1 Introduction

The interest in composite materials 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 [1]. Modern applications, such as in aerospace, nautical and prosthetics, demand a profound understanding of their nature and structure. 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 components. This is a consequence of the fact that these materials are known to develop specific types of failure under impact, and, differently to other materials, some of these can actually occur inside the material and have no superficial effect whatsoever (delamination, for example). These damages can go unobserved and result in dangerous further operation of the structure. Thus, it is important to keep track of areas exposed to impact of substantial energy, so as to submit them for later specific inspection. The role of impact localization within SHM is then to significantly reduce maintenance inspection time on the structure and hence allow for increasing the use of composite laminates in aerospace industry, in a safer environment and in an economically viable way.

Many attempts have been made to use piezoelectric sensors to address this issue. In the work of Ross [2], for example, triangulation algorithms were used as a tool to infer impact location in composite materials. Interesting results were presented by means of an alternate procedure using neural networks to aid in the evaluation of the computing arrival time of impact waves as recorded 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 [3] developed an impact localization and force reconstruction technique for composite panels with beam stiffeners, thus demonstrating that the method also works in more complex structures. The work considers a model of the system and generates the impact localization and force history via comparison between modeled response and actual response measured by sensors.

The work of Coverley and Staszewski [4] showed that it is possible to use genetic algorithms along with triangulation procedures to locate impacts in anisotropic systems. It assumes, however, previous knowledge of the moment of impact, which it is not an easy parameter to determine in real applications. The knowledge of such variable, direct or indirect, is fundamental in algorithms of impact localization.

Kundu et al. [5] studied a different approach to the problem, focusing in impact localization with piezoelectric sensors via error functions, i.e. 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 the proximity of the corresponding position to the point of impact. The study presented satisfactory results with fair precision, but was not tested for the case of highly anisotropic systems, limiting to the use of 4 sensors to estimate small errors for systems with small degrees of anisotropy.

The work of Ribeiro and Cimini Jr. [6] followed a similar approach. Having introduced a numeric model of wave propagation in composite laminates, the authors proposed a flexible methodology to allow for impact localization with multiple sensors in systems of different degrees of anisotropy, also based in the use of error function minimization. However, the error functions were defined in such a way to allow clear immediate interpretation and not to generate singular points in the domain. The study was developed via mathematical simulation of impact, which allowed testing the effectiveness of the method with deliberate control of noise and environmental interferences. For the sensor setup analyzed, consisting in a network of 9 sensors disposed in a square array covering the center and the borders of the plate, the methodology was found to provide motivating results, with errors of up to 1.1 cm in a 1 m by 1 m carbon-epoxy laminated plate.

The current study is a follow-up of this previous work. Experiments were performed in a 1 m by 1 m composite (carbon-epoxy) plate. Attention was given to analyzing different types of impact energies and adequate filtering of signals to better locate arrival time of impact waves.

2 Methodology

The 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 one of the most basic structures to be monitored. Results thus obtained are expected to be easily transferred to other common structures, e.g., 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 [(0/±45/90)₂]₅ carbon/epoxy quasi-isotropic laminated plate. In order to avoid boundary restrictions 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 the moment of impact only direct waves were taken into account as input for the method. The plate is shown in Figure 1.

2.1.2 Piezoelectric Sensors

The plate was instrumented with 6.4 mm diameter x 0.2 mm thickness piezoelectric sensor disks of the type “buzzer”, commonly used in acoustic applications and which consist of axial piezoceramic crystals 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 [7][8].

The sensors were carefully attached to the plate using 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. Figure 2 depicts one of the sensors attached to the structure.

Fig.2. Thin disk piezoelectric sensor, a.k.a. “buzzer”.

A total of 9 sensors were distributed in the plate and, since the method demands a smaller number of sensors (e.g., 5 in the current experiment), many setups were possible. For practical reasons, the elected setup covered the lower half of the composite plate, which was the region in which impacts were performed.

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 actual data acquisition device suffered from 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 should be given 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 the voltage levels of the sensors, which represent the arrival of impact waves. Accurate measurements are of great importance, and therefore background noise needed to be reduced. Figure 3 shows typical sensor output noise in the time and frequency domains.

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

It can be seen in Figure 3 that the typical sensor response presents background noise with important 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 present experiment was performed digitally, using sensor responses as input to a first order high-pass filter. Figure 4 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.
In order to investigate the impact wave speed in the present system, impacts such as the ones later conducted in 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, as shown in Figure 5. It was then possible to calculate impact wave speed at four angles of interest: 0°, ±45° and 90°. Values in between were interpolated so as to form a sinusoidal smooth curve (Figure 6). As quasi-isotropic, it was expected that impact wave speed did not vary much with propagation angle direction. Results, however, suggest otherwise, which may mean that impact waves travel closer to the surfaces, and thus the laminate 0° outer plies have greater influence on the impact wave speed than the others.

2.2.3 Charge Injection

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

Charge injection occurs basically during high rate data acquisition in multiple acquisition channels with different voltage levels and high output.
impedance [9], and is related to each data acquisition settling time, i.e., 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 measurements has not enough time to discharge back and thus affects the next measure. Figure 7 shows the responses of 5 sensors to an impact. Note that sensors 1 and 3 present similar responses, although they are not located symmetrically to the impact.

![Figure 7](image)

Fig.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 avoid this 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 interest. Four impact points were selected, so as to divide the setup region of the plate in four quadrants, and five impacts were performed in each of these points. Average value and standard deviation of the localization error were calculated for each of these impact points.

Impacts were performed using a 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. Sensor positions and impact positions are given according to Tables 1 and 2 and Figure 8.

Table 1. Position of numbered sensors in setup.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-350.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>350.0</td>
</tr>
<tr>
<td>4</td>
<td>-350.0</td>
</tr>
<tr>
<td>5</td>
<td>350.0</td>
</tr>
</tbody>
</table>

Table 2. Localization of sets of impacts made in the experiment.

<table>
<thead>
<tr>
<th>Set</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200.0</td>
</tr>
<tr>
<td>2</td>
<td>200.0</td>
</tr>
<tr>
<td>3</td>
<td>-200.0</td>
</tr>
<tr>
<td>4</td>
<td>-200.0</td>
</tr>
</tbody>
</table>

![Figure 8](image)

Fig. 8. System setup showing position of sensors (blue circles), impacts (red crosses).
2.4 Algorithm

In order to locate impacts in the plate, the algorithm was designed to work minimizing the error function. According to this methodology, the point of impact is found to be the point of minimum for 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 (impact wave speed as a function of the propagation angle formed with respect to the main coordinated system). The function is calculated for the entire domain of 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 time of impact waves at each sensor is defined as the moment in which this sensor’s responses go beyond the regular noise level. The definition of this threshold has great impact on the calculation of arrival times of impact waves, whose correct values in turn are responsible for the precision of the impact localization method. Figure 9 shows a typical filtered response of a sensor, with the threshold cut at 0.0385 V.

2.4.2 Error Function Mapping

One of the main features that distinguish the present algorithm among others is that it does not need previous knowledge of the real moment of impact in order to estimate its location. Such is a challenge for many impact localization methodologies and a characteristic inherent to every real practical application, since impacts occur at random and their moments of occurrence are impossible to predict a priori.

Nonetheless, for the present algorithm the moment of impact constitutes indirectly still an important variable, and the method manages to calculate it by means of a trial-and-error approach, minimizing the error function. Such method, besides effective, can also be enhanced for better and more intelligent search procedures of the desired points, which makes room for further improvements in terms of processing capacity requirements.

Given the impact waves arrival times recorded by each of the $n$ sensors in the setup, the algorithm calculates, for each point of the domain, the moment of impact $t_{imp}$ as seen by each sensor, according to Equation (1):

$$t_{imp} = t_{ai} - \frac{d_i}{v(\theta_i)}$$

Where $t_{ai}$ is the impact wave arrival time recorded by sensor $i$, $d_i$ and $\theta_i$ are respectively the distance and the 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 according to Equation (2):

$$E(x, y) = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}[t_{imp_i}(x, y) - t_{imp_j}(x, y)]^2}$$

Fig.9. Filtered response of a sensor. Notice defined threshold of 0.0385 V and respective impact wave arrival time calculated at 0.4674 s.
\( E \) is, then, a function whose domain coincides with that of the physical plate analyzed. It is possible to map \( E \) in order to better visualize how the point of impact was determined, as shown in Figure 10.

Since the error function must be mapped for the entire plate domain, the level of refinement of the domain in the algorithm is an important design choice. Dividing the domain into smaller regions provides more precise responses, but also increase the processing time necessary in order map it.

### 3 Results

Results are grouped so as to show impact localization error, in terms of average and standard deviation, grouped for each set of tests (Table 3). Each impact localization error was obtained via calculus of the distance between the impact real location and the algorithm estimation, for an array of 200 by 200 (40,000) points. This corresponds to a physical square mesh with element size of 5 mm by 5 mm.

Results are graphically presented in Figure 11, where the blue circles are the sensors, the red crosses are the impact locations and the green crosses are the algorithm estimations. Aircraft industry requires the impact location to be estimated within a circumferential locus of one-inch (25.4 mm) diameter. This target around the impact location is also presented in Figure 11 with red circles, to visually check for the algorithm precision.

### Table 3. Algorithm evaluation of impacts loci and associated errors grouped by impact sets.

<table>
<thead>
<tr>
<th>Set 1 (200.0, -100.0)</th>
<th>Set 2 (200.0,-275.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Error</td>
</tr>
<tr>
<td>x (mm)</td>
<td>y (mm)</td>
</tr>
<tr>
<td>184.7</td>
<td>-123.2</td>
</tr>
<tr>
<td>216.3</td>
<td>-151.1</td>
</tr>
<tr>
<td>237.4</td>
<td>-100.9</td>
</tr>
<tr>
<td>205.8</td>
<td>-100.9</td>
</tr>
<tr>
<td>184.7</td>
<td>-84.1</td>
</tr>
<tr>
<td>Avg. error (mm)</td>
<td>29.3</td>
</tr>
<tr>
<td>Std. deviation (mm)</td>
<td>17.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Set 3 (-200.0, -100.0)</th>
<th>Set 4 (-200.0,-275.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Error</td>
</tr>
<tr>
<td>x (mm)</td>
<td>y (mm)</td>
</tr>
<tr>
<td>-195.2</td>
<td>-95.3</td>
</tr>
<tr>
<td>-205.8</td>
<td>-106.4</td>
</tr>
<tr>
<td>-163.6</td>
<td>-67.4</td>
</tr>
<tr>
<td>-205.8</td>
<td>-123.2</td>
</tr>
<tr>
<td>-163.6</td>
<td>-100.9</td>
</tr>
<tr>
<td>Avg. error (mm)</td>
<td>24.9</td>
</tr>
<tr>
<td>Std. deviation (mm)</td>
<td>18.1</td>
</tr>
</tbody>
</table>
Although the results were encouraging, they indicated that the algorithm needs to be further refined in order to achieve the one-inch requirement precision.

Fig. 11. System setup showing position of sensors (blue circles), impacts (red crosses), one-inch diameter target (red circles) and respective impact localization estimates (green crosses).

4 Conclusion

The use of composite materials in the aerospace industry is a growing trend, with this kind of material progressively replacing components previously made of metallic counterparts. The use of composite materials in primary structural components, however, still lacks SHM systems to identify flaws not readily visible to the naked eye that arise from phenomena to which these components are routinely exposed during aircraft operation. In this context, the evaluation of impacts in composite components is a very important task. The present study was conducted with the intent of taking one step further towards this reality, allowing for real time localization of these impacts.

A methodology was presented to identify impact location in composite plates by means of a passive network of piezoelectric sensors. Average values of error obtained are in the range of two-inches (highest average error of 44.9 mm), which is way higher than the standards demanded by regulatory agencies for this kind of application. Although not yet within the one-inch error target requirement, results were promising presenting error margins that can be further improved.

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

Acknowledgements

Authors would like to acknowledge CAPES, CNPq, FAPESP and FAPEMIG for their support.

References