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# ACOUSTIC EMISSION SYSTEM APPLIED TO THE IDENTIFICATION OF EARLY STAGE CRACKS IN METALLIC COMPONENTS

Raul Gaspari Santos<sup>1</sup>  
Niederauer Mastelari<sup>2</sup>

School of Mechanical Engineering of the State University of Campinas, Rua Mendeleev, 200, Cidade Universitária, Campinas-SP.

<sup>1</sup>gaspari.raul@ifsp.edu.br, <sup>2</sup>niede@unicamp.br

**Abstract.** Components of machines and service equipment that are subjected to mechanical stress are subject to failure due to permanent deformation or fracture. In the case of fractures, the initial stage will always be characterized by the nucleation of small cracks that will meet to form a main crack that will propagate until the component breaks. The identification of these micro cracks can represent an increase in reliability, safety and a reduction in risks linked to equipment downtime. The so-called Acoustic Emission (AE) sensor, combined with different signal analysis techniques, can be used in the predictive maintenance routine of these mechanical components in order to identify these cracks at an early stage. Based on the above, the present work proposes the construction of a system composed by an AE sensor using piezoelectric diaphragms of the PZT type (Lead Zirconate Titanate), data acquisition system (DAQ) and techniques analysis of signals such as Fourier Transform, Wavelets, counting of events, and calculation of signal energy, to identify cracks caused by small deformations that will lead to failure by fracture of the material. An experimental validation bench was created for the development stages, which allowed the validation of the equipment for use in low-cycle tensile and fatigue tests in a dynamic testing machine. The data presented show that the system was able to identify cracks in the material in its initial stage, reaching the main objective of the work. By analyzing the frequency spectrum of the signal, it was possible to identify frequency patterns between 0 Hz and 20 kHz corresponding to crack formation or propagation events. The frequency spectrum over time (Wavelet) showed that these low frequency signals always occurred when events were recorded and that higher frequency signals, until 50 kHz, are linked to these events. It was also noted that the energy of the signal increases significantly when there are more events, if we compare signs of deformation of the specimen with signs of fracture of the specimen, showing that the deformation of the specimen is linked to the formation of micro cracks. **Keywords:** Acoustic Emission Technique, Structural Health Monitoring (SHM), Data Acquisition, Data Analysis.

## 1. INTRODUCTION

Metallic components of machinery and service equipment are constantly subject to failure due to the propagation of cracks, whether caused by static or dynamic efforts. The identification of these cracks in their initial stage can represent greater reliability in the system and greater precision in the preventive maintenance routine of the machine (Norton, 2014)

Non-destructive testing (NDT) contributes to the identification of the beginning of a crack as well as allowing the monitoring of its growth throughout the test or useful life of the mechanical component. This type of test refers to tests conducted in such a way as not to damage such a mechanical component using different techniques such as eddy currents, strain gauges, ultrasonic tests, and acoustic emission tests (Santos, 2018). The acoustic emission technique, the subject of study in this work, can be used in different ways to identify different stages of the failure, whether initial or throughout its propagation (Mizutani *et al.*, 2016).

Because they are of low amplitude, the signals generated by the crack inside the material, captured and stored by the acoustic emission equipment, may be imperceptible when analyzed only in the time domain; likewise, when perceptible in the time domain, they may not significantly represent the real level of degradation of the piece (Mizutani *et al.*, 2016). In order to bring greater capacity for understanding and richness of details about the sampled signal, the use of signal analysis techniques, such as statistical analysis, Fourier Transform (FT) and Wavelet Transform (WT), prove to be fundamental complements to the work that follows (Santos, 2018).

Based on the above, the main objective of this work is the construction and operation, considering the acquisition and analysis of data, of an acoustic emission system aimed at monitoring cracks in mechanical components made of metallic material and subjected to static or dynamic loads. It is considered that the monitoring system is composed of sensor, pre-amplifier circuit, source and data acquisition system.

## 2. THEORETICAL FOUNDATION

This section aims to support the entire development of the research and will be divided into 3 parts: the first will deal with the bases for understanding the process of nucleation and propagation of a crack until it causes the material to

fracture; the second part will deal with the theory behind the acoustic emission sensors used in this work; the third part will deal with data treatment tools that will be used in the work in order to further investigate the crack behavior during the low-cycle fatigue test.

## 2.1 Nucleation and propagation of cracks in metallic materials

The study of crack nucleation and propagation in metallic materials began with the German engineer August Wöhler, who between the years 1852 to 1869 studied fractures in train axles that were in accordance with static theories and even so presented fractures with brittle characteristics when subjected to cyclic loads. Subsequent to this, the theories of Inglis (1913) , Griffith (1921) and Paris and Erdogan (1963), supported what would be called mechanical fatigue fracture and the so-called fracture mechanics (Norton, 2014).

From the studies carried out by Inglis (1913) and Griffith (1921), a factor that contributes to crack growth was determined, the so-called Stress Intensity Factor  $K$ , which quantifies the severity of the crack as a function of its linear length, the geometry of the body undergoing the load, and the level of stress applied to this body. In other words, the  $K$  value numerically represents the damage. The equation describing the  $K$  Factor is presented below:

$$K = \beta\sigma\sqrt{\pi a}, \quad (1)$$

where  $\sigma$  is the mechanical stress applied to the part and  $a$  the linear length of the crack (Dowling *et al.*, 2013). The displayed  $\beta$  is called the geometric factor. The geometric factor is calculated from the dimensions of the specimen being tested. Analyzing Eq. ( 1), it is verified that  $K$  will increase with the increase in the linear length of the crack, until the moment when this value is so high as to fracture the mechanical component.

For a crack to nucleate and start propagating, an intrinsic resistance to the material must be overcome by applying a minimum mechanical stress variation called the threshold stress variation,  $K_{TH}$ , as shown in Eq. (2). When certain stresses make the crack growth levels exceed  $10^{-10}m/cycle$ , this barrier is overcome. The variation of the stress intensity factor required to overcome this level of crack growth is called the threshold variation,  $\Delta K_{TH}$ . The entire study focused on the Stress Intensity Factor will only be valid after transposing this primary condition (Dowling *et al.*, 2013). Therefore, the process of mechanical fatigue failure begins when the stress level concentrated in a notch or surface imperfection reaches a minimum value of the material ( $K_{TH}$ ), causing a microscopic crack, which has dimensions ranging from 2 to 5 grains, form (Meyers and Chawla, 2009). This is the first stage of crack formation.

$$\Delta\sigma_{TH} = \frac{\Delta K_{TH}}{\sqrt{\pi a}}, \quad (2)$$

The second stage of the crack is characterized by its constant growth as a function of the increase in the number of load cycles applied to a specimen. In metallic materials, this stage can be modeled using the Paris-Erdogan Law given by Eq. ( 3).

$$da/dN = C (\Delta K^m), \quad (3)$$

where  $a$  is the linear length of the crack,  $N$  is the number of load cycles,  $\Delta K$  the variation in stress intensity factor ( $K_{max} - K_{min}$ ).  $C$  and  $m$  represent empirical constants related to the material being tested, being calculated by means of the inclination of the straight line formed in region II of the graph  $da/dN \times \Delta K$ , shown in Fig. (1), and can be influenced by environmental conditions such as temperature, pressure, and whether it is corrosive or not, by test conditions, by the charge ratio  $R$  and by the way of load application wave (Meyers and Chawla, 2009).

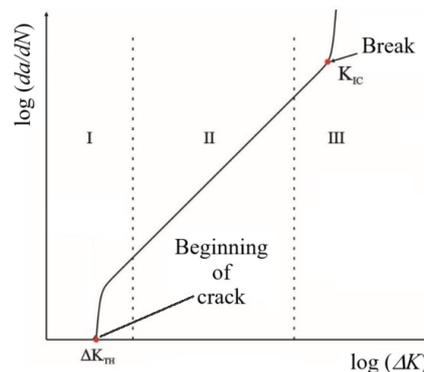


Figure 1.  $da/dN \times \Delta K$  chart of Paris and Erdogan. Adapted from Meyers and Chawla (2009).

The third stage of fatigue failure, also highlighted in Fig. (1), is represented by the sudden rupture of the piece. The failure occurs when  $K$  reaches a critical part stress value ( $K_C$ ), which will depend on the values of the applied mechanical stress ( $\sigma$ ), and length of the crack ( $a$ ), as demonstrated by Eq. (1) (Meyers and Chawla, 2009).

## 2.2 Acoustic emission sensor

Acoustic emission sensors are widely used in the industrial sector both in predictive maintenance processes and in preventive maintenance, to identify failures in pipes, structural components, aircraft fuselage, etc., and can be installed in metallic, polymeric, ceramic or composite materials. The Fig. (2). shows the simplest method of using an acoustic emission sensor in a type C(T) specimen. The sensor can be understood as a small microphone installed to listen to any and all sounds emitted by the crack during its nucleation or propagation. (Lyasota and Stankevych, 2013).

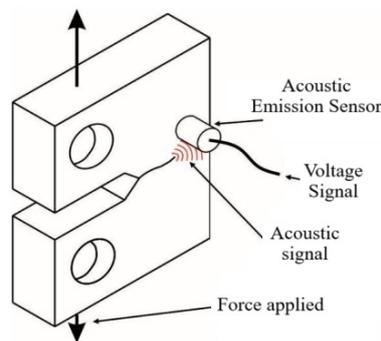


Figure 2. Crack measurement with acoustic emission sensor.

This type of sensor has a working principle similar to that of ultrasonic receivers (Webster, 1999). In the study of mechanical fatigue, it is used to identify acoustic emissions produced by the crack at the time of its initiation or propagation; in studies aimed at the first stage of the crack, high sensitivity acoustic emission sensors are used. The amplitude of the emitted signal, which must go through an amplification phase, is proportional to the size of the crack and also depends on the type of material studied; thus, the acoustic emission sensor is capable of providing data on the crack length and also on the stress intensity factor at the crack tip in a linear fashion. Such information is only possible after the equipment goes through a calibration process (Lyasota and Stankevych, 2013) .

Emissions in the initial stage of a crack are of low intensity and occur in scattered times of signal sampling, therefore, their identification is characterized by the sum of the amplitudes of the recorded signals. In their work, Lyasota and Stankevych (2013) used an acoustic emission sensor to monitor the propagation of a crack caused by mechanical fatigue in a specimen constructed with aluminum alloy 1201-T. The signal captured by the sensor was amplified at a level of 40dB and acquired by a signal conditioner working at a frequency of 0.2 MHz to 0.6 MHz with a sampling time of 0.25 ms. Fig. (3) shows the graph of amplitude and captured signal as a function of crack length growth (Lyasota and Stankevych, 2013). Fig. (4) presents an acoustic emission signal acquired by Antonaci *et al.* (2012). It is possible to notice that the signal has a peak at the initial moment and attenuates over time.

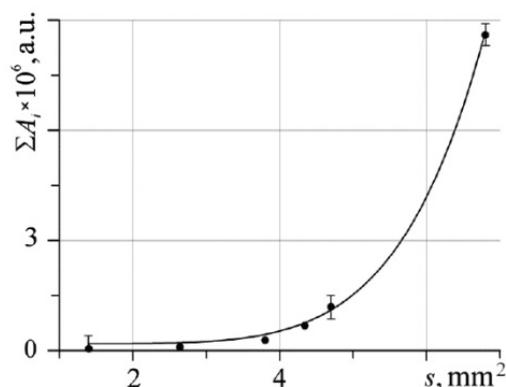


Figure 3. Graph representing the increase in the acoustic emission signal as a function of the crack growth. Adapted from Lyasota and Stankevych Lyasota and Stankevych (2013).

As cracks in their initial stage have low signal intensity and many external signals to the one of interest can influence

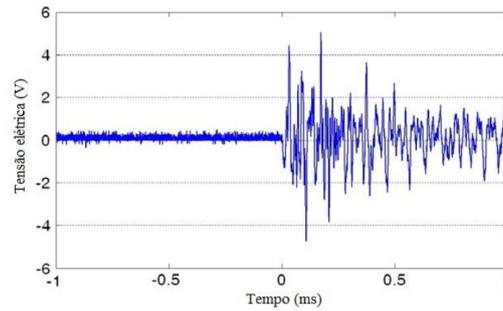


Figure 4. Acoustic emission signal acquired in fatigue test on specimens of concrete. Adapted from Antonaci *et al.* (2012).

their identification, noise minimization techniques can be applied. One of these techniques is based on the use of one or more acoustic emission sensors responsible for capturing only signals external to the signal of interest. This methodology is called Guard Sensor. Fig. (5) presents an example of the technique (Mizutani *et al.*, 2016).

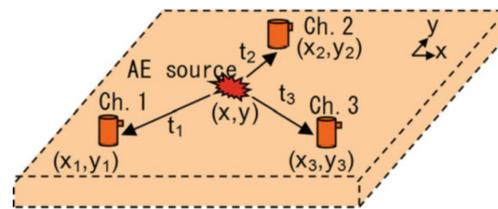


Figure 5. Configuration of Guard Sensor. Adapted of Mizutani *et al.* (2016).

### 2.3 Signal analysis techniques

In the present work, in addition to the statistical treatments of the signal, two signal analysis techniques, Fourier Transform (TF) and Wavelet Transform (TW) can be used to help identify cracks in a specimen tested in low-cycle fatigue.

The TF was developed by the French physicist and mathematician Jean Fourier (1768-1830) in the year 1822 and is widely used as a tool for analyzing discrete signals and also as a method for filtering a signal. Using the concept that a signal is a superposition of complex sinusoids, TF has the ultimate goal of representing a signal, as complex as it may be, as a function of frequencies and amplitudes. As an example of the application of a signal represented in the frequency domain, the musical score of an orchestra can be cited. Sheet music contains parts for instruments that have different frequency ranges, such as a string bass, which has a very low frequency. In its discrete version, that is, digitally acquired signals, the TF of a signal  $f(N)$  is calculated using Eq. (4):

$$F(\omega) = \sum_{x=0}^{N-1} f(x) e^{-i\omega x}. \quad (4)$$

Thus, it is understood that TF is a useful tool in the identification and monitoring of cracks in metallic materials subjected to varying loads over time. Through the analysis of signals acquired at different instants of time, it is possible to compare one state of the crack with another, thus proving its growth (Haykin, 2001).

The TF suffers from some limitations when applied in a windowed way in signals that do not fit in Linear and Time Invariant (LTI) systems, the so-called Gibbs Phenomenon (Galvão *et al.*, 2001). In order to minimize the problems caused by the Gibbs phenomenon in the TF, the Frenchman Jean Morlet, who worked at the oil company Elf Aquitaine, proposed a change in the TF, not very accepted by the academic community at that time, to improve performance in signal processing geophysicists. Through the research of the mathematician, also French, Yves Meyer, the theory proposed by Morlet was enriched and matured into a new theory, finding parallels with several other fields of mathematics previously studied separately. Soon afterwards, Stéphane Mallat, an image processing student, developed an algorithm to calculate the Wavelet Transform (TW) computationally, making the tool widely used in image processing (Galvão *et al.*, 2001). The mathematical formulation of the TW of a signal  $f(x)$  is expressed by the following equation:

$$W_f(a, b) = \sum_{x=0}^{N-1} f(x) \Psi_{a,b}(x), \quad (5)$$

which is an approximated version by a summation of an integral. The function  $\Psi_{a,b}(x)$ , called a wavelet, is derived from a function  $\Psi(x)$  through the equation:

$$\Psi_{a,b}(x) = \frac{1}{\sqrt{a}} \Psi\left(\frac{x-b}{a}\right). \quad (6)$$

By presenting effective results in the analysis of signals contained in systems that vary in time, TW has been gaining more and more space in the study of the phenomenon of crack propagation, mainly with regard to the identification of microcracks throughout a test or the use of the mechanical component.

The union of the best of both techniques, combined with the system operator's interpretations and signal metrics, may represent a breakthrough in the early identification of cracks that will culminate in the permanent failure of the mechanical component.

### 3. MATERIALS AND METHODS

The work will be divided into 4 distinct stages that culminate in the main objective: to identify cracks in the initial stage of formation in test specimens built in metallic material. The first stage is characterized by the design and construction of the acoustic emission sensor; the second stage is composed of the design and construction of the linear power supply for supplying the sensor; the third stage concerns the assembly of the system in isolated encapsulation; Finally, in the fourth stage, the system will be applied to identify cracks in specimens made of steel subjected to low-cycle fatigue.

#### 3.1 Acoustic emission sensor

The acoustic emission sensor used in the work is composed of a set of 4 main elements: piezoelectric diaphragm (PZT), transducer electronic circuit, polymeric base to accommodate the circuit and PZT and metallic coating to cancel external noise.

The PZT used is the 7BB-20-6L0 model from Murata Manufacturing Co., composed of a 20 mm metal base  $\pm 0.2$  and a 14 mm piezoelectric material layer  $\pm 0.6$  covered by a silver electrode of 12.8 mm. The element also has a resonant frequency of 6.3 kHz, impedance of 1000  $\Omega$  and capacitance of 10 nF. Fig. (6) shows the image of the sensor according to the manufacturer's datasheet (Murata, 2022).

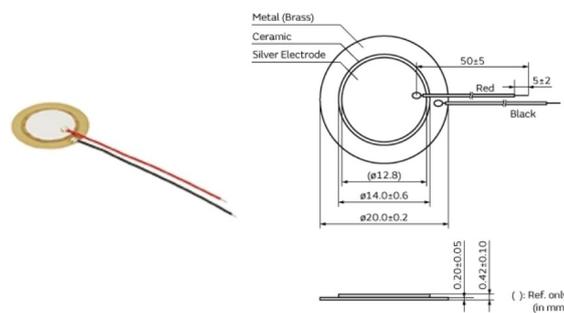


Figure 6. Murata's piezoelectric diaphragm.

In addition to the PZT, a transducer circuit is needed to adjust the signal. This circuit is an operational amplifier connected in differential mode as shown in Fig. (7a).

The AD8608, from Analog Devices, was chosen because it has a low level of offset and low susceptibility to electromagnetic noise. The amplifier gain is defined by the relation  $R1/R3 = R2/R4$ ; the manufacturer recommends that these resistors have a tolerance of 0.01% to minimize the Common Mode Rejection Ratio (CMRR). Thus, the circuit in question has a gain of 50x (AnalogDevices, 2004). Capacitors C1 and C2, made of tantalum, are installed on the positive and negative supplies of the operational amplifier to filter high-frequency noise from the supply, while capacitor C3 and resistor R5 form a high-pass filter with a cut-off frequency of 1 kHz at the output of the design circuit to minimize noise 60 Hz from the mains. Fig. (7b) shows a 3D representation of the circuit produced.

A polypropylene base was built to accommodate the PZT and the transducer circuit, whose 3D model is shown in Fig. (8).

#### 3.2 Linear source

To power the acoustic emission sensor, a linear symmetric source was built with filters designed to minimize the effects of harmonics coming from the electrical network, in addition to electromagnetic noise contained in the environment in which the system is inserted. To minimize such electromagnetic noise, the source circuit was placed in a grounded metallic

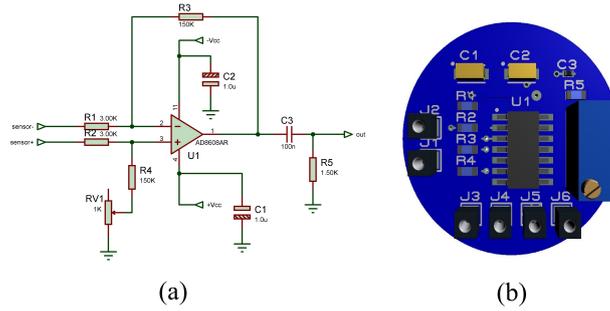


Figure 7. (a) Transducer electronic circuit and (b) 3D model of the circuit.

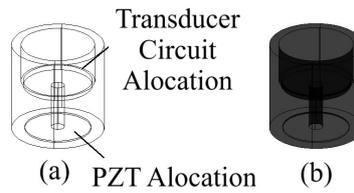


Figure 8. (a) Simplified 3D drawing for line visualization and (b) 3D view with X-Ray vision.

enclosure, acting as a Faraday cage. The circuit contained in Fig. (9) is designed for the sensor. In addition to the output filters, a commercial voltage input filter containing X and Y type capacitors was dimensioned.

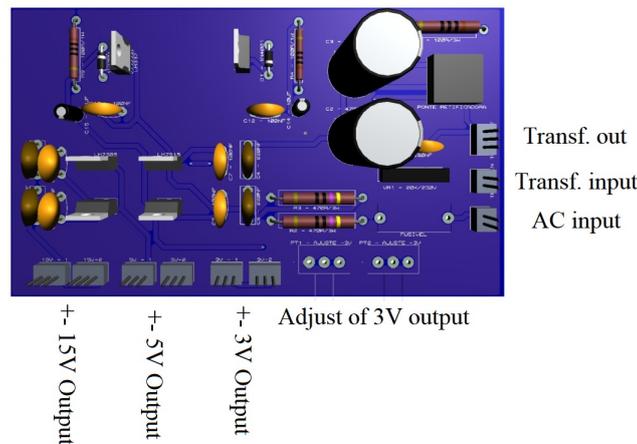


Figure 9. 3D representation of simetrical source used to system.

The designed linear power supply has 3 voltage outputs: 3 V for powering the pre-amplifier circuit and two more outputs, 5 V and 15 V, which can be used for future system expansions, such as signal amplifier circuits. The use of a linear source becomes more suitable for this type of application due to the frequency of the rectifier output ripples, around 120 Hz, while in switched sources the ripples can reach around 100 kHz. As a voltage step-down element, a transformer with 127 V / 220 V input and 18 V output was used, with a maximum current of 500 mA.

### 3.3 Complete system

The complete system comprises: 2 acoustic emission sensors (composed of a pre-amplifier circuit with differential arrangement and 50x gain and PZT element), symmetrical power supply and data acquisition system, mounted in a grounded metallic box. One of the sensors is responsible for capturing noise signals from the test environment, while the other is intended for the acquisition of signals of interest to the work at the time when the specimen is subjected to loads varying in time.

The data acquisition system used in the system is the National Instruments USB-6216 model, which has a maximum sampling frequency of 400 kHz, 16-bit resolution and a maximum sampling voltage of  $\pm 10V$ . Fig (10). presents the complete system.

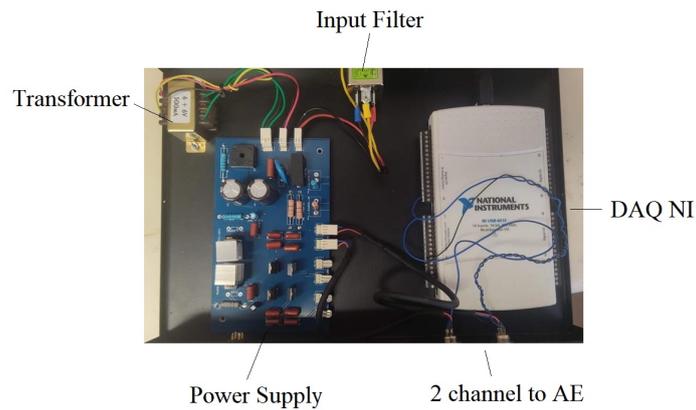


Figure 10. Complete system to monitoring cracks in mettalic materials.

### 3.4 Experiment in dynamic testing machine

The low-cycle fatigue test for validation of the system described in the sections above will be conducted on the Instron 8801 dynamic testing machine, with a load capacity of 100 kN. The test will be conducted on 1045 steel specimens measuring 200 mm in length  $\times$  2.95 mm in thickness; the maximum applied load is 3.4 kN and load ratio ( $R$ ) of 0.1; the load application frequency will be 50 Hz. Fig. (11) shows the dynamic testing machine with CDP installed.



Figure 11. Dynamic Testing Machine Instron 8801.

As the objective of this work is to validate the system, 4 low-cycle fatigue tests will be conducted, which will have the AE and noise signals acquired at a frequency of 200 kHz. The signals will be observed and, if there is agreement between the data, one of them will be analyzed in order to investigate the moments in which cracks appeared, their propagation and the moment of fracture.

## 4. RESULTS AND DISCUSSIONS

The test performed generated the signals shown in Fig. (12). It is possible to see that the sensor destined to capture the noise signal (Fig. (12)a) noticed the moment of fracture of the specimen; the signal captured directly on the specimen (Fig. (12)b) was capable of capturing low amplitude signals different from those captured by the noise sensor. Fig. (12)c shows a subtraction of the noise signal from the signal of interest with the sensor installed directly on the specimen. Background noise levels went from around 0.05V to around 0.03V, a reduction of around 40%.

With the signal subtracted from noise, a 0.03 V threshold was defined to identify events that concern the integrity of the specimen. Such events may represent the initiation or stages of crack propagation. The graph shown in Fig. (13) represents the sum of events that occurred above this threshold level throughout the entire test. It is possible to see, after 40 s of testing, that there were already significant amounts of events (348 events) above 0.03 V, evidencing the presence of cracks in the specimen; in 60 s of testing, the number of events more than doubles (848 events) and in 77 s of testing, after the events reach a number of 1576, there is an exponential increase followed by the fracture of the specimen.

To better understand what had happened throughout the test, the subtracted signal was divided into windows of 1000

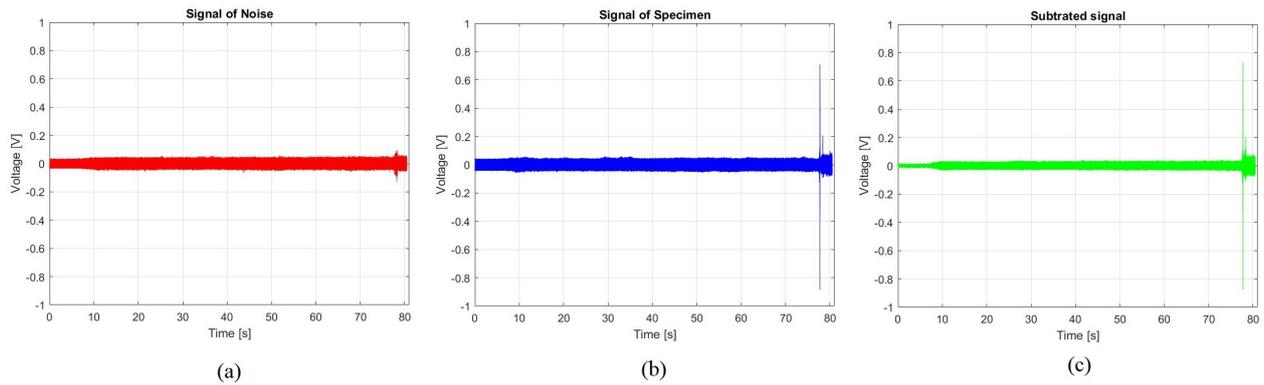


Figure 12. Signals of (a) external noise, (b) specimen and (c) subtracted.

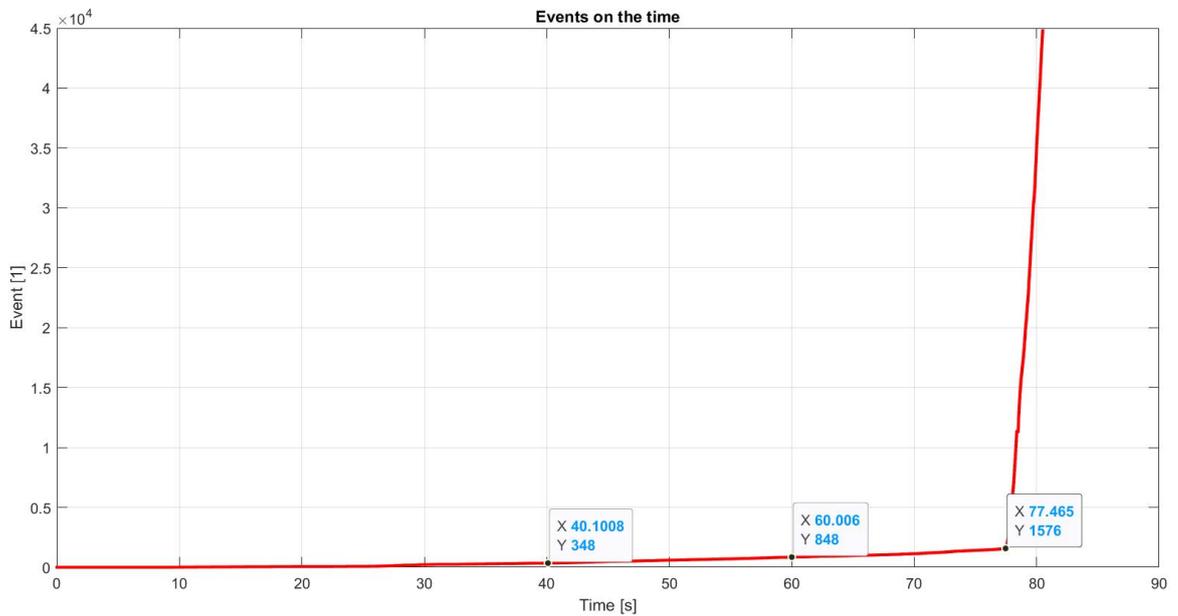


Figure 13. Events above 0.03 V throughout the test.

events each, totaling 16100 windows. Taking into account the sampling frequency of 200 kHz for each channel (sensor intended for capturing noise and sensor intended for recording AE events), each window of 1000 events takes place in 5 ms. For each window, the energy level was calculated in relation to the time in which it occurred. The objective was to understand what was the level of the signal captured not only by the voltage value. Fig. (14) shows, in a graph, the energy levels along the 16100 defined windows. It is possible to notice that in window 3040, about 15.2 s after the start of the test, there was an energy dissipation caused by the growth of a crack of about 1.57532 J; after that, in window 5256, about 26.28 s after the start of the test, there was another significant energy level of 1.58854 J; in window 7308, around 36.54 s after the start of the test, there was an energy dissipation of 2.07836 J, the highest level registered before the specimen fractured.

Finally, the frequency spectrum in time acquired through the TW (Fig. (16)), presents the signal acquired in the CDP with clear signs of changes in its characteristic in moments of possible appearance of cracks or its propagation. It is possible to notice that in approximately 10 s of test (1), there was a spread of the frequency spectrum, evidenced by the presence of cracks in the material; at approximately 49.2 s (2) there was further evidence of cracks in the spectrum through time-spreading of frequencies; at 77.4 s (3) the process of fracture of the specimen begins, with signal spreading throughout the frequency spectrum.

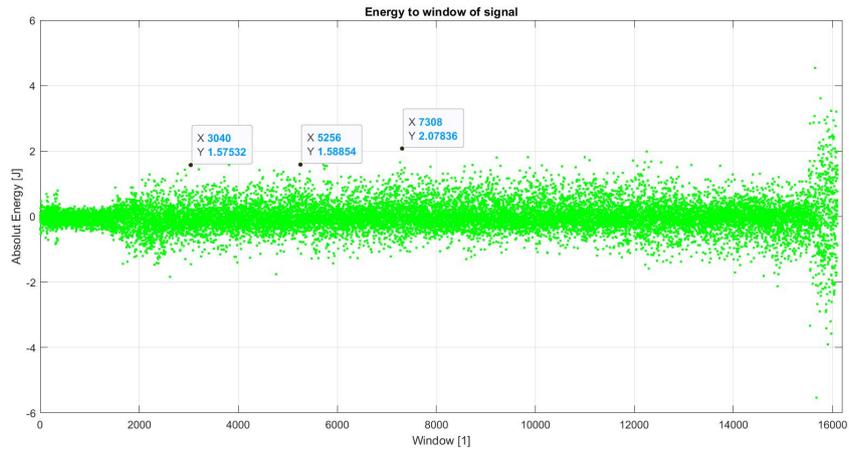


Figure 14. Signal energy over 16100 event windows.

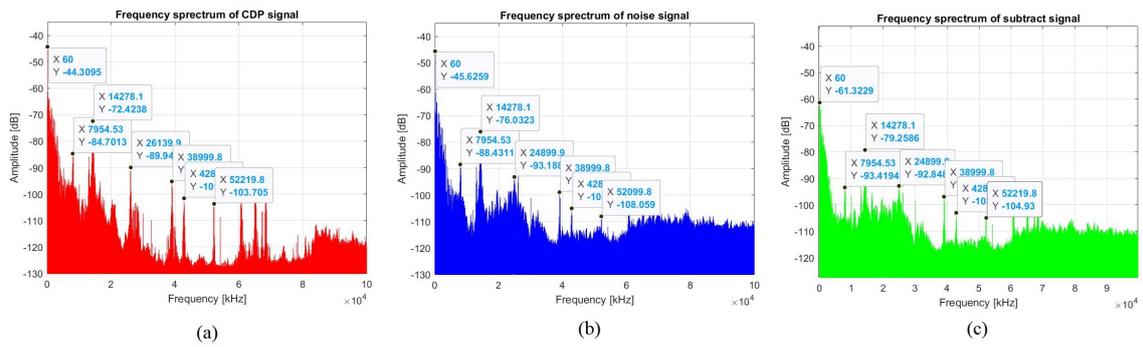


Figure 15. Frequency spectrum of the signals captured in the CDP (a), in the environment where the sensors were contained, taken as noise (b) and of the subtracted signal (c)

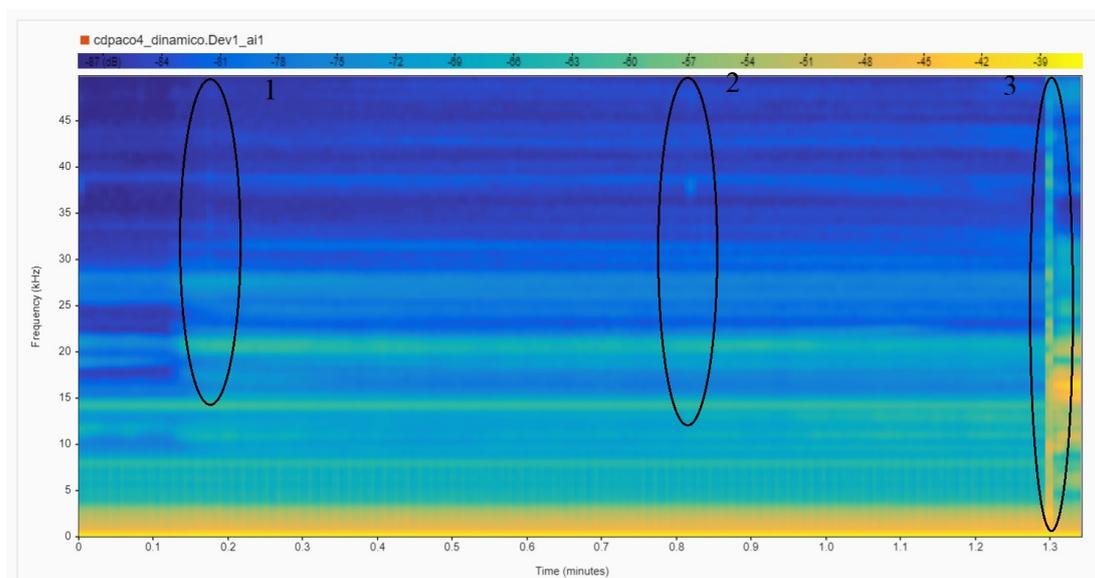


Figure 16. Frequency spectrum in time acquired by means of Wavelet Transform of the subtracted signal.

## 5. CONCLUSIONS

The present work dealt with the assembly of an acoustic emission transducer aimed at identifying and monitoring cracks in a specimen of metallic material subjected to a low-cycle fatigue test.

The system, composed of a sensor with a piezoelectric diaphragm, a pre-amplifier circuit, a power supply and a DAQ, was able to capture useful signals for the identification of failures in their initial stages in the specimen. Signal analysis techniques applied to signals collected throughout the test showed evidence of crack initiation and propagation throughout the test.

Finally, it is possible to list the following observations for the work:

1. The technique of counting events throughout the trial proved to be satisfactory in noting events at specific time intervals. From it, it was possible to go deeper into the investigation of a given event in a given time interval;

2. The windowing of the signal in intervals of 1000 events and the calculation of energy gave a broader view of what had happened in the instants of time evidenced by the technique of counting events; however, a future investigation of each window through TF analysis may help to identify specific frequencies of crack formation or propagation within the material;

3. The subtraction of the noise signal from the signal of interest was of great value for the identification of cracks. The decrease of about 40% in background noise levels helped to more accurately identify events of interest to the work;

4. Pure FT analysis contributed little to the identification of cracks and their propagation. A more in-depth study of the frequencies involved in crack propagation is necessary to achieve better results and more accurate notes. The search for a set of frequencies that characterize crack initiation and propagation proves to be a challenge to be overcome;

5. The WT analysis proved to be an interesting tool in identifying the crack and its propagation, since frequency spreads were identified at 10.8 s and 49.2 s, in addition to the moment of fracture. However, it will be necessary to invest in more research to correlate these events with the effective propagation of the crack, especially in its earliest stages.

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