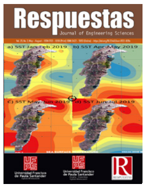
Respuestas, 25 (2) May-August 2020, pp. 93-101, ISSN 0122-820X - E ISSN: 2422-5053



Respuestas
Journal of Engineering Sciences

RESPUESTAS

Original Article https://doi.org/10.22463/0122820X.2188

Failure analysis in single-cylinder diesel engine SK-MDF300 through acoustic emissions

Análisis de fallas en motor Diésel monocilíndrico SK-MDF300 a través de las emisiones acústicas

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How to cite: J. Duarte-Forero, S.A. Ramón-Ramón, G. Valencia-Ochoa, "Failure analysis in single-cylinder diesel engine SK-MDF300 through acoustic emissions ". *Respuestas,* vol. 25, no. 2, pp. 93-101, 2020.

Received on February 07, 2020; Approved on April 5, 2020

ABSTRACT

Keywords:

Acoustic emission;
Condition monitoring;
Engine diesel;
Diagnosis;
Fault injector.

In the present study, the diagnosis of a single-cylinder diesel engine is evaluated through acoustic emissions. The acoustic signal from four engine locations, which include the engine block, the injection system, the fuel tank, and the fuel pump, is analyzed using the medium quadratic root technique. The analysis is carried out at a fixed speed of 3200 rpm and a load percentage of 20%, 40%, and 80%. The results obtained show that the comparison of the acoustic signals of two different time periods allows to quickly and easily evaluate changes in the engine conditions. The sensitivity of acoustic emissions makes it possible to identify different engine load conditions. The study of the acoustic signal in different engine locations allowed to identify the injection system as one of the main areas prone to fail or changes in its operating condition. Additionally, the analysis method based on the acoustic signal RMS allowed to clearly identify faults in the injection system. The above could be done by comparing signals and analyzing the variability of the signal. Therefore, the ability of acoustic emissions to perform a rapid and low-cost diagnosis is demonstrated, without requiring relevant physical modifications to the engine.

RESUMEN

Palabras clave:

Emisión acústica,
Monitoreo de la condición,
Motor diésel,
Diagnóstico;
Inyector de fallas

En el presente estudio, el diagnóstico de un motor Diesel de un solo cilindro se evalúa a través de las emisiones acústicas. La señal acústica de cuatro lugares del motor, que incluyen el bloque del motor, el sistema de inyección, el depósito de combustible y la bomba de combustible, se analiza mediante la técnica de la raíz cuadrada media. El análisis se lleva a cabo a una velocidad fija de 3200 rpm y un porcentaje de carga del 20%, 40% y 80%. Los resultados obtenidos muestran que la comparación de las señales acústicas de dos períodos de tiempo diferentes permite evaluar rápida y fácilmente los cambios en las condiciones del motor. La sensibilidad de las emisiones acústicas permite identificar diferentes condiciones de carga del motor. El estudio de la señal acústica en diferentes ubicaciones del motor permitió identificar el sistema de inyección como una de las principales áreas propensas a fallar o a cambios en su condición de funcionamiento. Además, el método de análisis basado en el RMS de la señal acústica permitió identificar claramente los fallos en el sistema de inyección. Lo anterior se pudo realizar comparando las señales y analizando la variabilidad de la señal. De esta manera, se demuestra la capacidad de las emisiones acústicas para realizar un diagnóstico rápido y de bajo costo, sin necesidad de realizar modificaciones físicas relevantes en el motor.

Introduction

At present, diesel engines are used in a large number of sectors and industries due to their characteristics, such as reduced operating costs, durability, high performance, and reliability [1]-[5]. Diesel engines are widely used in the transport sector in equipment such as construction machines, automobiles, mining machines, and ships [6], [7]. Additionally, they are normally employed in construction sectors, different types of industries, and agroindustrial activities. Despite the advantages present in diesel engines, its use generates high levels of polluting emissions [8]. Therefore, it is of the utmost importance that diesel engines operate in the best

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possible conditions, with the aim of minimizing their emissions and increasing their useful life. Due to the above, it is necessary to use techniques and methods to monitor the behavior of the diesel engine. Thus, the diagnosis of irregular behaviors and failures is possible.

Various techniques have been developed for the diagnosis of engine conditions. These include analyzes of oil, cylinder pressure, wear, vibration signals, and measurement of angular engine speed. Each method is used for the specific study of some internal engine processes [9], [10]. However, the use of these techniques is limited due to their intrusive characteristic. Additionally, the sensors used in these techniques are usually high costs. One of the most promising techniques for diagnosing the state of the engine is the acoustic signal measurements.

This type of signal originates from the elastic waves of a body influenced by an external agent [11]. Acoustic emissions have been widely used to analyze the state of different materials used in the construction of structures. Additionally, it has been used for fault diagnosis and bearing defect detection. Mba and Rao [12], concluded that acoustic signals could be used in various types of machinery. Table I shows the main sources of acoustic emissions and their transmission routes in the engine [13].

Table I. Normal sources of noise generation in an engine

Source	Transmission path	Noise
Combustion process	Engine block	Manifold
Admission system, fan, turbocharger	Airborne	Engine bay Intake ducts
Mechanical	Piston and cylinder connections	Cylinder head Oil pan Cover chain

Acoustic signal based monitoring has been used to minimize the intrusive nature of traditional diagnostic methods in diesel engines [14]. These types of signals from acoustic emissions are not influenced by the noise and vibration characteristic of engine operations. Among the first uses of acoustic signals for the diagnosis of the engine is the research of Fog et al. [15]. This investigation analyzes the detection of the state of the exhaust valves of a marine diesel engine. Gill et al. [16] caused a defect in the engine by varying the pressure of the injectors. The results indicate that the behavior of the acoustic signals changes. Similarly, El-Ghamry et al. [17] demonstrated that acoustic emissions are sensitive to changes in engine combustion.

Some research uses acoustic signals to study the conditions of fuel injectors. The results obtained show that acoustic emissions allow a higher degree of reliability at higher loads and speeds in the engine, compared to other diagnostic techniques [16]. Similarly, Bejger [18] studied the applications of acoustic signals for the diagnosis of the injection system of a marine diesel engine. The results obtained show that the non-intrusive nature of the sensors for measuring acoustic emissions allows cost reduction and simplifies configuration. Additionally, it was concluded that there is a direct relationship between the acoustic signals and the behavior of the injection system.

During normal operating conditions in a diesel engine, the combustion process is the main source of the noise. This noise signal is generated by the sudden increase in pressure in the combustion chamber, producing noise in the air. Li et al. [19] investigated the noise generated by the combustion process. The results obtained show that the signal analysis allows the combustion stages to be identified, such as the end of the compression stroke and the expansion stroke. Additionally, it was analyzed that the pressure change causes the vibration of other engine components such as pistons, cylinder head, and engine housing. The vibration of these elements produces additional sources of noise that can be studied.

Although acoustic emissions may be more affected by noise from other sources, the implementation of robust data acquisition systems can avoid these problems. These systems may include signal processing, the implementation of filtering methods, post-processing techniques, and the analysis of the characteristics of the signal [20]. The previous studies show the potential of the analysis of the acoustic signals for the diagnosis of the conditions and the detection of failures, thanks to their advantages such as low cost, versatility, and non-intrusive nature. Due to the above, the present study aims to implement acoustic emission analysis techniques for the diagnosis of a cylindrical mono diesel engine, which is normally used for the generation of electrical energy in isolated areas. Therefore, it is essential to use tools that allow maintaining the efficiency and useful life of the engine.

Section II of this document presents the materials and methods used in this investigation. This includes a description of the test engine, the instruments for measuring the signal, and a description of the acoustic emission processing. In addition, section III presents the results and discussions, specifically the characteristics of the acoustic signal in different engine locations, the residual signal as a means of comparison, the influence of the engine load and the different forms of fault detection in the injectors Finally, the conclusions are presented in the final section of the document.

Materials and methods

Description test bench

For the experimental tests, a SK-MDF300 diesel engine of 4.6 hp maximum at 3600 rpm, single-cylinder, 4 strokes, and natural aspiration was used. The engine is coupled to a dynamometer, responsible for controlling the level of load. The displacement of the diesel engine is 299cc, and its stroke - diameter is 62.57 mm x 78 mm.

Two classes of acoustic emission sensors were used to measure the acoustic signals, a high-sensitivity flat frequency response F15I-AST sensor, and a Micro80 sensor with a frequency range of 200-900 kHz. These sensors were located in four different engine locations. The locations correspond to the engine block, the fuel tank, the fuel injector, and the fuel flow pump. The acoustic emission sensors are connected to amplifiers. The signals are recorded at a maximum frequency of 2 MHz and with a lower filter of 100 kHz.

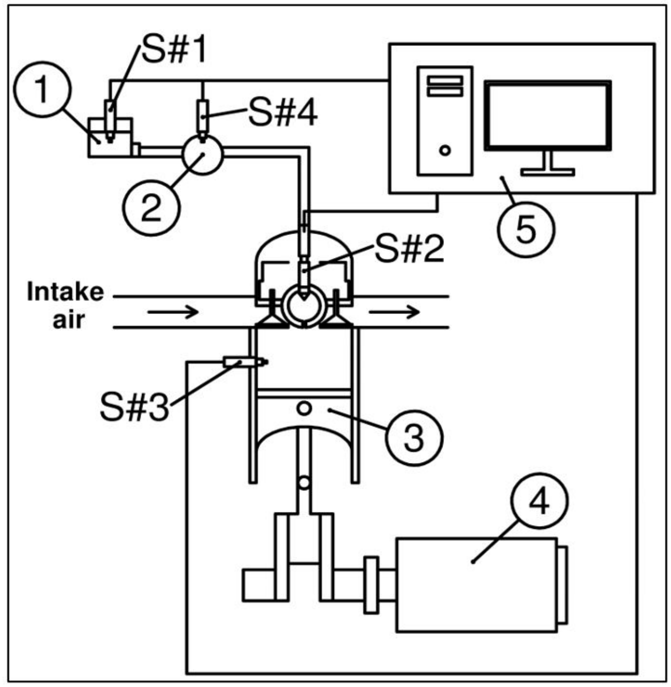

Figure 1. Experimental setup of the test bench

1. Diesel tank, **2.** Gravimetric fuel meter, **3.** Engine, **4.** Dynamometer, **5.** Data acquisition system.

Figure 1 shows the scheme of the test bench with their respective connections. The location of the acoustic sensors is identified by the nomenclature S#. Table II shows the main configuration of each sensor. The acoustic emission sensors were connected to the engine directly by means of an adhesive material (cyanoacrylate). By using a rotation sensor (NJK-5002C), the crankshaft angle is monitored.

Table II. Acoustic emission sensors

Sensor identification	Sensor AE	Gain	Sensor filter [kHz]
S #1	F15I-AST	+45 dB total	100 - 450
S #2		+45 dB total	100 - 450
S #3		+45 dB total	100 - 450
S #4	Micro80	+45 dB total	100–1000

Acoustic emission signal processing

Several approaches have been tested for acoustic signal processing in diesel engines. The research conducted by Wu [21] describes many of the techniques that have been employed. Normally, burst acoustic emissions are used for the diagnosis of cracks, damaged material, among other similar conditions. However, this type of methodology is difficult to implement to other engines, due to the necessary configuration of the parameters and thresholds of the acoustic bursts.

Due to the above, the acoustic signal diagnosis was made based on instantaneous value analysis. For this, acoustic emissions were processed in root mean square (RMS) signals, using a time counter of 130 µs. A sample length of 4500 was chosen from a population of 30 cycles. The number of cycles indicates a collection time of one second for data acquisition, maintaining a balance between data processing and storage.

Test procedure

For the measurement of acoustic emissions, three load conditions were tested: 20%, 40%, and 80%. At these load percentages, the engine maintained a constant speed of 3200 rpm because it is a stationary engine, mainly used for power generation. The tested engine torque was 3 Nm, 6 Nm, and 9 Nm.

For the study, it was used as commercial diesel fuel. The fuel properties are shown in Table III.

Table III. Diesel properties

Fuel	Test method		
	ASTM D1298	ASTM D445	ASTM D240
	Density [kg/m^3]	Viscosity [cSt]	CV [MJ/kg]
Diesel	820.5	2.62	44.15

Results and Discussion

Acoustic signal characteristic according to its location in the engine

The RMS signals of each acoustic emission sensor are shown in Figure 2.

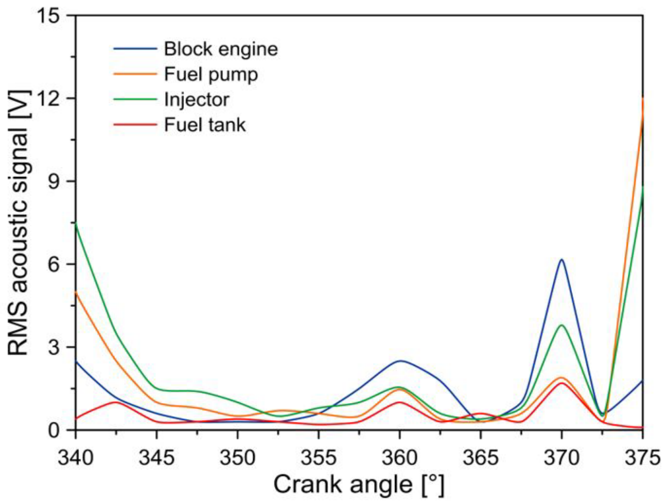

Figure 2. RMS of the acoustic signal in different engine locations

It is observed that the highest noise levels occurred in the injection system and in the fuel pump. The combustion tank records the lowest level acoustic signal. The combustion process and expansion are the cause of the greater amplitudes in the injector and the fuel pump.

The recording of the acoustic signals shown in Figure 2 allows the analysis and comparison of different locations in the engine. The above provides a guideline for comparison with measurements taken later. From this, it is possible to monitor and locate changes in the behavior of the engine, due to mechanical failures, failures in the injection system and /or fuel supply.

For the development of the described analysis, the average of the acoustic signals of each sensor at a specific engine operating condition is recorded. Subsequently, a difference is made with the recording of the signals taken in a future measurement. The result is a residual acoustic emission signal that symbolizes the inequality between the signals of each sensor. An example of this comparison technique is shown in Figure 3.

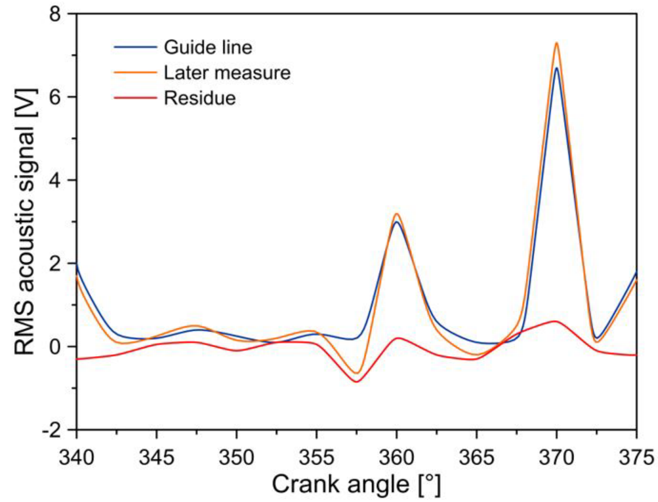

Figure 3. Comparison of the guideline and residual line obtained

In this way, it is possible to observe changes in the state of the engine and determine changes in such as the delay or advances in combustion processes.

Effect of engine load on the acoustic signal

The percentage of load at which the engine is operating influences the acoustic emissions of the engine. To observe this effect, Figure 4 shows the signal of each sensor for three different load percentages.

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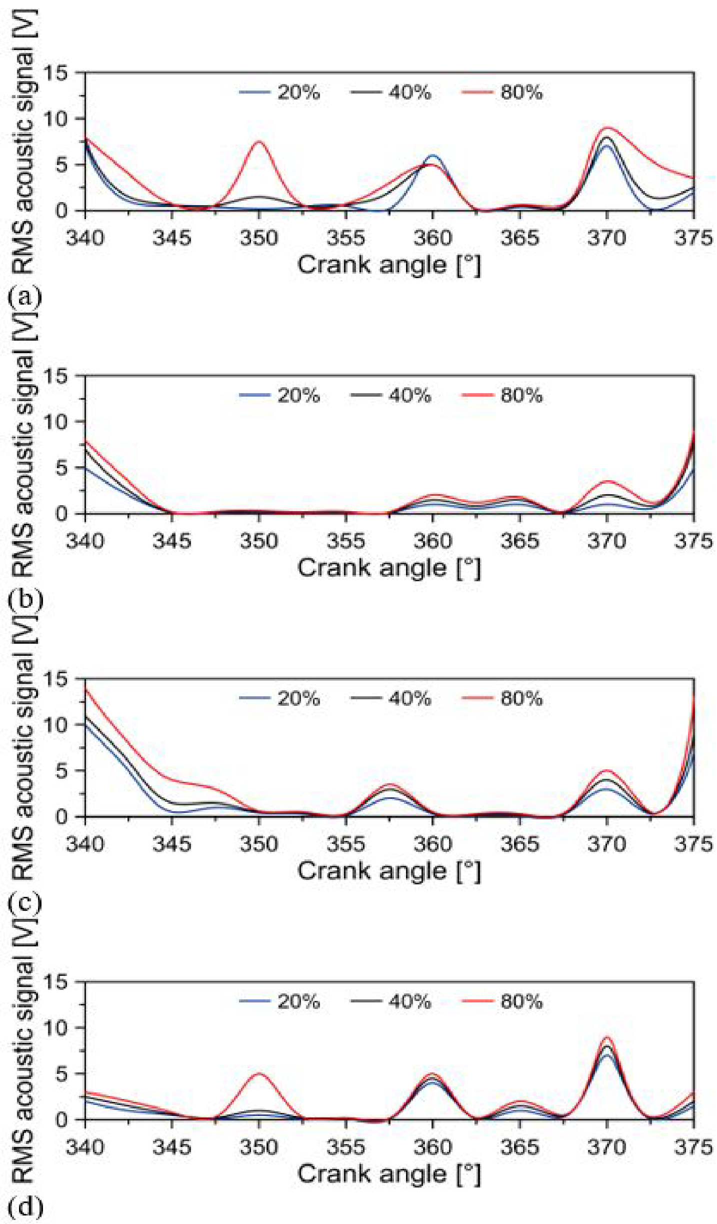

Figure 4. Acoustic signals for different load percentages in (a) block engine, (b) fuel pump, (c) injector, and (d) fuel tank

The results indicate that the increase in load causes a considerable increase in acoustic signals at all measured locations. This behavior is attributed to the increase in fuel flow and the higher heat release rate caused by the combustion process.

Of the four sensors installed, the one located in the injection system reported the highest noise peaks. Therefore, engine injectors are the most susceptible to failures and can be the main indication of changes in engine operation. This behavior is in accordance with the results reported by Parlak et al. [22].

Change in the acoustic signal in case of injection system failures

Because in the previous section, the injection system was identified as the main engine failure, the change in the acoustic signal is analyzed in the event of a defect caused in the injector. The results are shown in Figure 5.

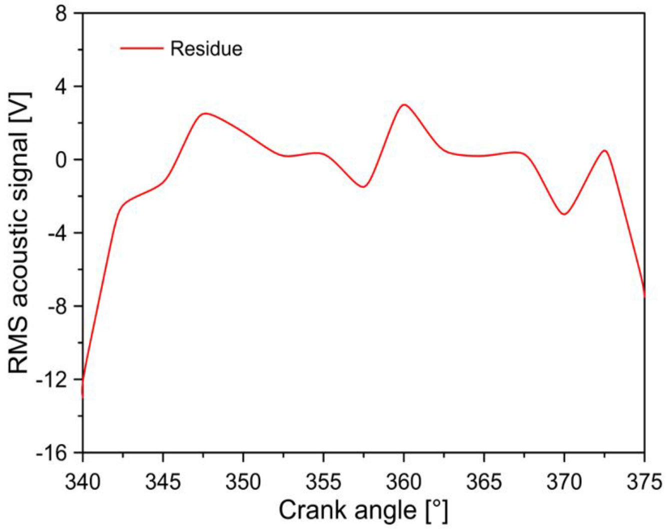

Figure 5. Residual acoustic signal with injector failure

It is observed that the failure caused considerably increases the variation of the acoustic signal compared to the results shown in Figure 3. The above is a consequence of the discontinuous pulses in the injection system.

To make a comparison with the injection system failure and the different engine loads, the calculation of the root mean square of the acoustic signal is made. The results are shown in Figure 6.

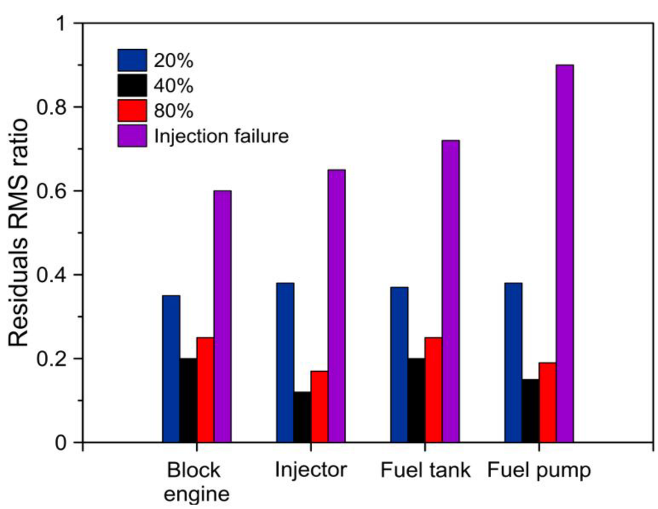

Figure 6. RMS residual signal acoustic

A noticeable increase in the ratio of the residual RMS signal is observed compared to all loading conditions. The residual RMS signal was maintained between 0.8 and 1 for the fault condition while the rest of the operating conditions do not exceed the value of 0.4.

In addition to the comparison of the residual signal, the variability of the acoustic signal is analyzed by comparing the operating conditions with the failure of the injection system. For this, the calculation of the standard deviation of each signal is performed. The results obtained are shown in Figure 7.

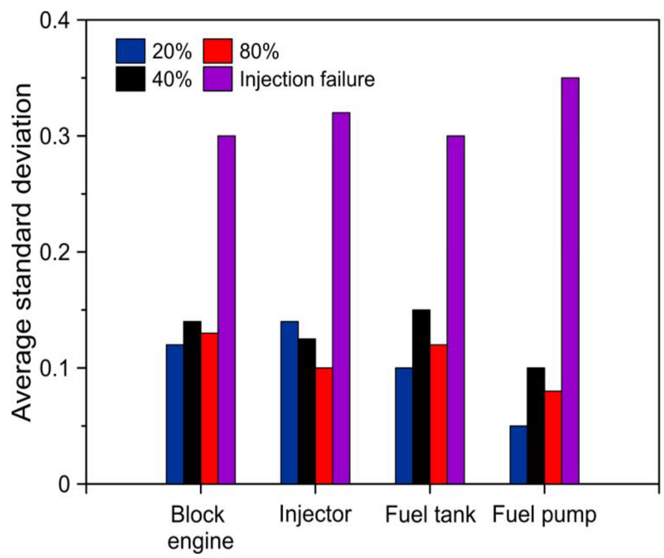

Figure 7. Standard deviation of the acoustic signal

It was observed that the highest variability values are found in the injector and in the fuel pump. For all normal operating conditions, the signal variability remained below 0.15. However, the sensor that recorded the injector failure reached values above 0.3. The foregoing allows a clear diagnosis of the dispersion of acoustic emissions to identify changes in engine conditions.

Conclusions

In the present study, it is evaluated the way to process and analyze the acoustic emissions of a cylindrical mono diesel engine for diagnosis.

The results obtained indicate that the processing of acoustic emissions through the calculation of root mean square, allows to generate a baseline that serves as a guide to compare subsequent measurements in the diesel engine. This facilitates the detection of changes in operating conditions.

The measurement in different engine locations showed that the highest noise emission peaks are located in the injection system. Therefore, it is one of the main areas to diagnose to avoid the problems associated with the combustion process.

The analysis of the signal using root mean square proved to be able to detect the changes in acoustic emissions caused by the percentage of engine load. Which is a consequence of the change in fuel flow and the higher pressures in the combustion chamber.

When evaluating the analysis of the acoustic signal in the event of a failure caused in the engine injector, it was observed that this change in condition could be clearly identified, even for the different engine load conditions. The change in behavior was identified by the considerable increase in the range of the residual signal obtained from the difference between the health condition and the injector failure. Additionally, the injector failure could also be identified by the analysis of the acoustic signal variability. On average, the fault condition doubles the variability in the signal.

The previous results show the analysis of acoustic emissions effectively allows the diagnosis of engine operating conditions. This type of diagnosis reduces the need for high data storage and without requiring physical modifications to the engine. The above features show the ability of acoustic signals to be an accessible diagnostic method to maintain engine performance and avoid high emission rates.

Acknowledgment

The authors would like to acknowledge the Universidad del Atlántico, Universidad Francisco de Paula Santander, and Sphere Energy company for their support in the development of this research.

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