

# PREDICTIVE MAINTENANCE IN ROTATING MACHINES WITH VIBRATION ANALYSIS AND FUZZY LOGIC

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**Abstract** - This work provides a detection method for faults in the operation of rotating machines based on a change of system vibration standard and in the operation status diagnosis by fuzzy logic. These changes are analyzed and used as parameters for predicting *incipient faults*, as well as their evolution in operation condition allowing *predictive maintenance tasks*. A mechanic structure (developed to insert the faults) called Rotating System (see Fig 1) has been used. The data acquisition of structure vibration has been made by a biaxial solid state accelerometer in a low-power chip. The outputs are directly measured by a microcontroller-based system without needing an A/D converter. The acquisition system is composed by two subsystems: a personal computer and a microcontroller-based front-end (Microchip PIC16C73A). The acquired data (stored in \*.dat files) are computed and analyzed in frequency domain with a signal processing tool (called SPTOOL) of the Matlab5 package. The faults analyzed in this work are due to the unbalancing of axle\_wheel by insertion of unbalanced elements. The relation of mass between the wheel and the smallest unbalanced element is 1 : 10,000. The fuzzy system was calibrated to detect and diagnose the normal, incipient fault, maintenance, and danger conditions of the Rotating System.

**Keywords** – Predictive maintenance, Incipient faults, Vibration analysis and Fuzzy Logic.

## 1. MACHINES MAINTENANCE

The process of maintenance includes all organizational and technical activities that are able to guarantee that machines and equipment, in general, work in an expected level of confidence. Maintenance and repair tasks that follow basic established procedures reduce chances of unexpected faults, and consequently unnecessary losses of production, time, and money. In more critical cases, faults in a process can bring serious damages, even causing danger to human lives. There are three maintenance strategies: corrective, preventive, and predictive. (see Table I) [1]

Table I - Kinds of maintenance and their characteristics

	Corrective Maintenance	Preventive Maintenance	Predictive Maintenance
Operation status of machine	out of service	out of service	working or out of service
Reason of interference	Fault	planned inspection	planned control or continuous
Tasks to be carry out on the machine	replace of components	to take machine down to inspect and replace components	measurement
Purpose of interference	return to work	to guarantee the working for a period	to predict and detect faults

### 1.1 Measured parameters in predictable maintenance

The parameters that will be measured (see Table II) [1] should provide information that allows the inspection of specific machine elements, or the kind of fault. The option of a given parameter or a more adequate form of investigation are relevant to determine the factors of machine malfunction (small mechanisms can have changes in vibration when connected with sensors) [4].

Table II - Parameters to be measured on predictive maintenance

Parameter to be measured	Nature of fault or defect to be detected
Amplitude of vibration displacement	unbalancing, misalignment, excessive gap, insufficient rigidity, bad coupling, flabby or wear straps down, a bent axle, non-adjustment, ...
Amplitude of vibration velocity	bearing or damaged gear...
Amplitude of vibration acceleration	mechanic status of ball-bearing, excessive friction between components, lack of lubrication, ...
Vibration frequency	data to complement the measurement of any characteristic of vibration, essential to the determination of any detected problem...

A technical analysis is possible through the obtained data, where the results can indicate the nature of the fault as expected, and establish which elements of the system are critical. The machine history record also allows the determination of the most frequently fault elements, as well as the time spent between them [4].

## 2. VIBRATIONAL ANALYSIS IN MONITORING MACHINES

Machines are complex mechanical structures with articulated elements. The parts that are excited could oscillate, where joints to other coupled elements transmit such oscillations. The result is a complex frequency spectrum that characterizes the system.

Each time a component changes one of its mechanical characteristics because of wear or crack, a frequency component of the system will be affected. A change in the coupling between parts also affects the transmission coefficient of the signal between them, and in consequence, the form of the global frequency of the system.

Gaps, failures, or misalignments of bearings of rotating machines reflect on the change of frequencies, or in the appearance of new ones. The bearing transmits the unbalancing of rotor.

The centrifugal, alternative and friction forces acting on different elements of a machine in operation originate proportional mechanical vibrations on bearings. Due to this fact, it is possible to detect and determine the presence of stress in any machine components and also some eventual functional abnormalities with the measurement of vibrations in selected points. In general, this measurement should be taken on bearings, since it is one of the valid points according to the rules in use to evaluate the operation of machines [1].

A fundamental premise upon which is based the vibration analysis as a technique applied to industrial maintenance is: "Each component or each kind of mechanical deficiency of a machine in operation produces one vibration of specific frequency which in normal conditions of operation, can reach a maximum known amplitude" [1]. That way, it is possible to identify each machine component, the kind of fault that is present, and to establish its origin measuring and analyzing the vibration pattern, as well as to evaluate the mechanical condition of the faulty component and the gravity of the detected deficiency.

The basic methodology [1] recommends measurement of:

1) The frequency to identify the origin of vibration. The knowledge of the frequency allows the identification of the machine component or the nature of the fault that produces the vibration.

2) The amplitude to evaluate the vibration level. The measurement of the amplitude allows evaluate, by comparison with previously established values, if the vibration corresponds to a normal or abnormal operation and also the level of importance of the detected fault.

### 2.1 Frequency of the vibration

Frequency is the ratio of repetition of a periodical event, generally expressed in rotations (or cycles) per second (Hz), rotations per minute (rpm), cycles per second (cps), or multiples of the rotation velocity (harmonics). Harmonics are commonly referred as being two, three, four, etc. times higher than the rotation frequency of the axle. Some conditions such as instability, unbalancing, misalignment changes in adjustment, wear, and even component fatigue, causes specific vibrations with particular frequencies. The more common specific vibration occurs in the rotation frequency of the machine

### 2.2 Spectral Analysis

The method for frequency analysis, based on the Fourier theorem, establishes that any periodical function can be decomposed by a series of pure sinusoidal waves with distinct frequencies and multiple harmonics from the fundamental frequency. These components constitute the frequency spectrum of vibration. When using transducers (accelerometers) to the acquisition of such parameter and later analysis, the vibration spectrum of a system can be listed. Observing the amplitudes of the peaks in some frequencies and relating them to the amplitude of the fundamental frequency of the system, it is possible to come to a diagnosis about the state of operation or the evolution of the fault running in the system.

### 2.3 Determination of the variable to be measured

Each exciting force existing in different points of the machine will generate one harmonic of the vibration determining a certain displacement, velocity, and acceleration; the sum of all harmonics to each variable will result in one multi-harmonic, present on bearings.

It is possible to classify the total of harmonic components of vibration in two groups, outlined by the value of the frequency rotation of the axle. Thus, the following division is established [1]:

- 1) Components of low frequency (frequency values up to 5 times the axle rpm);
- 2) Components of high frequency (frequency values higher than 5 times the axle rpm).

It is convenient to explain that the set values above follow one orientated division.

## 3. THE ACQUISITION PROCESS OF SPECTRAL SIGNATURE

### 3.1 The Rotating System

The Rotating System, Fig.1, (developed to insert the faults), composed by a AC motor with a nominal rotation of 1,800 rpm and an axle with a wheel disc; the motor drives the axle by a belt with a speed relation of 1 to 1.3. This axle is double supported, as we can see in Figure 1, and rotates at 2,270 rpm. The main rotating mass of the axle subsystem is a metallic disc weighing 1,012 g with 15 cm of diameter. The rotating speed is measured with a L20 MICROTTEST tachometer.

According to Ya' Cubsohn [1], failures can be divided into two main generic classes: low frequency faults (for example: unbalancing, misalignment, etc.) and high frequency faults (as: ball bearings defects, lack of lubrication, etc.). However, it is not sufficient to measure the frequency of each one of the vibration components to identify the fault. The absolute value must be known and related to the rotating speed of the axle. Therefore, the knowledge of the rotating speed of the axle is essential for diagnosing faults.

Some modifications such as unbalancing, misalignment, excessive gap, insufficient rigidity, bad coupling, flabby or wear strap down, bent axles, etc, will change the vibration amplitude at the rotation frequency of the Rotating System [1]. These faults can be classified as a cluster of low frequency faults and in this work are called non-adjustments.

One of the difficulties with motor fault detection is the motor high dimensionality [2]. There are many variables that can affect the fault detection process, including load conditions, saturation effects, unpredictable operating conditions, electrical noises, and temperature effects, which can result in dozens of possible combinations for different patterns that will mask the vibration measurement.

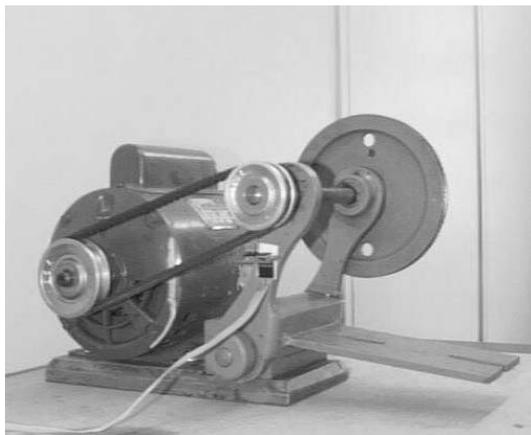


Fig.1 – Rotating System.

### 3.2 The Accelerometer

The accelerometer used in this experience is an accelerometer from Analog Device (ADXL202), a solid state biaxial low-power device. The ADXL202 can measure dynamic acceleration (vibrations) in the span of  $\pm 2$  g and the static acceleration (gravity). This electronic circuit has two digital outputs (x and y) that give information about the accelerations in two orthogonal directions. The accelerations are coded as pwd signals: one can set the frequency of the oscillator and the circuit modulates the duty cycle. The two signals can then be used directly as input by some digital circuit that is able to compute the duration of the “on” period of the signal without using an A/D converter.

## 4. THE ACQUISITION SYSTEM

The acquisition system is composed by two subsystems: a personal computer and a microcontroller based front-end.

The computer runs the application software with the algorithms to process the acceleration data, the fuzzy diagnosis and user interface. The front-end is microcontroller based (Microchip PIC16C73A) digital systems, interfacing the accelerometer and the computer. The interface between the microcontroller and the accelerometer is charged of the counting of the ON period of the PWM wave. The software running on the microcontroller build a data structure containing the information of the sampled biaxial acceleration. This data are sent to the host computer through a serial. The acceleration is computed by the ratio of the ON time and the fixed period of the PWM wave. The vibration standard of the Rotating System, called the spectral signature, (see Fig. 2) has been obtained by the acquisition of ten \*.dat files where the average value has been computed by a C function.

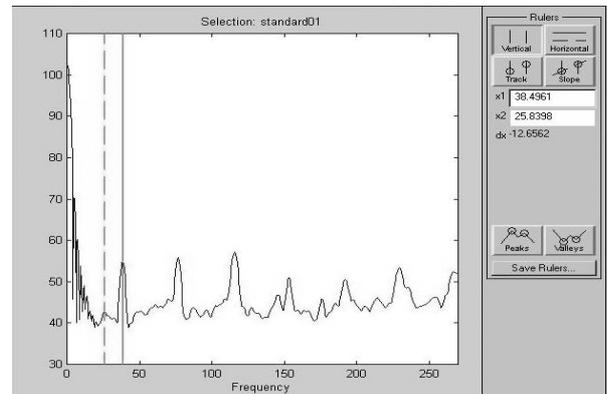


Fig. 2 - Spectral Signature

## 5. THE EXPERIMENT

Some modifications such as unbalancing, misalignment, excessive gap, insufficient rigidity, bad coupling, flabby or wear strap down, bent axles, etc, will change the vibration amplitude at the rotation frequency of the Rotating System [3]. These faults can be classified as a cluster of low frequency faults and in this work are called non-adjustments.

In this way, possible changes that occur in the current status of the Rotating System or by turning on/off the system to insert the faults, are considered. The faults inserted in this stage are the unbalancing of axle\_wheel, by the insertion of unbalanced elements.

The axle\_wheel has a hole where the unbalanced elements are inserted. The relation of mass between the wheel and the smallest unbalanced element is the 1:10,000. (the mass of the wheel is 1,012 g and the smallest element is 0.1 g). Others relations are established (1:140 and 1:200) (see Fig. 3) according to an adopted criterion for classification of linguistic variables used by the fuzzy system [3]. There are

many variables that can affect the fault detection process, including load conditions, saturation effects, unpredictable operating conditions, electrical noises, and temperature effects, which can result in dozens of possible combinations for different patterns that will mask the vibration measurement [5].

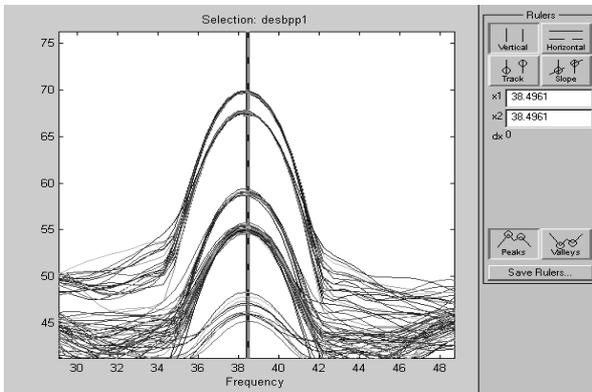


Fig. 3 – Amplitude variation by insertion unbalanced elements

## 6. FUZZY DIAGNOSTIC

The method permits the diagnostic of the Rotating System operation status, by the fuzzy system, based on a collection of logic rules in the form IF-THEN statements. The “antecedent” statements are: the rotation frequency of axle\_wheel and the vibration amplitude in this frequency. The “consequent” statement is the diagnostic of the system. The Fuzzy diagnostic is furnishing by quantitative and qualitative form (see Fig. 4).

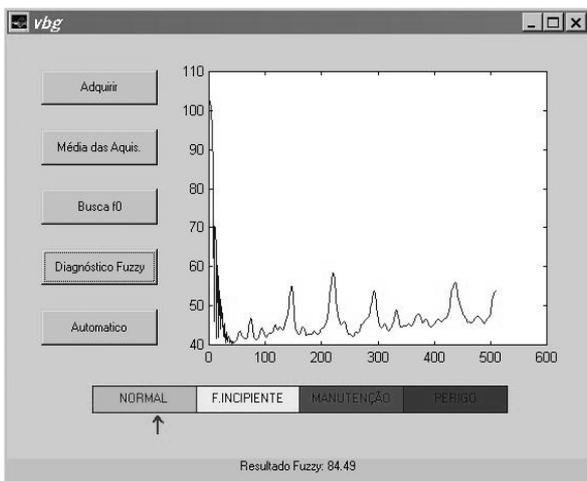


Fig. 4 – The Fuzzy Diagnostic

The easiness to alter rules and update values of variables, allows the method become a versatile one. The adjustment permits that the method can support the specific requests of the process whose Rotating System is inserted. It is possible to set it considering the desired performance range for the

system, the quality of the employed material in the construction, risk factors, and tolerance.

## 7. CONCLUSIONS

The obtained results show that is possible to become the method better. Actually, this is the theme of my academic research and it has didactic objective. The next aim is to improve it and perhaps become it an industrial product. We wish to make it more efficient in your purpose.

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