Expert System Based on Fuzzy Rules for Monitoring and Diagnosis of Operation Conditions in Rotating Machines

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***Abstract*--This work provides a detection method for failure in rotating machines based on a change of vibration pattern and offers the diagnosis about the operation conditions using Fuzzy Logic. A mechanic structure (as an experimental prototype where faults can be inserted) called Rotating System has been used. The vibration standard of the Rotating System, called "The Spectral Signature", has been obtained. The changes in the vibration standard have been analyzed and used as parameters for detecting incipient failures, as well as their condition evolution, allowing predictive monitoring and planning of maintenance. The faults analyzed in this work are caused due to insertion of asymmetric masses for unbalancing in the axle wheel. The system for diagnosing Fuzzy System was calibrated to detect and diagnose the conditions: normal, incipient failure, maintenance, and danger, using linguistic variables. The frequency of rotation and the amplitudes of vibration of the axle wheel are considered in each situation as parameters for analysis, diagnostic, for the decision by the Expert System based on Fuzzy rules. The results confirm that the proposed method is useful for detecting incipient failures, monitoring the evolution of severity and offering grants for planning and decision making about maintenance or prevention of rotating machines.**

I. MAINTENANCE IN EQUIPMENTS

The process of maintenance includes all possible organizational and technical activities to guarantee that machines and equipments, in general, can work in an expected level of confidence. Maintenance and repair tasks that follow basic established procedures can reduce chances of unexpected failures, and consequently unnecessary losses of production, time, and money. In more critical cases, failures in a process can bring serious damages, even causing danger to human lives [11].

Some authors have the same opinion that "while maintenance is still considered as a cost centre, researches have showed the impact of the maintenance function on the overall plant performance i.e. productivity and profitability [1] [2] [3] [4] [5] [8].

An unexpected failure in equipment not only results in loss of productivity, but also can offer risks to human, can cause environmental and patrimonial damages. Therefore the policies of maintenance are not just questions about profitability and productivity; they must be applied for safety reasons.

The maintenance is defined as the set of all techniques and management procedures to keep working the equipment (the production line) safeguard people, protect the environmental and patrimony. Some concepts and methodologies about maintenance, such as Reliability Centered Maintenance (RCM), Total Productive Maintenance (TPM), Business Centered Maintenance (BCM), Capital Asset Management (CAM), and Integrated Logistic Support (ILS), can be found in [10] [15] [17].

Many experts and practitioners have suggested several strategies. A lot of this appears using codenames, but all treat about corrective, preventive or condition based interventions.

There are three procedures about maintenance: corrective, preventive, and predictive. The other designations are variations of them. The Table 1 shows the kinds of maintenance with some characteristics of its.

In this study, the agreements with two classifications such as interventions in maintenance (corrective and preventive tasks) are considered. The predictive maintenance is a monitoring procedure on-line that provides information for future decisions and tasks of maintenance

In this study, the predictive kind is dealt, because is believed that if it is possible the monitoring the equipment all the working time, a lot of failures could be avoided. If the predictive monitoring could have characteristics like sensibility and resolution, could detect incipient abnormalities, which need for only fixing small interventions (e.g. lubrication, attach, and alignment).

TABLE 1 - 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	Failure	planned inspection	planned control or continuous measurement
Tasks to be carry out on the machine	replace of components	to take machine down to inspect and replace components	
Purpose of interference	Return to work	to guarantee the working for a period	to predict and detect failures

TABLE 2 - PARAMETERS TO BE MEASURED IN PREDICTIVE MAINTENANCE

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

A. *Measured parameters in predictive maintenance*

The measurement or monitoring of parameters can provide information that allows the inspection of specific elements of machine also about the condition of operation of it or the kind of failure. See Table 2.

The option of a given parameter or a more adequate form of investigation is relevant to determine the factors of machine malfunction. Small mechanisms can have changes in vibration when connected with sensors [18].

A technical analysis is possible through the obtained data, where the results can indicate the nature of the failure as expected, and establish which elements of the system are critical. The historical of machine also allows the determination of the most frequently failed elements, as well as the time spent between these failures.

II. VIBRATION ANALYSIS IN MONITORING MACHINES

Machines are complex structures with articulated mechanical elements. The parts that are linked 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 behavior of 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.

The centrifugal, alternative and friction forces acting on different elements of a machine in operation originate proportional mechanical vibrations. 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 [18].

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” [18]. That way, it is possible to identify each machine component, the kind of failure 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 recommends the measurement of:

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

A. Frequency of 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 [16].

B. 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 failure running in the system.

C. Determination of 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 [18]:

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 follows one orientated division.

III. EXPERT SYSTEMS (ES)

One of the most valuable goods in any line of business is the experience and skills of professionals involved, such as the knowledge acquired through long years of work in the area. A professional with such skill and knowledge in the subject is known as an expert.

Allied to the knowledge and experience of these professionals is possible to use of information technology, which can help to store information, to make combinations between them, and to get the immediate response in these interactions.

The development of a program that can use the expertise of specialists is called the expert system.

The expert systems are considered as a branch of artificial intelligence science. They are better understood when are classified as subgroups of a Knowledge Based Systems (KBS). The expert systems and a KBS allow the modeling of intuitive knowledge and the trials of these specialists. Some authors call this knowledge and trials as "rules of thumb" [7]. The "rule of thumb" is considered knowledge with practical purposes without the rigor of accuracy, when the situation allows.

According to [7] an ES is made up of the following components:

(i) The knowledge acquisition and knowledge representation component, known as the user interface. This is used to enter and elicit information. (ii) The knowledge base, which has facts about the problem area. It also contains procedures to make logical deductions between symptoms and causes. (iii) The blackboard, which is an area of working memory set aside for the description of a current problem. (iv) The inference engine, which provides a methodology for reasoning about information in the knowledge base and in the blackboard, and for formulating conclusions, i.e. it looks for similarities by matching the situation being analyzed with information within the computer.

There are a number of reasoning methodologies, i.e. various ways in which matching can be achieved. They can be rule-based, model-based, and case-based reasoning. In this further study, we will see, they will be based on rules or based on relational equations. Again, in [7] is possible to find that: to the different reasoning methodologies, different levels and types of knowledge can be required. These are heuristic reasoning, qualitative reasoning, and quantitative reasoning. Heuristic reasoning uses a symbolic approach to define problems, generate hypotheses, and draw conclusions. A symbolic approach is similar to the approach taken by human experts and the way they think when first looking at problems.

To develop an ES is necessary the storage and transference of knowledge from the specialist into the computer. The development process can be divided into two steps: a) first, an engineer of knowledge through a process of knowledge acquisition, which can be done by eliciting, gets the knowledge from the expert human; b) second, this elicited knowledge is stored within computer in the form of facts, rules, case histories and procedures in the knowledge base. The process for getting the knowledge is essential for the efficiency of ES. After the development it needs to be tested, for that the system can be useful.

The application of ES is possible in several areas like Engineering, Medicine and Economy. Normally an ES is prepared for helping professionals about diagnostic, support decision making, and in tasks that demand high processing. At Engineering, besides this, expert system is used to detect and correct failures and check quality in industrial processes [4]. In [9] is possible to find a review from 1995 to 2004 about ES's methodologies and applications.

IV. FUZZY LOGIC ON THIS PROCESS

Systems based on the concept of Fuzzy Logic, developed by Lofti Zadeh in 1960's, have been used successfully in several areas, such as medical, auto industry, industrial control, systems to aid decision-making and establishment of diagnosis.

Specifically in the area of tracking and analysis with the aim of having a diagnosis of the state of operation of machinery, it is possible to classify the result as a conclusion based on knowledge heuristic. Such knowledge comes from the experience of a specialist. Some settings and arrangements are made without regard to need or numerical accuracy.

An engine wear by the continuous use or improper operation may present abnormalities. The abnormality can be considered a defect (incipient failure) or as a failure (the status machinery is unable to fulfill their duties). In this universe of possibilities there may be different levels of defects to the total failure of the machine.

Determining the state of operation (normal or abnormal), the classification of the severity (defect or failure) and the severity diagnoses are important and necessary for the monitoring and predictive maintenance of machine [12].

The conclusion trust (diagnosis) is only possible if quantitative and qualitative variables involved have been observed. Our view is that the various states and potential for abnormal machine and trial of specialist are characterized as a typical case that can be treated by Fuzzy Logic.

A. The Fuzzy system

According to [6] the modeling Fuzzy has two distinct stages, identification and estimation of the system. The identification system is to determine the structure and parameters of the model to be used. The choice of the structure of fuzzy-model is generally based on any prior knowledge of the system to be modeled. The “a priori” knowledge has been based on the topics described in literature earlier and the experience of experts consulted. The second stage, the estimation is the establishment of the weights of the parameters chosen in the step of identifying the structure and the relationship between them. It has been used again to the experience of specialist.

As [6] the fuzzy modeling can be made by relational equations or based on rules. The method that uses relational equations may dispense the knowledge of the specialist because uses quantitative measurements all the time.

In this case is essential the experience and expertise of specialists. Due to the fuzzy-modeling on the basis of rules has been used. Fuzzy-modeling based on rules is simpler, allows quickly up dates and is more in line with the original premise of Fuzzy control; i.e. offers a method that allows the transformation of human experience in the control laws.

According to [14] the design of a fuzzy controller depends heavily on of empirical adjust, i.e. based on the experience of an expert.

The controller is composed of: input variables, which are called antecedent statements, a set of rules, by a machine of inference, and the output variables called consequent statements. The combination of fuzzy sets within a rule is called aggregation. The aggregation and the combination of all the fuzzy rules are called the "basic rules" of the controller. The first phase of the project of a fuzzy controller is the construction of the base of knowledge, this basis that determines the antecedent statements. After it comes the stage of estimating these statements and following the construction of the basis of rules that will be used in the inference.

The adjustments on the experimental prototype and the simulations of failures and defects, such as the estimation about the severity them, has been made by specialists. Theirs expertise and experiences has been the basis this search. We have participated with the development of knowledge base for doing the correlation from adjustments and simulations to ES.

Here it is possible to prove the importance and necessity which has been a specialist in building the controller. The machine of inference will be the responsible of providing the result of possible combinations that could arise (the consequent statements).

V. THE ACQUISITION PROCESS OF SPECTRAL SIGNATURE

A. The Rotating System

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

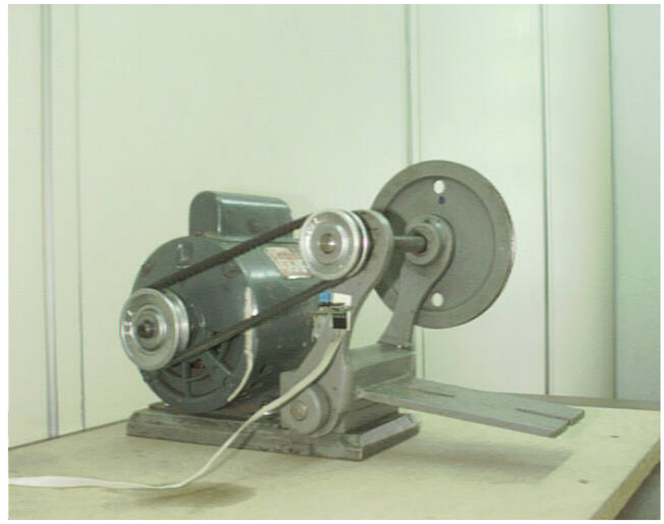

Fig. 1. The Rotating System.

The rotating speed has been measured with a L20 MICROTEST tachometer. The nominal rotation frequencies are calculated by division 60 Hz. However when the experimental prototype is working the measured real rotation frequencies are: 25.83 Hz to axle motor and 38.49 Hz to axle wheel. These frequencies can be seen in Fig. 2 and 3.

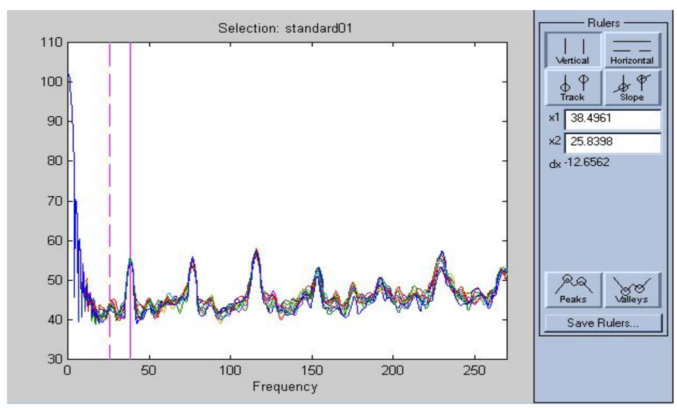

Fig. 2. Spectrogram with the cluster of 10 acquisitions.

According to Ya’Cubsohn [18], failures can be divided into two main generic classes: low frequency failures (for example: unbalancing, misalignment, etc.) and high frequency failures (e.g.: 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 failure. 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 failures.

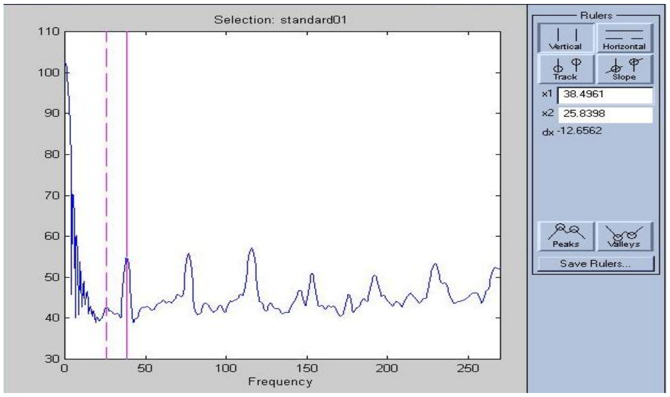

Fig. 3. The Rotating Machine's spectral signature.

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 [13a]. These failures can be classified as a cluster of low frequency failures and in this work are called non-adjustments.

One of the difficulties with motor failure detection is the motor high dimensionality [13b]. There are many variables that can affect the failure 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.

B. The accelerometer

The accelerometer that has been used in this experience is the Analog Device ADXL202, a solid state biaxial low-power device. The ADXL202 can measure dynamic acceleration (vibrations) in the span of ±2 g and the static acceleration (gravity). This electronic circuit has two digital outputs (x and y) that provide information about the accelerations in two orthogonal directions. The accelerations are coded as PWD (Pulse Wide Duration) 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.

C. The Psi25 system

A development system designed for digital signal processing, based on a TMS320C25 microprocessor (the Psi25), has been used for the acquisition of vibration signals of the Rotating System. The Psi25 system permits the acquisition of signals above 18 Hz. The interface provides the connection with the microprocessor-based counter inside a personal computer. A program compiled in C Language commands the beginning and the ending of acceleration data acquisitions recording them in *.dat files [10].

D. The acquisition of simulations

The vibration standard of the Rotating System, called the spectral signature has been obtained by the acquisition of ten *.dat files (see Fig. 2), where the average value has been computed by a C function (see Fig. 3).

The Fuzzy model may be seen in Fig. 4. The antecedent statements are the rotation frequency of axle wheel and vibration amplitude of the machine's rotation system (see Fig. 5 and 6). The consequent statement is the diagnostic of the system (see Fig. 7).

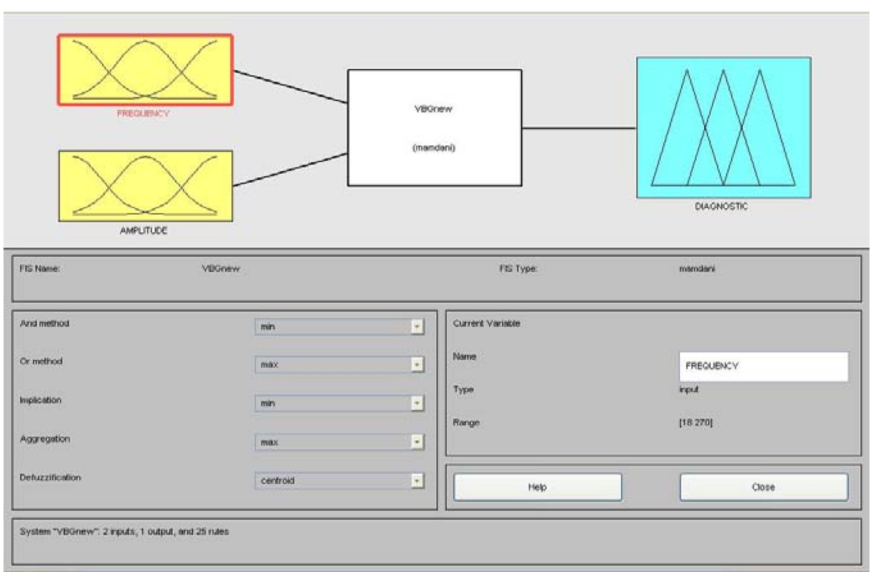

Fig. 4. The Fuzzy-modeling.

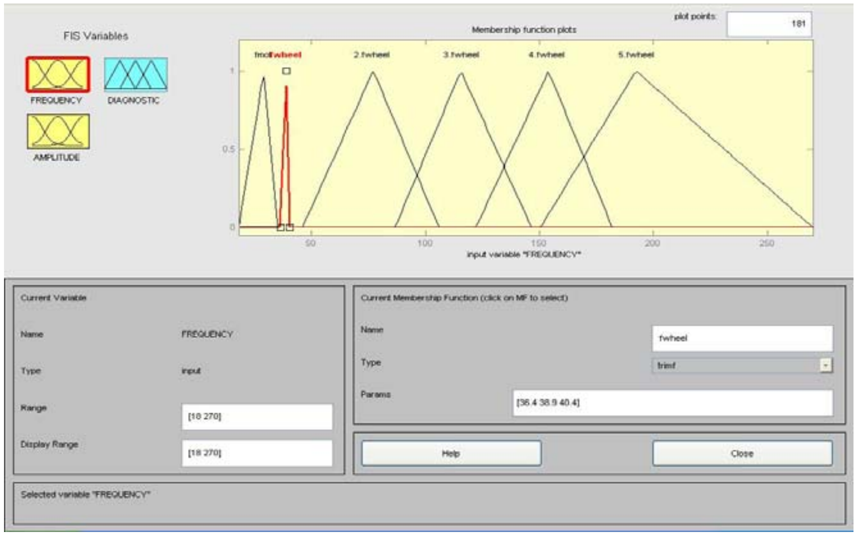

Fig. 5. The antecedent statement – Frequency.

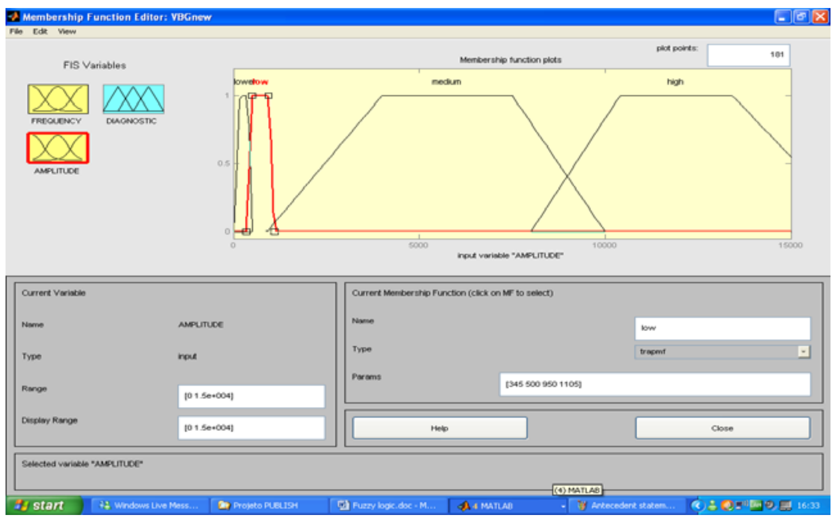

Fig. 6. The antecedent statement – Amplitude.

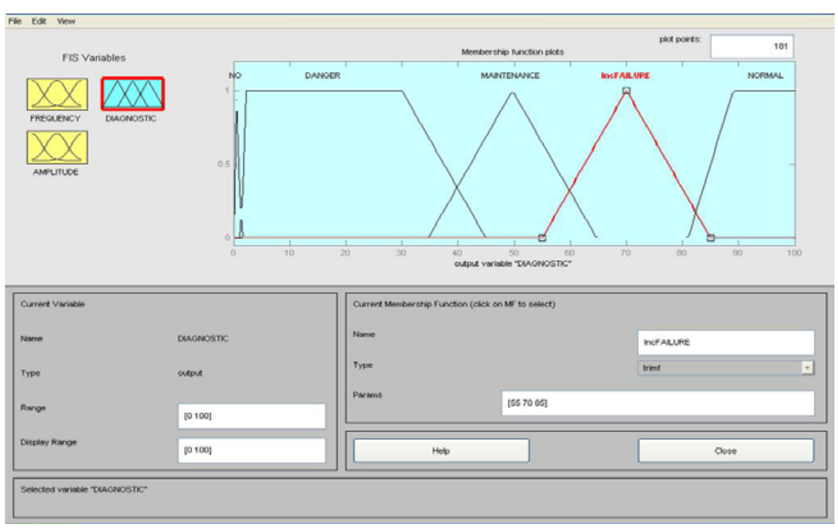

Fig. 7. The consequent statement – Diagnostic.

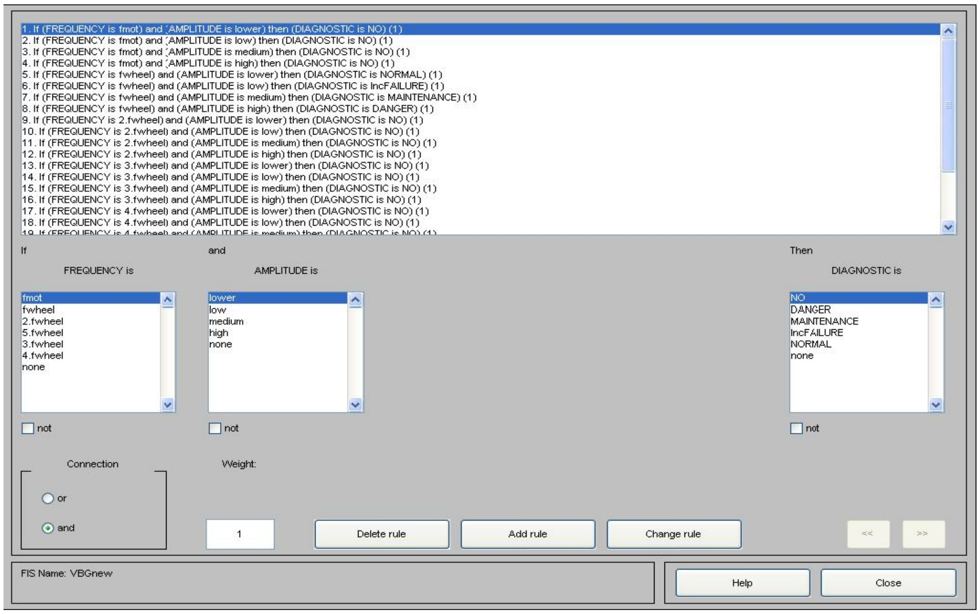

Fig. 8. The Fuzzy inference rules.

E. The Fuzzy inference rules

The combination among antecedent statements: frequency and amplitude, offer the diagnosis of the state of operation of the machine (Rotating System).

The diagnostic of the Rotating System's operation status is based on a collection of logic rules in the form IF-THEN statements (see Fig. 8).

The easiness to alter rules and update values of variables, allow the method becomes 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.

F. The simulated defects

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 failures are considered. The defects inserted in this stage are the unbalancing of axle wheel, by the insertion of asymmetric elements.

This is because the insertion of unbalanced elements is not possible with the Rotating System turned on.

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 1:1,666. The mass of the wheel is 1,012 g and the smallest element is 0.1 g. Others relations are established according to an adopted criterion.

G. The Fuzzy diagnostic

An Interface Human Machine (IHM), see Fig. 9, has been used for presenting the results from fuzzy rules inferences.

It is possible to run it by steps such as:

- Acquire data (*.dat);
- Mean of the data Acquisition (*.mat);
- evaluation and plotting of the spectral signature;
- Search of amplitude values in the axle wheel's rotation frequency; and
- Fuzzy Diagnostic.

It allows the automatic execution of all stages by a command, adjustment of the acquisition time, number of acquisitions, range of frequency for analyzing, and setting of the fuzzy system. The *.dat files are computed and analyzed in the frequency domain with the signal processing tool (called SPTOOL) of the Matlab package. It allows, beyond many advantages, the framing in a specific frequency range. Any modifications due to unbalancing will alter the axle wheel rotation frequency amplitude. Due to this, it is possible to make the analysis in this frequency range of the spectrum.

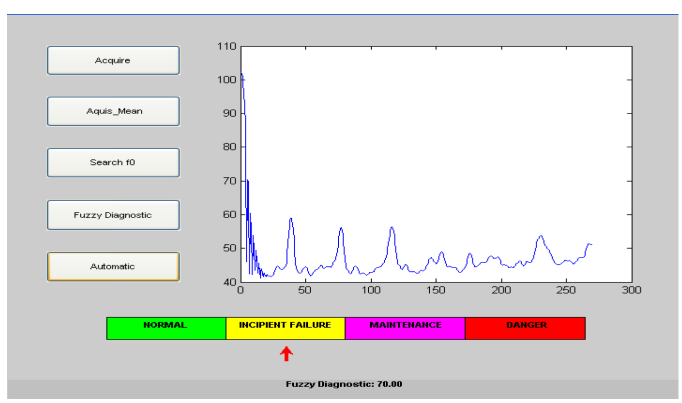

Fig. 9. The diagnostic in IHM.

VI. CONCLUSIONS

The obtained results show that it is possible to predict and diagnose incipient failures. The developed ES presents "sensibility" and "similarity", two requested characteristics for an efficient and consistent ES.

The ease of altering rules and updating variables makes the ES versatile. It can accommodate the desired performance range of the system, the quality of the construction, risk factors, and tolerance due to the constant use of machines.

Actually, this is the object of an academic research and it has been used as didactic platform. The goal is to make it a robust tool such that it can become perhaps an industrial product. We wish to contribute to a clever maintenance strategy for a more efficient manufacturing process.

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