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IMPACT LOCALIZATION IN ANISOTROPIC COMPOSITE PLATES INSTRUMENTED WITH A NETWORK OF PIEZOELECTRIC SENSORS

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Abstract. *The interest in the development of composite materials has followed a growing trend in the last decades. In this sense, impact localization is of utmost importance when composite materials are to be designed for use in critical areas of aerospace industry, that is, such as in airplane fuselage. This is consequence of the fact that these materials are known to develop specific types of failure, and, differently to other materials such as, metals, some of these can actually occur and have no superficial effect whatsoever. In the present work, the problem of impact localization was approached via development of an algorithm designed to work with error function minimizing. According to this methodology, the point of impact is found to be the point of minimum of a specifically designed domain applicable function that, as defined, returns values as small as the distance of the function argument to the real point of impact. Arrival times of impact waves to sensors play an important role in the definition of this function along with the plate impact wave speed profile (i.e., speed of propagation as function of angle with respect to a coordinated frame). Results obtained thus far have been encouraging, with average values of localization errors close to the standards demanded by regulatory agencies for this kind of application.*

Keywords: *composite materials, impact localization, structural health monitoring.*

1. INTRODUCTION

The interest in composite materials' development has followed a growing trend in the last decades. These materials are characterized by the presence of two or more phases at a macroscopic level specifically designed as to exhibit superior properties than those of the component materials alone (Daniel and Shai, 1994). Modern applications of interest of these materials demand a profound understanding of their nature and structure, such as in aerospace, nautical and prosthetics. The present work fits into such an initiative, aiming to provide a new tool for Structural Health Monitoring (SHM) of composite materials in the aerospace industry by means of an impact localization method.

Impact localization is of utmost importance when composite materials are to be designed for use in critical areas of aerospace industry, that is, such as in airplane fuselage. This is consequence of the fact that these materials are known to develop specific types of flaws, and, differently to other materials such as metals, some of these can actually occur and have no superficial effect whatsoever (e.g., delamination, fiber pull-out), therefore going unobserved and rendering the material dangerous for further operation. Thus, it is important to keep track of areas exposed to substantial impact or stress, so as to submit for latter specific inspection. This is the role of impact localization, that is, significantly reduce maintenance times on aircraft SHM and hence allow for increasing, economically viable, use of composite laminates in aerospace industry.

Many attempts have been made to use piezoelectric sensors to address this issue. Ross' (2006) is an example of such a work, having used triangulation algorithms to infer impact location in composite materials. The work presented interesting results and an alternate procedure via use of neural networks to aid in computing arrival time of impact waves as accused by sensors, a variable of great importance in impact localization methodologies. Nonetheless, the methodology does not account for possible plate anisotropy, therefore allowing for its use only on materials that do not present this characteristic typical of composite laminates.

Seydel and Chang (2001) developed an impact localization and force reconstruction technique for composite panels with beam stiffeners, thus demonstrating that the referred method works also in more complex structures. The authors' work considers a model of the system and generates its output, consisting of impact localization and force history, via comparison between modeled response and actual response measured by sensors. The method provided the location of impacts with average errors of 24.1 in, 23.1 mm and 19.1 mm regarding respectively bay, flange and stiffener impacts.

The work of Coverley and Staszewski (2003) presented interesting results, showing that it is possible to use genetic algorithms along with triangulation procedures to locate impacts in anisotropic systems. The method's error margins were of up to 11.91% and 13.16% in the x and y axis, respectively. It assumes, however, previous knowledge of moment of impact, which does not occur in real applications. The knowledge of such variable, direct or indirect, is fundamental in algorithms of impact localization.

Kundu (2007) studied a different approach to the problem, focusing in impact localization with piezoelectric sensors via error functions, that is, functions that take into account plate properties and arrival time of waves and assign values to each position in the plate domain. Those values reflect that corresponding position's proximity to the point of impact. The study presents satisfactory results and precision, but limits itself to using 4 sensors and isn't tested for the case of anisotropic systems, limiting itself to estimate small errors for systems with small degrees of anisotropy. Tests with an isotropic plate provided the impact location with associated errors of up to 39.5 mm. However, data was presented for impacts performed in only one location of the plate.

Ribeiro and Cimini's (2012) work followed a similar approach. Having designed a numeric model of wave propagation in composite laminates, the authors designed a flexible methodology to allow for impact localization with multiple sensors in systems of different degrees of anisotropy. The presented method is also based in the use of error functions, however defining then in such a way that allows clear immediate interpretation and does not generate singular points in its domain. The study is carried via simulations, which allows testing of the method's effectiveness via deliberate control of noise and environmental interferences. For the sensor setup analyzed (i.e., in center and corners of plate), the methodology was found to provide motivating results, with errors of up to approximately 11.0 mm in a plate of elevated degree of anisotropy.

The present study follows the work performed by those authors. Experiments are being held with plates of different natures, notably aluminum and composite laminated ones. Attention is being given to analyzing different types of impact energies and adequate filtering of signals to better locate arrival time of impact waves. Preliminary trials with the plates have provided encouraging results.

2. METHODOLOGY

The hereafter presented impact localization method consists of an algorithm, an associated data acquisition apparatus into which it can be embedded, and a plate representing the airplane area onto which the overall system it is to be mounted.

2.1 Experimental Setup

Impact localization on plates was the focus of the present study, since plates represent the most basic structures to which the designed application are to serve. Results thus obtained are expected to easily transfer to other common structures such as curved plates. Being idealized as a cost-effective technology, the present experiment was designed to operate with simple piezoelectric sensors and data acquisition devices, so as to the implementation of such a system in real-like applications represent no additional challenge.

2.1.1 Composite Laminated Plate

Tests were carried with a 1000.0 mm x 1000.0 mm x 2.0 mm $[(\quad 4 \quad)\ ]_s$ carbon/epoxy quasi-anisotropic laminated plate. In order to avoid restrainment and hence emulate free boundary conditions, the plate was laid above quilted pads. This way, generation of impact waves due to indirect contact with the circumventing ambient was avoided, thus assuring that at this moment only direct impact waves were taken into account as input for the method. The system as described can be seen in Fig. 1.

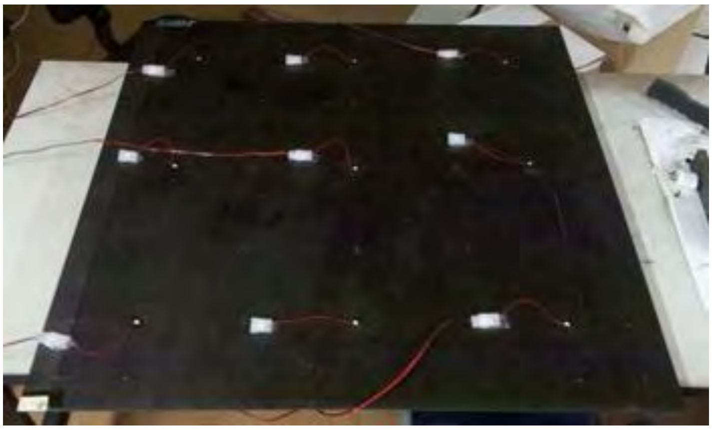

Figure 1. Composite carbon/epoxy plate instrumented with piezoelectric sensors.

2.1.2 Piezoelectric Sensors

The plate was instrumented with 6.4 mm diameter x 0.2 mm thickness piezoelectric sensors disks of the type "buzzer", such as the one in Fig. 2, which are of common use in acoustic applications and consist of axial piezoceramic capable of generating high output voltage in response to relatively small strain. For many applications in SHM, such components are known to demand very little signal conditioning (Giurgiutiu, 2008; Giurgiutiu, Ziehl and Ozevin, 2009).

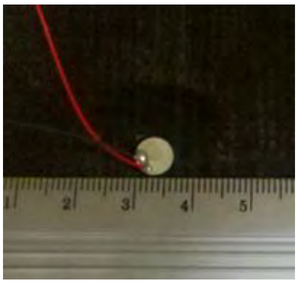

Figure 2. Thin disk piezoelectric sensor, a.k.a. "buzzer".

The sensors were carefully glued to the plate using a methacrylate adhesive via procedure that included previous polishing of the region and cleaning with isopropyl alcohol. Sensor wiring was extended with the help of connector joints, allowing for fast change of cabling between sensors and data acquisition device. A total of 9 sensors were distributed in the referred plate and, since the method demands a smaller number of sensors (e.g., 5 in the current experiment), many setups were possible. For reasons that will be explained afterwards, it was an elected a setup that covered only half of the plate.

2.1.3 Data Acquisition

Data acquisition was performed with a simple bus-powered USB data acquisition device which could promptly be connected to a laptop and provide measurements. For such, 10 analogic inputs were used in differential configuration, relatively to a 5 sensor setup. An acquisition rate of 15 kS/s was proven sufficient for the algorithm to provide good results.

The data acquisition device presented a phenomenon common to this type of equipment called "charge injection" which, due to the importance of accurate measurements to the method, will be covered in more detail in the next topic.

2.2 Preliminary Considerations

Proper functioning of the present method demand that extra attention be paid to certain aspects of the system, notably impact wave speed, signal noise and charge injection. Each of these and their importance to the method will be covered in the present topic.

2.2.1 Noise Filtering

In the present method, the system must be able to account for sudden variations in sensors' voltage levels, which represent arrival of impact waves. Accurate measurements are therefore of great importance, what gives rise to the need to reduce background noise. Fig. 3 depicts the type, magnitude and frequency characteristics of noise in the experiment.

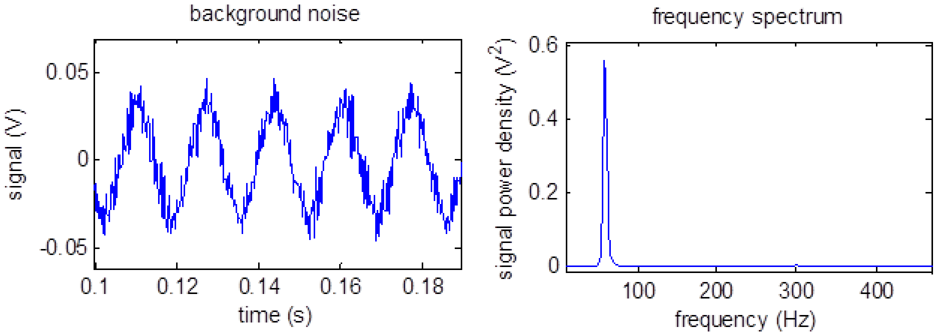

Figure 3. Sample of background noise and its respective frequency spectrum. Notice peak at 60 Hz.

As can be seen, in the present setup a typical sensor response presents background noise with significant components at 60 Hz. Such a level of noise can significantly affect the measurement of the real moment of arrival of an impact wave. The use of filters is therefore necessary in order to prevent this from happening. Filtering in the experiment was performed digitally, using sensors' responses as input to a first order high-pass filter. Fig. 4 below compares the frequency spectrum of a sample of measurements and its equivalent filtered response when the cutoff frequency of the filter was set to 800 Hz, around 10 times greater than the actual peak at 60 Hz, in order not only to attenuate noise, but considerably reduce it.

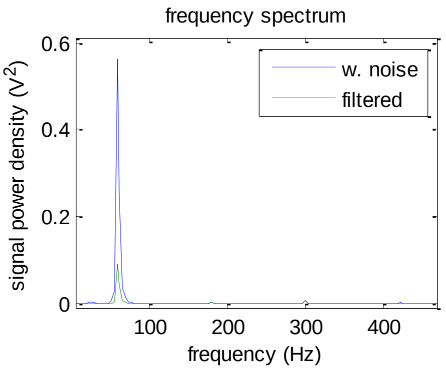

Figure 4. Comparison between the frequency spectrum of signal with noise and its equivalent filtered response to a first order high-pass filter with cutoff frequency at 800 Hz.

2.2.2 Plate Anisotropy

As will be exposed, one fundamental input to the present method is the wave speed profile of the impact waves being studied, that is, the impact wave speed as a function of the angle formed with respect to the main coordinate system. Normally the behavior of such a variable is constant, but in anisotropic plates such as the one object of the present study, and of interest to the aerospace industry, that is not true. Consequently, it's important to monitor the behavior of such variable.

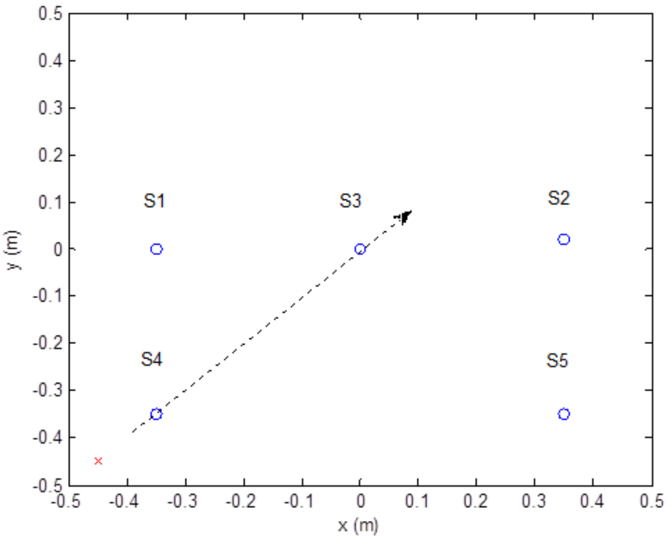

Figure 5. Scheme of the system showing position of sensors (blue circles) and strategically located impact (red cross) performed in order to calculate impact wave speed at angle defined by sensors 3 and 4, i.e., 45°.

In order to investigate the impact wave speed in the present systems, impacts such as the ones from the experiments were performed in strategic positions of the plate, so as to compare responses between sensors and obtain the respective value of impact wave speed at specific angles, as outlined in Fig. 5. Thus, impact wave speed was calculated as follows:

$$\frac{\quad}{-} \tag{1}$$

Where is the impact wave speed at angle formed between the line connecting the two sensors and the main coordinate system, is the distance between sensors *i* and *j*, and and are the arrival times of the impact waves respectively at sensors *i* and *j*.

This way, it was possible to calculate impact wave speed at certain angles of interest, mainly 0^o, 27^o, 45^o, 63^o, 90^o and supplementary angles. Values in between were fitted so as to form a smooth curve. Since the plate was quasi-isotropic, it was expected that impact wave speed didn't vary with direction. Results, however, suggest otherwise, which may mean that impact waves travel closer to the superficies of the element, and thus the composite materials' superficial plies have greater influence on the impact wave speed than the others.

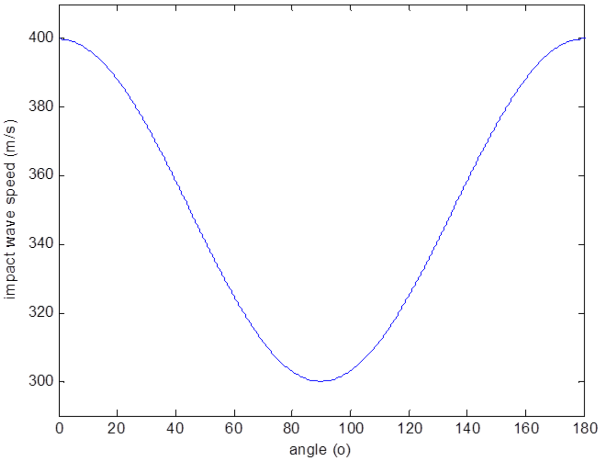

Figure 6. Impact wave speed as a function of the angle formed with respect to the main coordinate system.

2.2.3 Charge Injection

Charge injection is a phenomenon that can drastically affect the precision of the present method, and that of any method that depends on the correct measure of impact wave arrival time to sensors. Such phenomenon consists in interference between acquisition channels, and greatly affects impact localization due to generating false measures of arrival times. Its occurrence, however, is relatively easy to spot: distinct channels will present nearly identical impact wave arrival times (see Fig. 7).

Charge injection occurs basically during high rate data acquisition in multiple acquisition channels with different voltage levels and high output impedance (NI, 2009), and is related to each data acquisition device's settling time, that is, the time necessary for the device to scan a new voltage level. When the voltage levels between channels is high, so as the output impedance, the charge accumulated during different measure has no enough time to discharge back and thus affects the next measure.

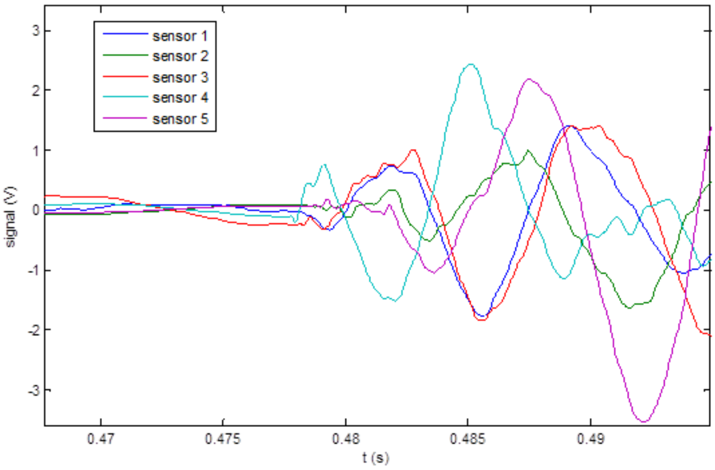

Figure 7. Measurements showing phenomenon of charge injection between channels of sensors 1 (blue) and 3 (red), which present very similar responses and nearly identical impact wave arrival times of 0.4788 s and 0.4879 V respectively.

Corrective measures to the phenomenon include reducing the output impedance of the channel (e.g., using a voltage follower such as an operational amplifier), or scanning fake readings of appropriate voltage level (e.g., grounded channels or, better yet, dummy readings of the next desired channel) in between channels of interest, so as to allow the device enough time to settle to the new voltage level.

2.3 Experiment

In order to test the robustness of the method and provide a deeper understanding of its statistical behavior, experiments were conducted by performing several impacts in predetermined points of interests, that is, 4 impact points were chosen so as to divide the plate in 4 quadrant and 5 impacts were performed in each of these points. This way, the average value and standard deviation of the localization error was calculated for each of these impact points.

Table 1. Position of numbered sensors in setup.

Nr.	Position	
	x (mm)	y (mm)
1	-350.0	0.0
2	0.0	0.0
3	350.0	20.0
4	-350.0	-350.0
5	350.0	-350.0

Sensor and impact positions are given according respectively to Tab. 1 and Tab. 2, along with a schematic view of the experiment given by Fig. 8. Impacts were performed on different areas of the plate by means of the 100.0 mm height fall of a small rubber ball of 55.0 mm diameter and 42.0 g mass, resulting in an approximated 41.2 mJ impact.

Table 2. Localization of numbered impacts made in experiment.

Nr.	Position		Nr.	Position	
	x (mm)	y (mm)		x (mm)	y (mm)
1	-200.0	-100.0	11	-350.0	-100.0
2	-200.0	-200.0	12	-350.0	-200.0
3	-100.0	-200.0	13	-100.0	-350.0
4	-100.0	-275.0	14	100.0	-350.0
5	0.0	-200.0	15	350.0	-200.0
6	0.0	-275.0	16	350.0	-100.0
7	100.0	-275.0	17	-200.0	200.0
8	100.0	-200.0	18	-200.0	100.0
9	200.0	-200.0	19	200.0	200.0
10	200.0	-100.0	20	200.0	100.0

According to the previous definitions, impacts number 1 to 10 fall in the ISZ. Impacts number 11 to 20 fall in the OSZ, impacts number 10 to 16 being exactly at the limit of the geometry defined by the sensors.

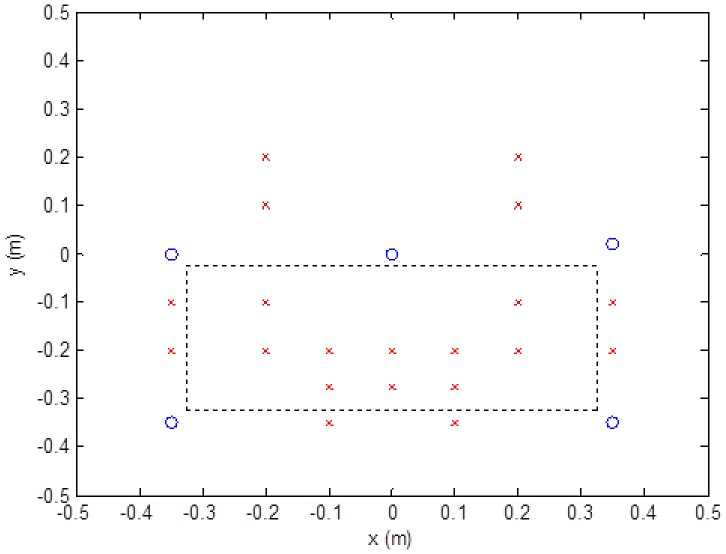

Figure 8. Representative scheme of the system showing position of sensors (blue circles), impacts (red crosses), ISZ (inside dotted rectangle) and OSZ (outside dotted rectangle).

2.4 Algorithm

In order to locate impacts in the plate, the algorithm used was designed to work with error function minimizing. According to this methodology, the point of impact is found to be the point of minimum of a domain-applicable function that, as defined, returns values as small as the distance of the function argument to the real point of impact. Arrival times play an important role in the definition of this function along with the plate's impact wave speed profile (i.e., impact wave speed as a function of the angle formed with respect to the main coordinated system). The function is calculated to the entire domain of interest, that is, the spatial region defined by the plate, in order to assure impact localization.

2.4.1 Arrival Times of Impact Waves

According to the present methodology, the arrival times of impact waves is defined as the moment in which the sensor responses go beyond the regular noise level. The definition of this threshold has significant impact on the calculation of impact waves' arrival times, whose correct values in turn are responsible for the impact localization method's precision. Fig. 9 below shows how sensor response can suddenly vary, signaling arrival of an impact wave.

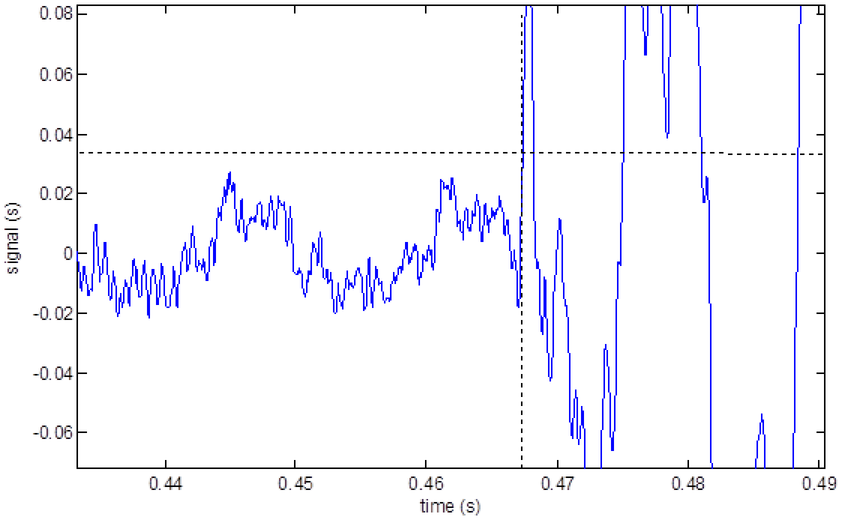

Figure 9. Filtered response of a sensor. Notice defined threshold of 0.0385 V and respective impact wave arrival time calculated at 0.4674 s.

2.4.2 Error Function Mapping

One of the main features that distinguishes the present algorithm is that it does not need previous knowledge of the real moment of impact in order to work. Such is a challenge for many impact localization methodologies and a characteristic inherent to every real practical application, since impacts occur at random and are a priori impossible to predict. For the present method, the moment of impact still constitutes indirectly an important variable, but the algorithm manages to calculate it by means of a trial-and-error, error function minimizing approach. Such methods, besides effective, can also be enhanced for better and more intelligent search procedures of the desired points, what makes room for further improvements in terms of processing capacity requirements.

The algorithm itself works as such: given the impact waves arrival times recorded by each of the n sensors in the setup, calculate, for each point of the domain, the moment of impact as seen by each sensor, i. e.:

$$= \quad - \frac{\quad}{(\quad)} \tag{2}$$

Where is the impact wave arrival time recorded by sensor *i*, and are the distance and angle between the point analyzed and such sensor and *v* is the function that, given a direction regarding the main coordinate system established in the plate, returns the corresponding wave speed in the material for that direction.

For reasons of coherence, the moment of impact calculated for the sensors must not differ between themselves. Hence, we use an error function *E* to associate each point analyzed to a corresponding value measuring how close the values of moment of impact calculated are. Finding the point of minimum of this function returns the real point of impact.

A possible choice for *E* is, given the calculated moments of impact:

$$(\quad) = \sqrt{\Sigma_{=} \Sigma_{=} \left[\quad (\quad) - \quad (\quad)\right]} \tag{3}$$

E is, then, a function whose domain coincides with that of the physical plate analyzed, and thus it is possible to map it in order to better visualize how the point of impact was calculated, as in Fig. 10 below.

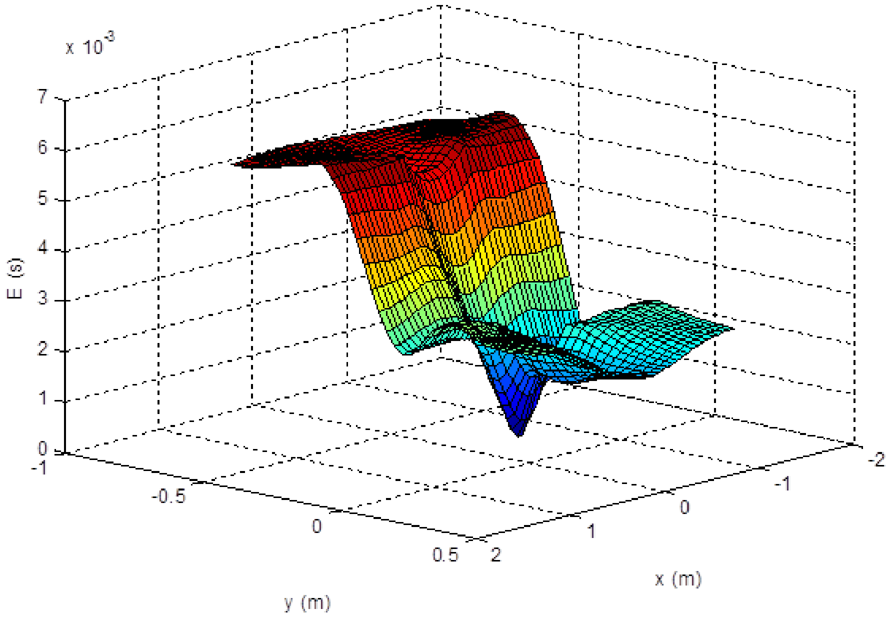

Figure 10. Example of error function mapping (impact at x = 200.0 mm and y = -200.0 mm).

3. RESULTS

Results are grouped according to the division previously established of the plate into ISZ and OSZ. Errors were obtained calculating the distance between the impacts' real location and that supplied by the algorithm.

3.1 Inside Sensor Zone

For the ISZ, Tab. 3 shows the method provided results with an average error of 39.7 mm, proving itself very reliable for practical applications. Fig. 11 provides a schematic view of the results. Small deviations were observed in impacts close to sensor 1, which may have occurred due to some malfunctioning of its part (e.g., due to it not being glued adequately to the plate), or due to the charge injection phenomenon, which wasn't completely eliminated. Notwithstanding, overall results were accurate.

Table 3. Localization of numbered impacts calculated via algorithm and associated errors in the ISZ.

Nr.	Position		Error
	x (mm)	y (mm)	(mm)
1	-145.6	-197.3	111.5
2	-108.0	-257.2	108.3
3	-136.2	-177.4	42.7
4	-108.1	-261.8	15.5
5	23.5	-196.1	23.8
6	-4.7	-261.8	14.0
7	98.7	-256.9	18.1
8	117.5	-214.9	23.0
9	202.0	-196.1	4.4
10	192.6	-135.0	35.8

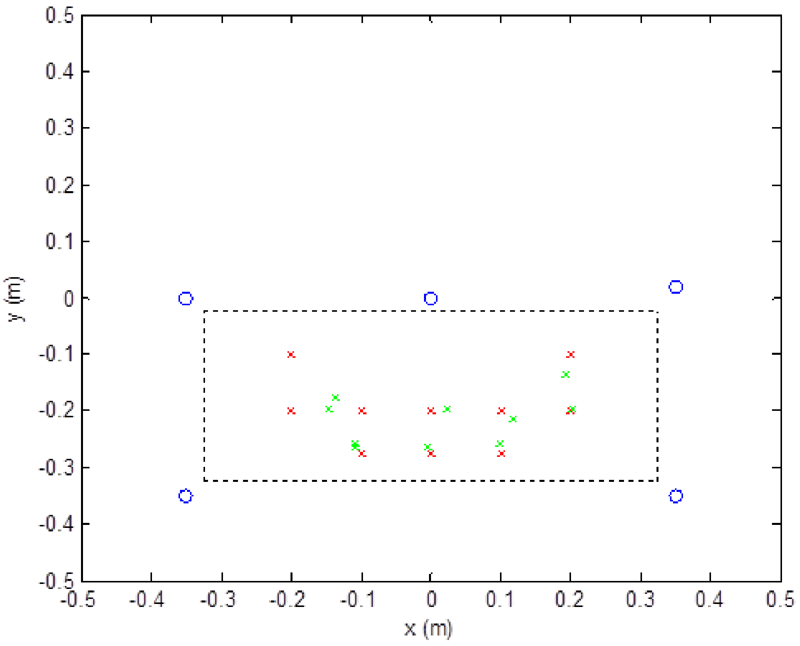

Figure 11. Representative scheme of the system, zooming on ISZ and showing position of sensors (blue circles), impacts in the ISZ (red crosses) and respective localization (green crosses).

3.2 Outside Sensor Zone

As expected, Tab. 4 shows that for the OSZ the algorithm presented error margins far from the minimally acceptable, that is, with average error of 171.8 mm. Fig. 12 provides a schematic view of the results. That being said, this result suggests that, in practical applications, the area of interest monitored by the system must be enclosed by the sensor setup. That, however, should not pose a problem, since sensors need not be close together.

Table 4. Localization of numbered impacts calculated via algorithm and associated errors in the OSZ.

Nr.	Position		Error
	x (mm)	y (mm)	(mm)
11	-220.8	-266.8	211.0
12	-202.0	-266.8	162.4
13	-89.3	-331.4	21.5
14	164.4	-341.3	65.0
15	239.6	-207.2	110.6
16	333.6	-157.6	59.9
17	-163.4	-128.7	330.7
18	-131.9	-155.5	264.4
19	184.7	-106.4	306.8
20	174.1	-84.1	185.9

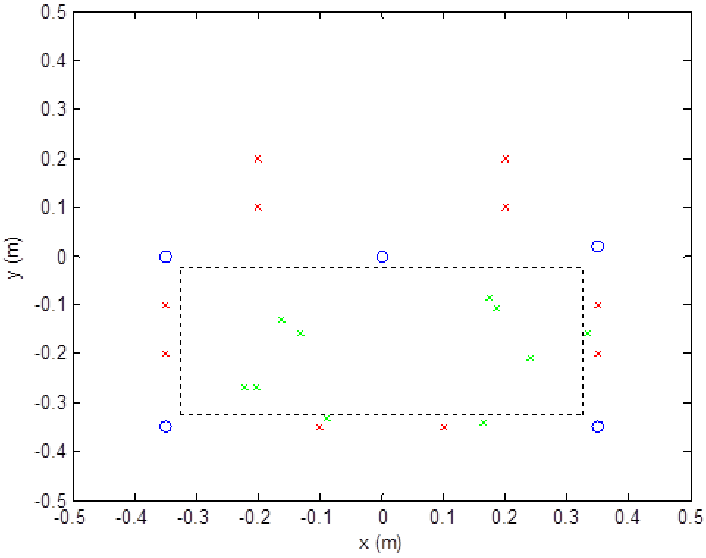

Figure 12. Representative scheme of the system showing position of sensors (blue circles), impacts in the OSZ (red crosses) and respective localization (green crosses).

4. CONCLUSION

The use of composite materials in the aerospace industry is a growing trend, with this kind of material replacing progressively components previously made of metallic counterparts. The use of composite materials in certain strategic parts (e.g., fuselage), however, is still not a reality, as these materials are subject to flaws not visible to the naked eye that arise from phenomena to which these components are routinely exposed, one of which is very important being impacts from different kinds of objects. In this sense, the present study was conducted with the intent of taking one step further towards this reality, allowing for real time localization of these impacts.

The present methodology is accounting for promising error margins and proving itself to be an interesting impact localization technique, despite the challenges to which this technology is subject. Average values of error presented are in close proximity to the standards demanded by regulatory agencies for this kind of application, this meaning that the present method is feasible for implementation and study under more complex environments (e.g., other geometries, restraining boundary conditions). Regarding other successful works in the area (Seydel and Chang, 2001; Coverley and Staszewski, 2003; and Kundu, 2007), the method provided results comparatively as precise, but with instrumentation of considerably low cost.

Also, the method allows room for further improvements via study of different sensor setups and more efficient approaches of mapping of the error function, what may significantly improve processing times of the algorithm. Concomitantly, the advances in localizing impacts give rise to more interest in the development of methodologies to regenerate impact force history and to actively investigate hot spots such as high energy impact locations in search of flaws.

5. ACKNOWLEDGEMENTS

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