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Research Paper

Prognosis and Detection of Experimental Failures in Open Field Diesel Engines Applying Wiener's Artificial Immunological Systems

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Abstract. The high costs of open-field diesel engines arise from the lack of maintenance of these systems. Thus, the maintenance of this equipment has been treated as a great challenge, as some methods of data monitoring are not possible to be implemented, given the inadequate sensing conditions, plant location, local climate, facilities, even the methods and maintenance routines. In a second step, the labor is not qualified and of sufficient quantity to meet the demand, resulting in a slow and inefficient system. One of the challenges of predictive systems is to inform damage and failures in real time of the operating conditions of these machines and equipment. This work demonstrates the possibility of analyzing and detecting failures in open field predictive systems, using the concepts of vibration and acoustics in artificial intelligence. One of the results of this work demonstrates the robustness of the negative selection artificial immune system algorithm, whose application of the Wiener filter was of fundamental need. The other result demonstrates the versatility of conditioned use both or just one of the concepts between vibration and acoustics, in prognosis and fault detection. Considering the versatility of using these two techniques, it is possible to affirm that, the predictive systems of real time analysis have an effective solution directed to the area and, if implemented, it is of low cost and high efficiency.

Keywords: Vibration; Acoustics; AIS-negative selection; Wiener filter; Predictive system.

1. Introduction

Agriculture, in general, has undergone technological changes in recent decades to benefit farmers and consumers in the production of products. Thus, several technologies have been used in order to overcome challenges such as costs, productivity and quality. Many programs to encourage technological production are successful in their implementation, but they are considered difficult to access by users of these technologies. The reason for this difficulty is associated with the lack of familiarity and knowledge of the technology in question.

In the transformation industries, the familiarization process of these technologies is more familiar and accepted, which is possible to mention the management of the information generated in the process of optimization, reductions, waste, sustainable adaptations, are considered data, commonly known as big data [1]. Much of this information is generated by the sensors and filtered by robust monitoring and control algorithms, in order for continuous improvements to occur, given the complexity and precision of certain operations [2].

The sensors act by sending information through signals, considered the digital representation of a certain amount of information, such as analog voltage, current, resistance, among others, whose function allows to demonstrate and identify the physical behavior of a given dynamic system [3]. Filters use spectral analysis and, when compared to other data analysis techniques, have a significant advantage over other techniques, as they reduce distortion, resulting in a significant improvement in reading performance and data speed, increase reliability and are low cost [4]. Given the randomness of a noisy signal, composed of numerous information, the Wiener filter when applied, provides a clean signal in real time. This occurs through the mathematical calculation of the mean square error, which can be decreased through the performance of the algorithm, converging to a minimum condition [5].

Dynamic systems positioned in the open field are difficult to analyze, as the control variables are numerous. Techniques such as structural health monitoring (SHM) are applied to provide information on the health status of a given structure, thus, the

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evolution of structural damage is minimized by increasing the life span. This technique acts directly in the prognosis of damages and failures using sensors, intelligent materials, data transmission, computational power and processing capacity, reducing the risk and safety factor through the analysis of historical data and measurements in real time[6; 7; 8]. One of the several concepts, however, fundamental for the analysis of structural dynamic systems is the experimental modal analysis, which identifies the frequencies of resonance and damping of acoustic signals and vibration, demonstrated by the frequency response function (FRF) [9].

The physical modeling of a dynamic system is done using a free body diagram, which when decomposed, demonstrates the general equation of motion. This partial differential equation can be solved by different methods, one of which is the optimization method that is directly linked to bioengineering. The biological immune system (BIS) represents a complex, adaptive, distributive learning system that acts in defense against pathogenic organisms such as bacteria, fungi and parasites, which learns through adaptation by distinguishing foreign and dangerous antigens from the body's own cells [10; 11; 12]. The artificial immune systems (AIS), derived from BIS and linked to the concept of SHM, has the function of solving computational problems of engineering systems, as it is considered robust and efficient [13; 14]. From this condition, it is possible to cite as an example, the detection of failures in rotating systems using AIS, whose AIS technique applied in the database, demonstrated the same behavior of failures as that of the statistical methods linked to failure prognosis [15].

The objective of this work is to demonstrate at first the robustness of the AIS algorithm applied to fault detection, using the concepts of acoustics and vibration under the Wiener filter. In order for this to be done, intrinsically, subobjectives are determined, as the first, the decomposition of the noisy vibration and acoustic signals in clean signals from the Wiener filter results; the second deals with the formation of the database of vibration signals filtered by the Wiener method (Data-Wiener); the third deals with the application of the AIS algorithm in the Data-Wiener; and finally, the demonstration of the separation and classification of Data-Wiener in prognosis and fault detection.

2. Signal Processing - Wiener Filter

The Wiener filter is a technique that predicts a signal condition applied to continuous one-dimensional signals obtaining the minimum mean squared error and can also be generalized for discrete signals [16; 17].

Mathematically the Wiener filter can be considered as a generalization of an integral convolution equation, and can be represented as,

$$\int_{-\infty}^{\infty} g(x-x')\, f(x')dx' = f_0(x) \tag{1}$$

which $-\infty < x < \infty$, $f(x)$ is an unknown function [18; 19]. The solution to this equation, written in the Fourier transform, can be written as,

$$F(\alpha) = [G(\alpha)]^{-1} F_0(\alpha) \tag{2}$$

where $F(\alpha)$, $G(\alpha)$ and $F_0(\alpha)$ are Fourier transforms of $f(x)$, $g(x)$ and $f_0(x)$ respectively, according to the definition, $F(\alpha) = \mathbb{F}[f(x), x, a] = \int_{-\infty}^{\infty} f(x)\; e^{j\alpha x} dx$; $G(\alpha) = \int_{-\infty}^{\infty} g(x)\, e^{j\alpha x} dx$; $F_0(\alpha) = \int_{-\infty}^{\infty} f_0(x)\, e^{j\alpha x} dx$ [18; 19]. The Wiener integral equation consists of assuming integration in a semi-infinite domain from 0 to $-\infty$, and thus,

$$\int_{0}^{-\infty} g(x-x')\, f(x')dx' = f_0(x) \tag{3}$$

which $0 < x < \infty$ [18; 19]. So, rewriting equation 3, as a convolution product, we will have,

$$\int_{-\infty}^{\infty} g(x-x')\, f(x')\, u(x')\, dx' = f_0(x)\, u(x) + f_-^s(x) u(-x) \tag{4}$$

where $-\infty < x < \infty$, $u(x)$ is a step function unit, and f_-^s is a new unknown that represents the continuation on the left side of the equation, $\int_{-\infty}^{\infty} g(x-x')\, f(x')\, u(x')\, dx'$, for $x < 0$ [18; 19]. Applying the Fourier transform, in the equation, we will have,

$$G(\alpha) F_+(\alpha) = F_-^s(\alpha) + F_{0+}(\alpha) \tag{5}$$

and $F_{0+}(\alpha)$ and $F_-^s(\alpha)$ are, respectively, the Fourier transform of the right axis function $f_0(x)\, u(x)$, and the left axis function $f_-^s(x)\, u(-x)$, therefore, considering the equation $G(\alpha)F_+(\alpha) = F_-^s(\alpha) + F_{0+}(\alpha)$ in the spectral form [18].

The Wiener equation is considered a vector or a scalar. Scalars involve only scalar quantities, whereas in vectors, vectors are of order n, as in the arguments, $F_+(\alpha)$, $F_{0+}(\alpha)$, and $F_-^s(\alpha)$, and the amount of matrix of the same order $G(\alpha)$. The $G(\alpha)$ is called the Wiener operator kernel and is the inverse $[G(\alpha)]^{-1}$, written as $G^{-1}(\alpha)$ [18].

3. Artificial Immune System

The immune system has the capacity to recognize and stimulate differences in its own and non-own mechanisms (self-nonself), whose precision of the response allows the concept to be applied in the construction of artificial intelligence models, known as artificial immune systems. These intelligence systems or models, act directly in the functions of pattern recognition, learning and memory acquisition, fault tolerance and detection, and fault diagnosis, and can be applied directly in the engineering area [12; 13; 20].

Basically, the biological immune system (BIS) determines the basic flow for the development of the algorithm using the functions of learning and memory. Therefore, the artificial immune system (AIS) algorithm can be developed using a general criterion: the antigen corresponds to an objective function and solves problems and restrictions; the antibody corresponds to the candidate solution; the degree of antigen and antibody affinity corresponds to the candidate solution with an objective function [12; 13; 20]. Figure 1 shows the steps of the AIS for the development of the algorithm.

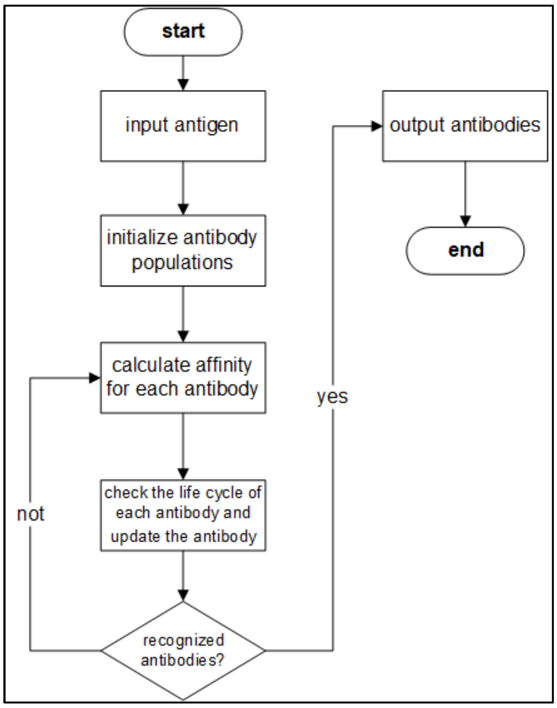

Fig. 1. Stages of Development of the AIS Algorithm

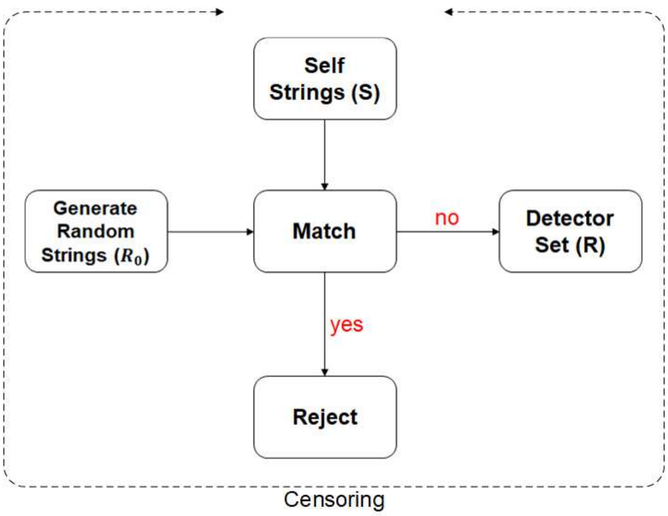

Fig. 2. Censorship (Generation of Detectors)

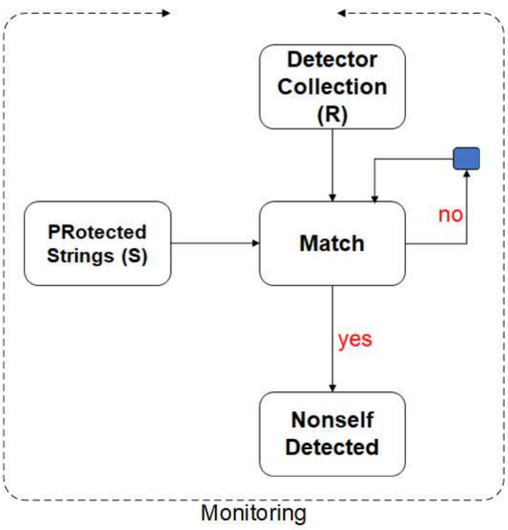

Fig. 3. Monitoring (Data Monitoring).

The biological immune system contains different theories, proposed by immunologists, as it has the capacity for continuous learning and adaptation. With that, several models were developed, being the clonal selection theory, immune network model and danger theory [13; 20]. Negative selection is considered a process of recognition of a ligand by a cell receptor, whose process of interaction between the lymphocyte and the antigen can result in the clonal deletion (death) or clonal anergy (anergy) of this lymphocyte [21].

Based on the biological immune system of negative selection, Forrest et al. (1994), proposes a negative selection algorithm that detects anomalies in computer systems, using the principle that detectors are generated by negative selection that recognize who invades or not the computer. The method is to distinguish the own and non-own cells, that is, to recognize the molecules that are of the organism (own), of the foreign molecules (not own). The algorithm of the negative selection artificial immune system has two phases: the first is considered the detector generator; the second is the monitoring of protected data compared to the detectors, considering that, if a detector is activated, it is known that the change has occurred. Figure 2 shows the generation of detectors, considered censoring, and figure 3 shows the monitoring of the protected characters for the changes [22].

The concept of perfect match between two strings of equal size, means that each location in the chain (string) contains identical symbols, however, this case is considered extremely rare, and therefore, it is necessary to introduce the concept of correspondence partial. The partial match rule is applied when r close matches have corresponding symbols and positions, thus, any two strings (x, y) are matching (true) when x and y, correspond at least to r nearby locations. The probability (P_m) of any two chains that match can be calculated by the equation,

$$P_m \approx \left(\frac{\left(\frac{(l-r)(m-1)}{m+1} \right)}{m^r} \right) \tag{6}$$

where, l corresponds to the number of symbols in the chain (length); m corresponds to the number of symbols in the alphabet; and r is the number of close matches needed to match [22].

Considering that the proximity correspondence is determined (r), the concept of the chain affinity rate (T_{af}) is introduced, which determines the degree of similarity necessary for the correspondence to occur. This condition can be described, considering the equation,

$$T_{af} = \left(\frac{A_n}{A_t} \right) 100 \tag{7}$$

where, A_n corresponds to the number of normal chains in the problem (own), A_t corresponds to the total number of chains of the problem (own and non-own chains) [23].

The quantification of the affinity of the analyzed patterns (Q_{af}), can be defined mathematically by the equation,

$$Q_{af} = \frac{\sum_{i=1}^{L} V_c}{L} 100 \tag{8}$$

which, V_c corresponds to the corresponding variables; L corresponds to the total number of variables; $\sum_{i=1}^{L} V_c$ corresponds to the sum of the corresponding variables. Thus, for the correspondence with the standards to occur, the condition $Q_{af} \geq T_{af}$ must exist [24].

4. Experimental Methodology

The experiment was carried out in an open field on an orange plantation farm, located near the city of Uberlândia/MG. On the farm, in a place protected from sunlight, without walls, there are two diesel engines of the brand MWM TCA 9010, with power of 220 CV. These two engines belong to a group of several engines distributed in the farm plant. The experiment was based on capturing the vibration and acoustic signals from the diesel engine coupled to a water pump, and simulating the stress conditions of the pump engine with closing of the inlet and outlet valves, connected to the pressure vessels, of the pump of water.

The water is displaced through pressure vessels to the various irrigation points, resulting in the irrigation of fruit plants, improving the quality and production of the oranges. The diesel engine and pump set are considered to be the main points of support for production, the stopping of which must be done in a planned manner, because, otherwise, one of the results is the poor quality of the fruit. Figure 4 shows the water tank and figure 5 the MWM TCA9010 diesel engine.

In the figure, the pumping system is in blue, coupled with the shaft of the diesel engine. The cage that covers the diesel engine has the protection function defined by the work safety standard. The motor and pump fixing base are located on a gantry (metal structure) fixed to the floor. Considering that the gantry is fixed to the ground, the displacement of the system can be considered null. Thus, the motor-pump assembly vibrates only when the diesel engine is running.

In the current motor-pump system, an automatic set of plates and sensors for activation and shutdown is coupled, based on the hours of the day. The maintenance of the motor-pump system only occurs when the set is not activated, determining the departure of one of the company's employees to check the conditions of stopping or not activating the system. The method of monitoring the life of the engine components by remote sensing is not done.

The collection of the vibration and acoustic signal was developed based on a pattern of positioning of the sensors, so the collected signals could better demonstrate the reality of the motor-pump system, considering the operation without the simulated loads and with the stress loads. The schematic drawing of the positioning of the vibration and acoustic sensors can be seen in figure 6 in a simplified way.

The capture of the vibration and audible signal was made using the following equipment: 01 vibration sensor (three-axis accelerometer MPU-6050), 01 generic electret microphone, 01 UNO arduino board, wires and cables for the connection. Figure 7 shows the detail of the positioning of one of the vibration sensors positioned on the motor-pump coupling.

With the sensors in place and the data acquisition system in operation, the motor-pump system was activated to form the databases. The vibration databases were separated as follows:

Fig. 4. Water Reservoir

Fig. 5. MWM TCA9010 Diesel Engine

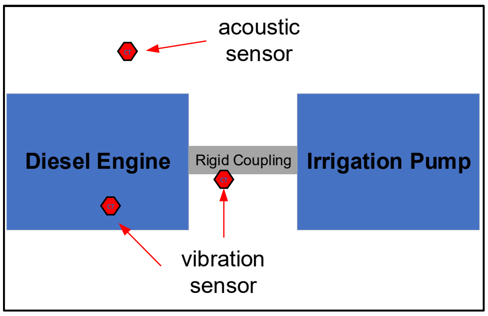

Fig. 6. Schematic Drawing of Sensor Positioning

Fig. 7. Detail of the Sensor Positioning

- Normal signal bank, it is the motor-pump system operating normally with a continuous flow of water to the irrigators;
- Signal bank with load 1, the motor-pump system is operating normally, but with the water inlet valve on the pump closed;
- Signal bank with load 2, it is the motor-pump system operating normally, but with the water outlet valve on the pump closed;

These 2 behaviors of simulated load of the motor-pump system, demonstrate the conditions of possible stops of the motor that usually happen in the routine of the day to day without notice. The normal signal database is composed of 10 signals of size 1x6870 samples, considered signals without fail. The signal database with load 1 and 2, is composed of 2 signals of each load, considered as failures, of size of 1x6870 samples. Thus, a total of 14 1x6870 size signals were collected. The database of the acoustic signal is composed of a signal with load 1, of size 1x6870. The reason for the collection of an acoustic signal was conditioned to the possibility of comparing the FRF of the vibration and acoustic signals, considering the ease of use of the sensors in the open field. Figures 8 and 9 show the signals with vibration and acoustic noise, respectively.

Figures 10 and 11 show the vibration and acoustic signal already processed by the Wiener filter and in the frequency domain. Note that figures 10 and 11 show that the FRF of both the vibration signal and the acoustic signal have similar values, differing at most 1%. This demonstrates the possibility that the vibration signal and the acoustic signal can be used in the processing of fault analysis signals. Another point of view of the use of the two signals is that, depending on the conditions of the place, it is possible to use one of the two sensors so that the signal is captured, and its subsequent application in the failure analysis.

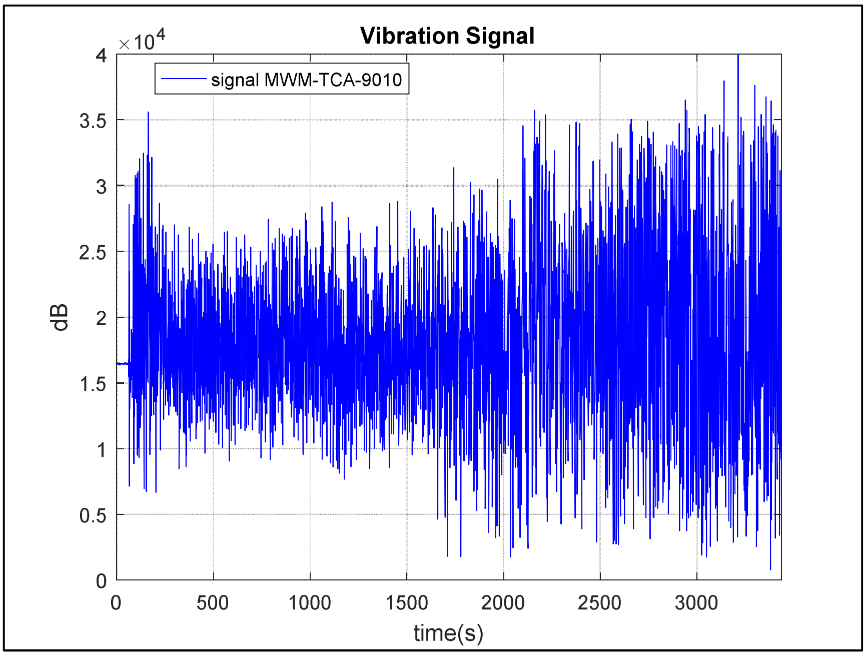

Fig. 8. Noise Vibration Sign

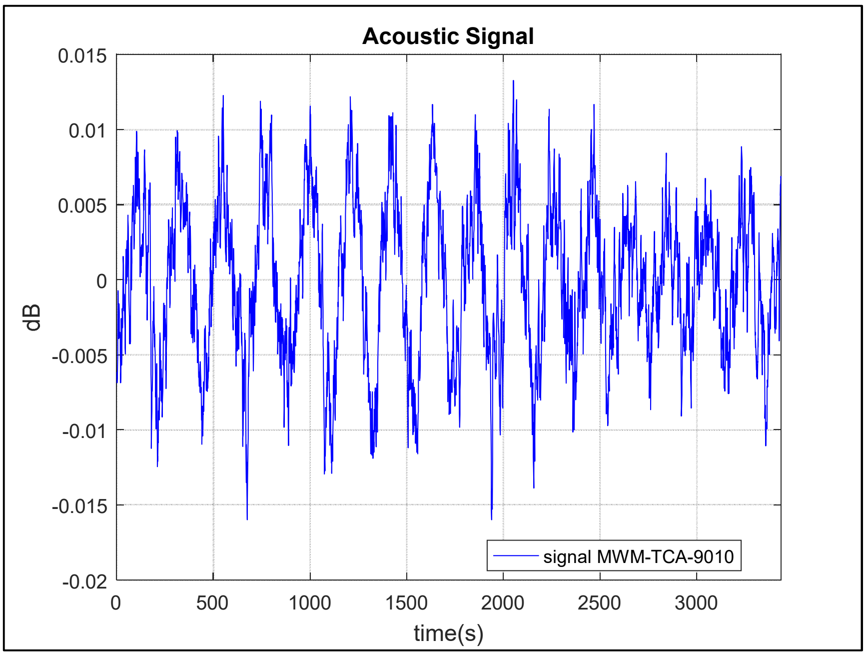

Fig. 9. Noise Acoustic signal

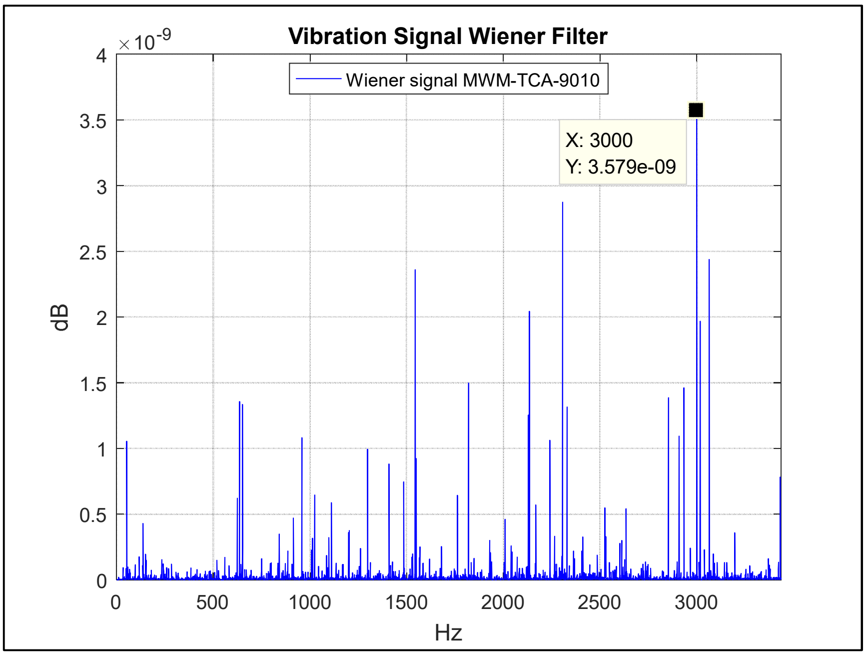

Fig. 10. Vibration signal Processed by the Wiener Filter

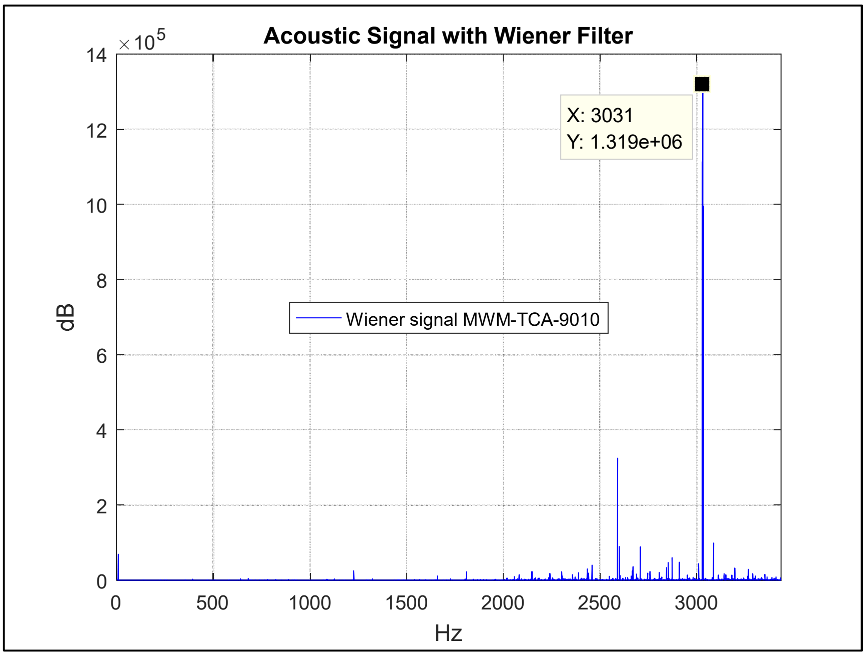

Fig. 11. Acoustic Signal Processed by the Wiener Filter

It should also be noted that the Wiener filter applied to both signals, allowed to demonstrate the similarity of FRF. Thus, in this work, the Wiener filter is extremely important and can be considered as an essential reference tool for later application of AIS.

Figures 12 and 13 show the comparative signal of vibration and acoustic, before and after the application of the Wiener filter.

The database of all signals was processed by the Wiener filter, so that the noise was eliminated. This condition is necessary, as it is a process that precedes the analysis of the signals by the AIS, demonstrating the improvement of the quality of the signals.

In the sequence, the signals processed by the Wiener filter, form a new set of information, of which, they are called Data-Wiener, and thus, processed by the negative selection AIS algorithm. The signal processing algorithm by AIS, conditioned to the proper and non-proprietary method, should detect the anomalies of the system using the detectors generated by the negative selection that will recognize the different signals, separating them. Afterwards, in the monitoring, each separate signal will be classified using the synonyms of prognosis of the type of failure and its respective probability, by the condition of the signal change. The result of engine 1 can be shown in table 1 and in figure 14; the result of engine 2 is shown in table 2 and figure 15.

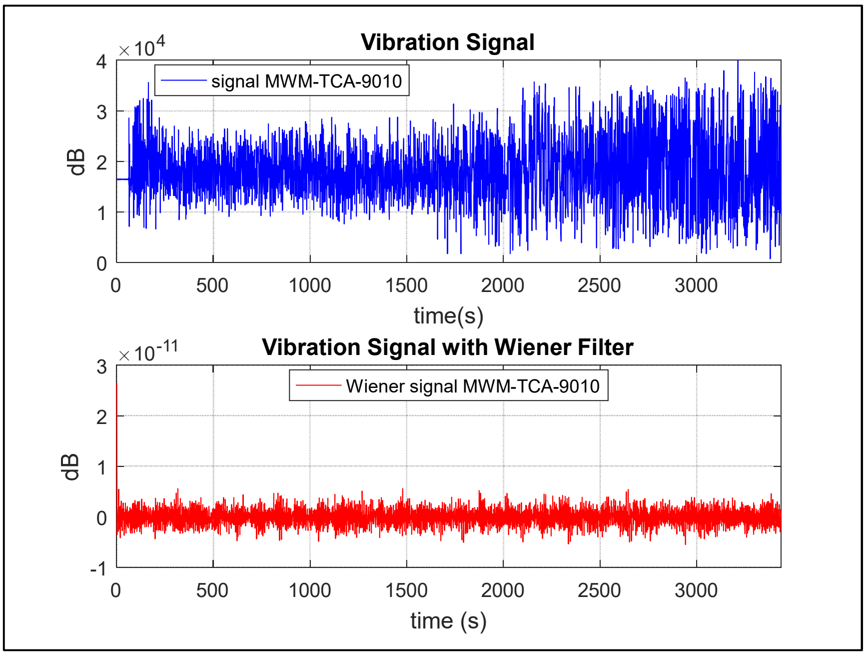

Fig. 12. Comparative Vibration Sign (Wiener Filter)

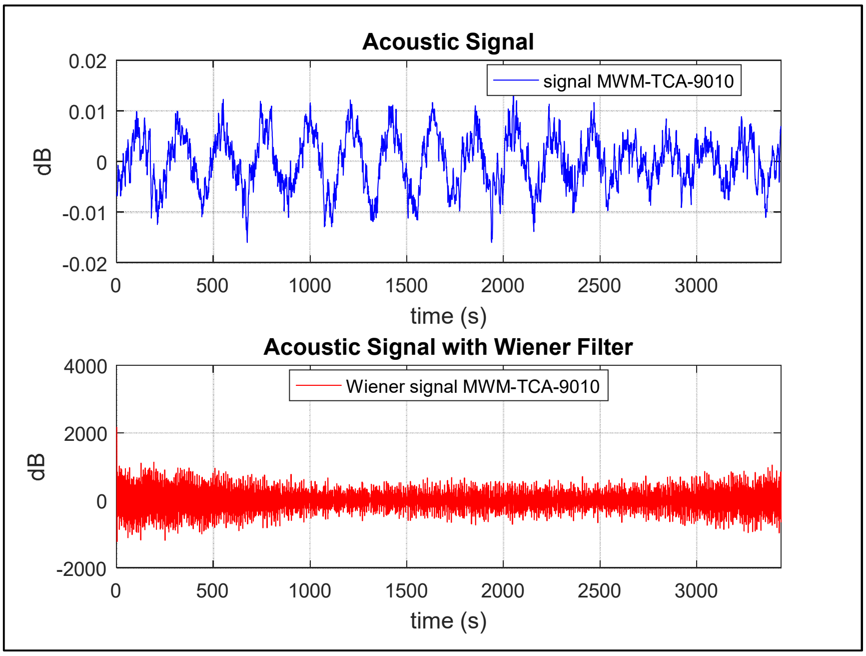

Fig. 13. Comparative Acoustic Signal (Wiener Filter)

Table 1. AIS classification applied to the Data-Wiener (Engine 1)

Classification		Motor-Pump 1			
		Severity Level			
		very low	low	medium	high
Failure Probability	low	-	-	-	-
	moderate	-	-	-	-
	high	-	-	-	-
	very high	1	-	-	1

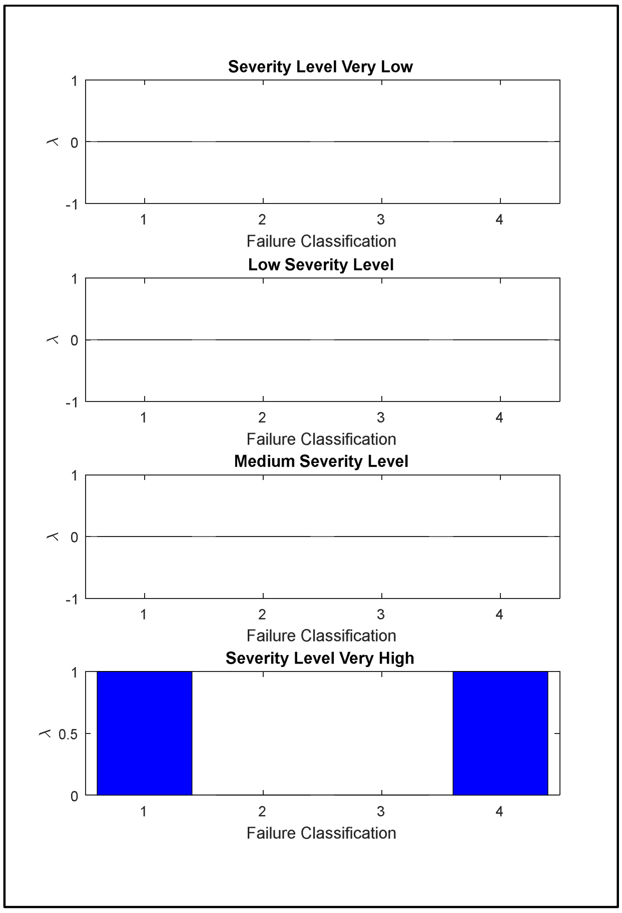

Fig. 14. AIS applied to the Data-Wiener (Engine 1)

Table 2. AIS classification applied to the Data-Wiener (Engine 2)

Classification		Motor-Pump 2			
		Severity Level			
		very low	low	medium	high
Failure Probability	low	-	-	-	-
	moderate	-	-	-	-
	high	-	-	-	-
	very high	-	-	-	2

The reading of the bar graphs, figures 14 and 15, can be interpreted as follows: each graph corresponds to the degree of severity of the failure, which is distributed in very low, low, medium and very high. On the x-axis, the probability of failure is classified as low, moderate, high and very high; the y-axis shows the number of signals read on each graph. Note that, given the group of 14 signals, 10 normal signals with no failures, and 4 signals with failures, the result demonstrated was that 2 motor-pump 1 signals are located on the very high severity level graph with failure probability rating low and very high. In the motor-pump 2 graph, the 2 signals are located in the graph of very high severity level, with a classification of the probability of failure located in very high.

The result of the analysis of figures 14 and 15, show that the system's precision in the perfect match condition, clearly defines the condition of the failed signals.

5. Discussion of Results

In agriculture, the challenges are diverse, one of which is what this work demonstrates, which is the lack of management and application of an intelligent predictive maintenance system in the motor-pump system. If the motor-pump system stops at random, it is difficult to know the reason for this stop and the degree of reliability of the parts that make up this system. This work demonstrates the possibility of implementing an intelligent predictive maintenance system, based on the following steps:

In the first stage, it is necessary that the vibration and acoustic sensors capture the information, a noisy signal, which must be processed by the Wiener filter. The objective of the Wiener filter is to clean the signal noise, so that, in the next step, this signal is used in the analysis of the negative selection AIS. Note that, with the application of the Wiener filter, the possibility has been demonstrated that either of the two sensors, acoustic or vibration, can be used successfully, as the FRF can be considered similar. The insertion or choice of only one type of sensor to be applied in the system can make the operator's condition difficult, or even limit the possibilities of reading the system conditions. The result of applying the Wiener filter is the formation of a database called Data-Wiener.

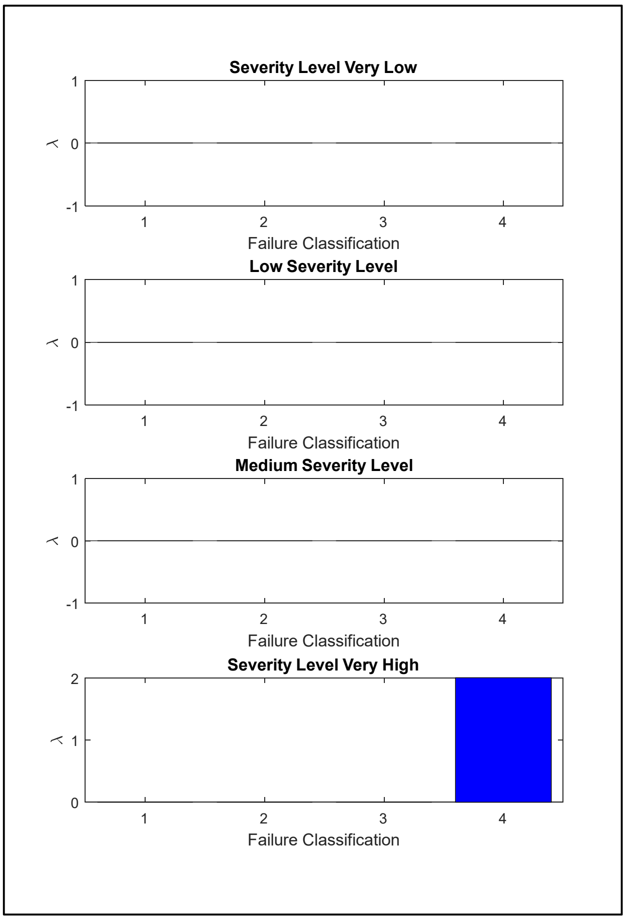

Fig. 15. AIS applied to the Data-Wiener (Engine 2)

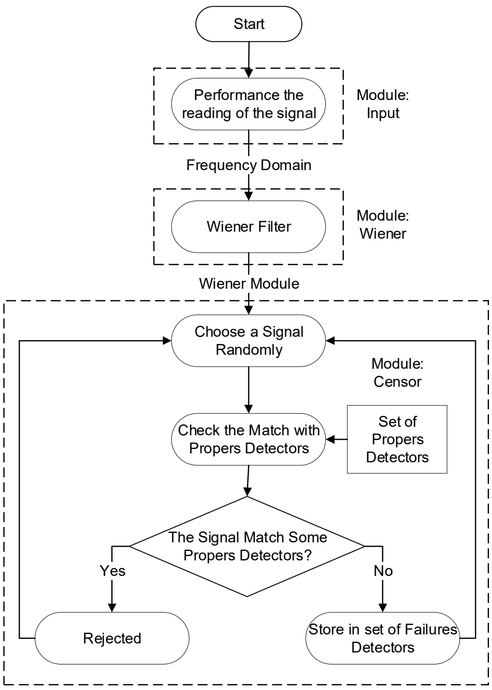

Fig. 16. Wiener-AIS Processing Methodology (censoring)

In the second stage the Data-Wiener is processed by the negative selection AIS algorithm, demonstrating that the separation and classification of signals can be done based on the stages of processing of censorship and monitoring, separating the 4 signals with failures of the motor-system. MWM TCA 9010 pump.

Considering the results found, it is possible to affirm that this research demonstrates a new concept for the formation of signal analysis in AIS, conditioned to the signal quality by the Wiener filter. The primary consideration occurs when demonstrating the FRF criterion of the vibration and acoustic signal, which allows the choice to adopt the best choice of sensor at the analysis site. The secondary consideration, perhaps the main one, is that, given the elimination of signal noise, it is possible to improve the quality of the AIS analysis, reducing the system error, so much so that the correspondence analysis made it possible to use the perfect match. Another point of view that allows the introduction of this condition is that, given the improvement in signal quality, other concepts of bioengineering processing can be applied to FRF.

Thus, it is possible to consider the importance of the Wiener filter and even define the condition as a mandatory and innovative procedure for cases similar to this work. The methodology in signal processing and prognosis analysis and fault detection applied to the negative selection AIS, can be seen in figures 16 and 17, respectively.

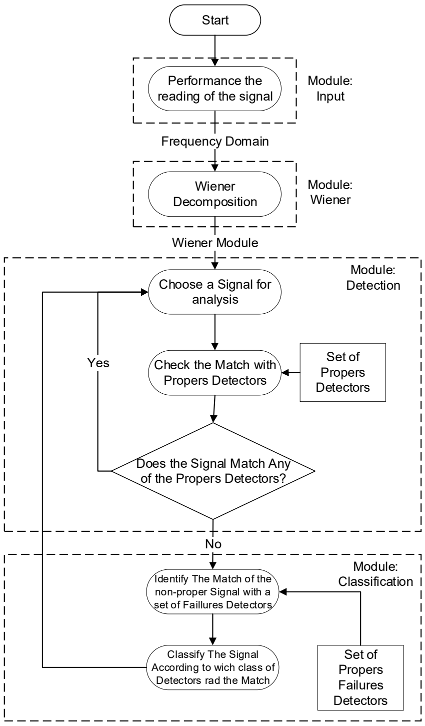

Fig. 17. Wiener-AIS Processing Methodology (Monitoring)

6. Conclusion

This work demonstrates several qualitative aspects for the application of negative selection AIS in the detection of failures in dynamic open field systems. The first condition is in the proposal that it is possible to choose the best sensor to be applied in capturing the signal. This demonstrates versatility and practicality, as the applications of embedded devices used in industry cannot always be applied in the field, as in the case of a maintenance system in agriculture. This fact occurs due to the diversity of weather, climate, protection of the place to be introduced and the sensor is fixed. The second condition was that the independence of the use of the vibration and / or acoustic sensor was caused by the introduction of the Wiener filter concepts. The main objective was to clean the noisy signal, and the FRF result clearly demonstrated that the difference between frequencies is 1%. This can be considered a result of similarity between the FRF of each signal, captured by different sensors. In this way, the proposal for versatility in applying the sensor is true. The third condition can be conceptualized with the statement by Forrest et al. (1994) that explains that the perfect match is an extremely rare case, but it can be determined. In this work with the signal filtered by the Wiener filter, the FRF when applied in the negative selection AIS, resulted in the perfect match. This demonstrates that the condition of applying the Wiener filter is a necessity that improves and guarantees the quality of the signal to contribute to the perfect match. The fourth condition demonstrates that the negative selection AIS separated and classified the signals, conditioning them to the groups of level of failure severity and probability of failure, with the perfect match. This demonstrates the precision and robustness of the algorithm and the systematic approach in using the Wiener filter. Therefore, this work demonstrates that low cost vibration and acoustic sensors can be used with versatility in predictive systems to monitor the behavior of components of the motor-pump system, and also that the negative selection AIS has better efficiency and robustness when analyzing a signal processed by the Wiener filter. The needs of this work were met and demonstrated by the robustness of the negative selection AIS process and algorithm and can be considered as an innovation research that contains technological development.

Author Contributions

This work demonstrates the importance of the diversity of vibration and acoustic techniques in the detection of failures of dynamic systems applied in the open field. Specifically in agriculture. One of the important points of this work is to demonstrate that the Wiener filter allowed the predetermined perfect matching condition for the application of the artificial immune system explained by Forrest et al. (1994). Another strong and intrinsic point to the system is the use of sensors and acquisition plates for low cost universal use, of which they performed an excellent result in the search for a low cost solution. The last strength and conclusion of this work demonstrates the robustness of the negative selection AIS algorithm in the application of fault detection, contributing to the classification of failure prognosis and pre-establishing the condition of the probabilities of failures. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

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Conflict of Interest

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