation that can be made with respect to some of the levels of vibration collected is that their levels were not sufficiently high to justify an incipient fault – and effectively there were none, however it may be deemed interesting to have some type of indication, that although the levels of vibration were not sufficiently high, the data could possible indicate the presence or start of a defect mode and that observations in future analyses would be interesting to understand better how the incipient defect evolves – something that could be added to the system in the future.

References

[1] C. W. Silva, *Vibration and Shock Handbook*, New York: CRC Press, 2005.

[2] R. F. William, M. H. Mark, and G. H. Warren, "An analytical approach to solving motor vibration problems," *IEEE*, vol. 99, no. 20, 1999.

[3] N.-T. Nguyen, H. Lee, and J. Kwon, "Optimal feature selection using genetic algorithm for mechanical fault detection of induction motor," *Journal of Mechanical Science and Technology* vol. 22, pp. 490-496, Springer 2008.

[4] R. Yan and X. G. Robert, "Multi-scale enveloping spectrogram for vibration analysis in bearing defect diagnosis," *Tribology International* vol. 42, pp. 232-302, 2009.

[5] T. I. Liu, J. H. Singonahalli, and N. R. Iyer, "Detection of roller bearing defects using expert system and fuzzy logic," *Mechanical Signals and Processing Academic Press Limited*, 1996, vol. 10, no. 5, pp. 595-614.

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