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Investigation on low velocity impact damage identification with ultrasonic techniques under different sensor network conditions

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Abstract. Direct or indirect damages due to foreign object impacts on aeronautical structures, represent a major concern. The problem potentially intensifies with the adoption of composite materials, especially due to Barely Visible Impact Damage (BVID). In this context, understanding whether an impact event gives rise to delamination or debonding is highly desirable in view of the optimization of the maintenance strategies and, at the same time, of the safety margins associated to the operation of the structures. One possible method to achieve this goal is that of integrating damage monitoring systems within the vehicle architecture itself. By doing so, in fact, the enhanced structural health state awareness allows the implementation of Predictive Maintenance philosophies and the possibility to detect damage with size/severity and indentation smaller than the BVID currently applied by design and certification. In this work, a simple and a stiffened carbon fiber panel are subjected to Low Velocity Impacts using falling masses to generate a structural damage. A sensor network made of Piezoelectric elements (PZT) allows the application of Ultrasonic techniques, to monitor the damaged structure and calculate signal related features called Damage Indexes (DIs). The DI capability to identify the damage is then thoroughly investigated, with specific reference to: (i) effect of signal averaging, (ii) effect of reduced sensor network configurations and (iii) effect of sensor faults.

1. Introduction

Every year, aeronautical companies deal with the problem of impact events, that could hamper the flight safety throughout all the vehicle operation phases [1], [2]. Moreover, economic consequences are present too, in terms of unreliability, inefficiency and unpredicted maintenance, as well as life losses [3], [4]. In fact, the damages produced to the vehicle as consequence of the impact event, could lead to critical accidents depending on their severity. This is even amplified if composite materials are considered, because of the possible generation of Barely Visible Impact Damages (BVID) that could remain hidden in the structure [5].



This damage is the upper limit of Category 1 of damage (EASA AMC 20-29) [6], that includes permissible defects caused in manufacturing or low energy impact damage (induced by tool drops, runway or ground debris, hailstones) that are not detectable by the standardized and current visual inspection technique and that have substantiation data showing ultimate load is retained for an aircraft structure's life span. An appealing solution to the problem is the implementation and integration on a vehicle of an impact damage monitoring system, typically based on Ultrasonic techniques [7].

The key for the impact damage identification is the development of a Structural Health Monitoring (SHM) strategy based on the generation and acquisition of ultrasonic waves and the comparison of the acquired signals between two conditions: when the structure is pristine and the current state. Typically, the ultrasonic waves are generated using Piezoelectric (PZT) transducers, while the signal differences are evaluated using a Damage Index (DI). The higher the DI on a generator-sensor path, the higher the probability of damage presence on that path. Finally, tomography technique can be used to gather the information from all the paths present in the sensor network, to give a picture of the actual state of the monitored area [8].

Once the most promising SHM strategies had been identified, an Engineering Ground Support Station (EGSS) software was developed. The objective of this work is the Functional Hazard Assessment (FHA) and Preliminary System Safety Assessment (PSSA), through the analysis of the EGSS software outputs for known damage scenarios. To this aim, two Carbon Fibre Reinforced Polymer (CFRP) specimens representative of a real Outer Wing Box (OWB) are sensorized with PZT transducers. Then, the specimens are damaged using a drop-weight tower. The PZT signals acquired in pristine condition and after the damage generation, are used to evaluate the most promising DI among that made available by the software. The need for signal averaging is investigated first, then a sensitivity analysis is carried out reducing the number of sensors considered in the configuration. Finally, some sensor failures are simulated altering the PZT outputs, to investigate their influence on the results, in terms of damage identification capability.

The structure of the paper is as follows: the EGSS software overview, including the available DI definitions, is briefly described in Section 2. Then, the experimental setup is shown in Section 3 and the results analysis is reported in Section 4. Finally, some conclusions will be given in Section 5.

2. EGSS software overview

The EGSS software receives as input the PZT sensor signals and gives as output a graphical representation of the structure, based on a multipath mesh-less approach. The graphical representation superimposes the colored contour of the DI values to the geometrical shape of the component, allowing the evaluation of its structural health condition at a glance. The features made available by the software for the DI evaluation are:

- *Energy level.* Given the signal $s(t)$ and its initial and final time step t_{in} and t_{fin} , it can be calculated as:

$$f = \int_{t_{in}}^{t_{fin}} s(t)^2 dt \quad (1)$$

- *Pearson coefficient.* Given the baseline signal s_1 , the actual signal s_2 and the number of samples of each signal N_p , it can be calculated as:

$$f = 1 - \frac{\sum_{i=1}^{N_p} (s_{1i} - \bar{s}_1)(s_{2i} - \bar{s}_2)}{\sqrt{\sum_{i=1}^{N_p} (s_{1i} - \bar{s}_1)^2 * \sum_{i=1}^{N_p} (s_{2i} - \bar{s}_2)^2}} \quad (2)$$

- *Signal amplitude.* It is calculated simply as the maximum of the signal.
- *Time of Flight.* It is calculated, based on the Power Spectral Density (PSD) of the signals, as the difference between the times when the sensor and the actuator reach their maximum values:

$$f = T|_{\max PSD,SEN} - T|_{\max PSD,ACT} \quad (3)$$

- *Transmission factor*. It is calculated, based on the Power Spectral Density (PSD) of the signals, as the ratio between the maximum values reached by the sensor and the actuator:

$$f = \frac{\max_{PSD,SEN}}{\max_{PSD,ACT}} \quad (4)$$

Finally, the DI can be calculated as, based on the values of signal features just introduced in pristine (f_P) and damaged (f_D) condition:

$$DI = \frac{|f_D - f_P|}{f_P} \quad (5)$$

The EGSS software procedure consists of four steps, each one performing a specific functionality. The initialization step allows to sort the transducers creating a selection queue to obtain predefined subsets of actuators and sensors. Then in the pre-processing step, the specific diagnostic wave (i.e. tone burst) is assigned to each queue previously defined. The processing step allows to manage the acquisition phase and collect raw data from the field. The post-processing module provides the analysis of the data, extracting the signal responses and evaluating the damage metrics [9], [10]. Finally, it provides the graphical representation of the results on the structure geometry.

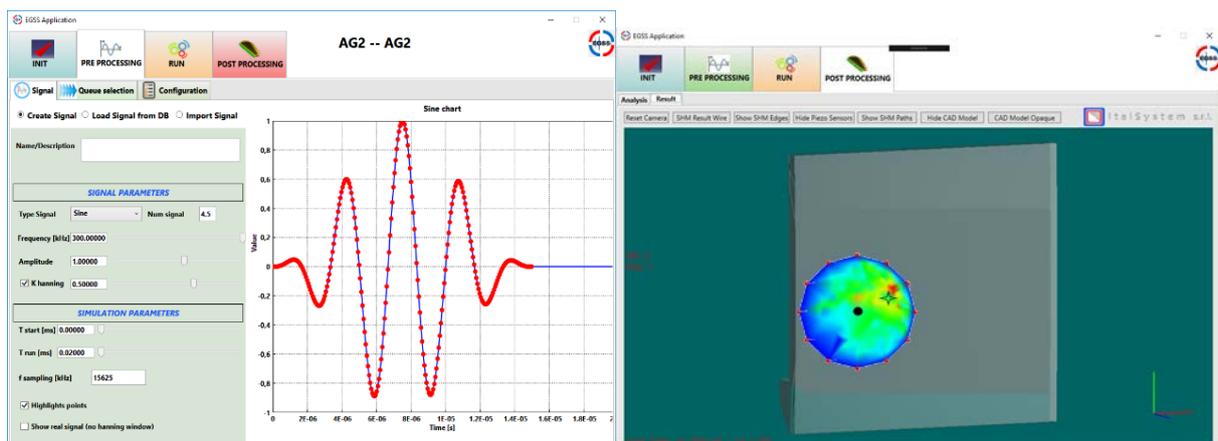


Figure 1. Example of the tone burst definition in the pre-processing module (sx) and the results graphical representation in the post-processing module (dx).

3. Experimental setup

The experimental setup comprises the specimens, the sensor network, the generation/acquisition system and the drop-weight tower for the damage generation.

3.1. Specimens

Two panels representative of the composite OWB are considered: (i) a flat panel and (ii) a stiffened panel. Their dimension is 400x400mm and the material is a CFRP made of PRISM EP2400 resin system and tenax-E IMS65E2324K830tex fibres. The panels have been manufactured by SICAMB S.p.a. and checked with Non-Destructive Inspections (NDI) by RAV S.r.l, for the evaluation of defects possibly generated in the manufacturing process. The panels are hold in position using specific metallic fixtures closed with bolts to control the boundary conditions.

3.2. Sensor network

The PZT transducers are simple cylindrical elements with diameter of 10mm and thickness of 0.2mm, enclosed into a 17x13mm Kapton case and with metallic electrodes produced by Physik Instrumente GmbH on UNINA specifications. They are attached using the HBM X60 bicomponent glue. The PZTs are wired with coaxial cables with a BNC connector. A total of 18 PZTs are installed in a circular shape on the flat panel, while 12 PZTs are installed in a rectangular shape on the stiffened panel.



Figure 2. The sensors (left), the flat panel (middle) and stiffened panel (right) with the sensor networks installed.

3.3. Generation/acquisition system

A Keysight 33220A waveform generator creates the 4.5-cycle tone-burst (i.e. a sinusoidal signal windowed with a Hann function) with carrying frequency of 63kHz, used to excite the PZT transducers. This is amplified to around 160V using a Krohn Hite 7602M voltage amplifier. The acquisition is operated using a PicoScope 4824 and the PicoScope 6 software. The tone-burst parameters are set considering the PZT material and the voltage amplifier electrical properties.

3.4. Drop-weight tower

A mass is used to hit the panels with specific energies (i.e. 31J for the flat plate and 57J for the stiffened). A speed trap made of two Omron Corporation E3FALP21 photoelectric sensors is used to measure the final speed of the mass, allowing the experimental verification of the impact energy. Finally, the damages are checked with NDI by Unina (see Figure 3). Specifically, a C-scan is performed using an Olympus OmniScan SX flaw detector with a 5MHz phased array probe.

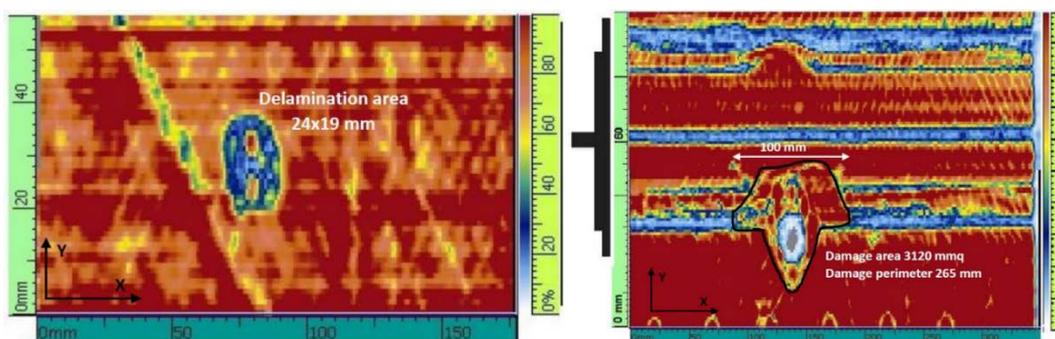


Figure 3. NDI of the damages on the flat panel (left) and on the stiffened panel (right).

4. Results

The PZT signals are acquired with the specimen mounted in place under the drop-weight tower just before the damage generation, thus recording the reference signal database (i.e. baseline). Then, the same set of acquisitions is repeated after the damage generation, to collect the database in damaged conditions. This has been done trying to exclude all the possible interferences (i.e. temperature,

boundary condition variations, humidity, generation/acquisition system operation variations, external interferences) that could cause natural changes in the signals, thus meaning undesired changes in the DI values too. Finally, the EGSS software is used to calculate the DI and produce a graphical representation of the results. The software results will be discussed with reference to: (i) the need for signal averaging, (ii) a sensitivity analysis reducing the number of sensors considered in the sensor network configuration and (iii) single/multiple sensor failures simulated altering the PZT signals.

A preliminary investigation allowed the selection of the most promising signal feature for the DI calculation. Referring to Figure 4, the chosen parameter is the transmission factor, that allowed to correctly identify the damage in both the panels. It will be used to show and analyze the software results. The red dots in the figure are the PZT positions while the gray dots are the damage position.

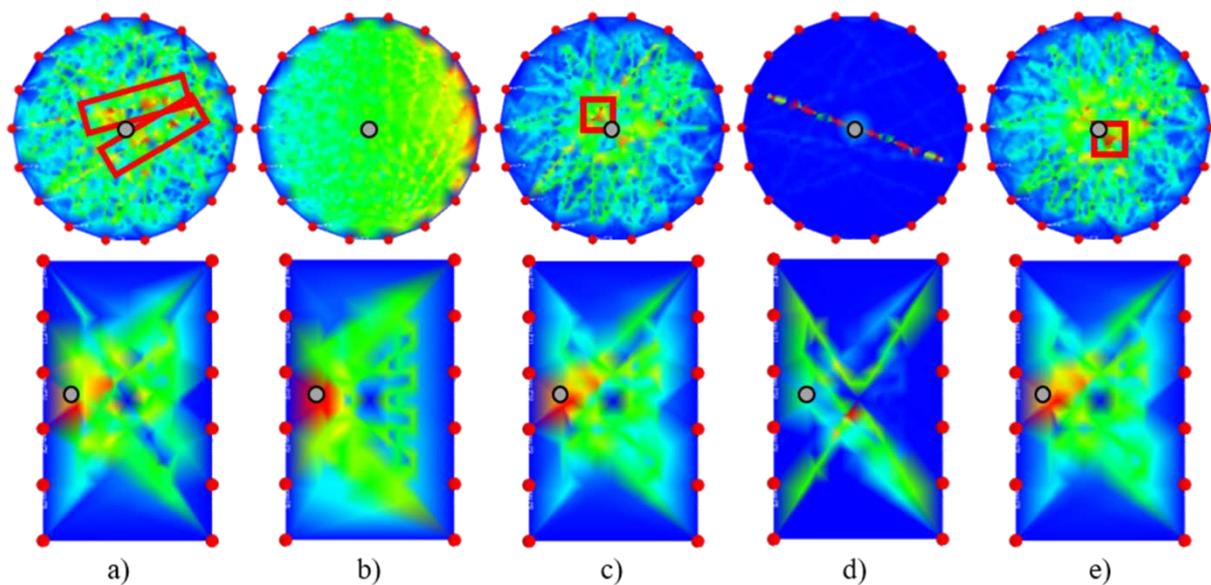


Figure 4. Software results for: energy level (a), Pearson coefficient (b), signal amplitude (c), time of flight (d) and transmission factor (e). Flat panel (top row) and stiffened panel (bottom row).

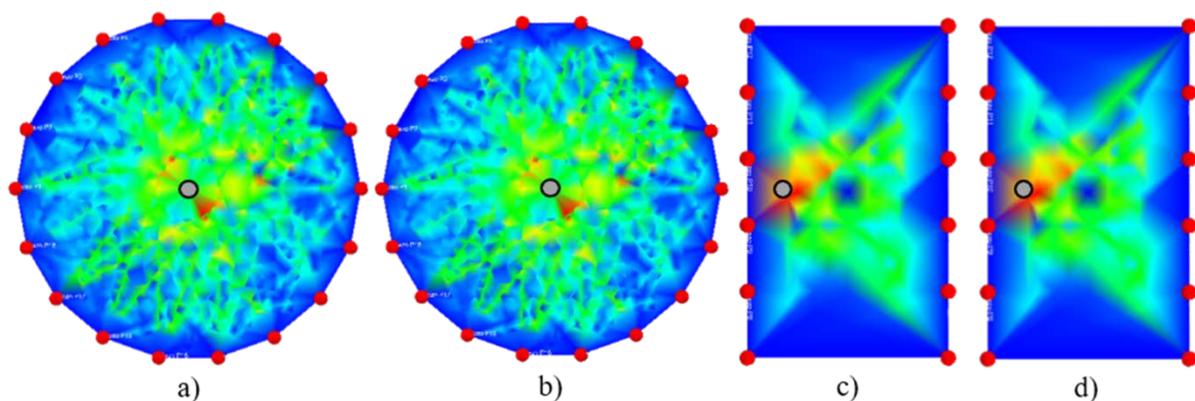


Figure 5. Signal averaging analysis results, for the flat panel and the stiffened panel: with 10 averages (a, c) and without averaging (b, d).

4.1. Signal averaging analysis

The first investigation is made to determine whether the software needs multiple signal acquisition repetitions for its optimal operation. Each PZT is acquired 10 times and the graphical results are compared after: (i) averaging the signal 10 times, (ii) averaging the signal 3 times and (iii) without

averaging. The result of the investigation is reported below, for the case without averaging only. This because of the absence of noticeable changes between the three cases, meaning that no averaging is needed. The result can be motivated considering the high Signal to Noise Ratio (SNR) of the PZT transducers, allowing to easily identify the damage without the need to improve the result by averaging (Figure 5).

4.2. Sensitivity analysis

As the software calculations are based on the sensor network, this means that the damage identification performances are influenced by the number of sensors installed on the structure and the sensor network shape. The latter influence can be already seen in the previous figures, comparing the circular shape to the rectangular one. However, this investigation is focused on the number of sensors that compose the network. Specifically, the sensor number will be reduced considering a configuration with the 66% of the sensors and a configuration with the 50% of the sensors. Again, the grey dot represents the damage position and the graphical results are reported in Figure 6 for all the considered configurations.

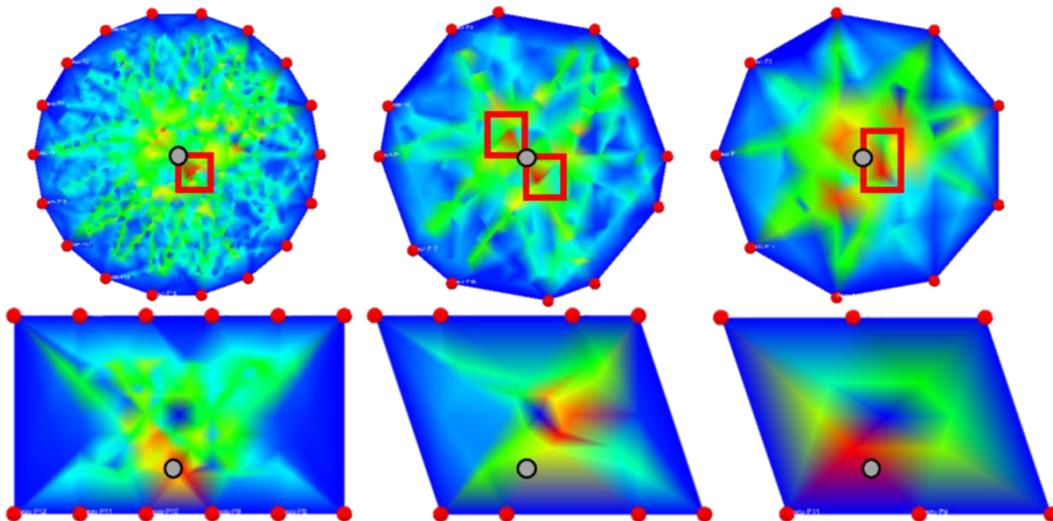


Figure 6. Comparison between the full sensor network (a) and the reduced configurations: 66% of the sensors (b) and 50% of the sensors (c). Flat panel (top) and stiffened panel (bottom).

As can be noticed, a progressive degradation of the software performances arises reducing the sensor number, as expected. Despite that, the circular configuration demonstrated to be able to give good indications even in presence of a reduced configuration, obtaining again the strongest indications around the real damage position. On the other hand, in the rectangular configuration the sensor number reduction produces incorrect indications. It is worth to notice that it seems a correct identification is present in the 50% configuration. However, the red area covers around a quarter of the sensor area, meaning that a very wide area would be considered damaged making the monitoring process more expensive in terms of maintenance procedures. For these reasons, the minimum reliable configuration for the circular configuration is the one with 66% of the sensors (i.e. 12 PZTs), while the rectangular configuration needs the full number of sensors (i.e. 12 PZTs).

4.3. Sensor failure simulation

Again, as the software calculation are based on the sensor information, it is of interest understand how sensor failures affect the monitoring results. To this aim, a single and then a double sensor failure (i.e. sensor detachment) are considered in this investigation. The detachment is simulated substituting the sensor signal with its typical noise. The first finding is that the transmission factor, considered the

most effective for damage monitoring, cannot give any indication about the sensor failure. In fact, looking at Figure 7 basically nothing changes even with a double failure, for the circular configuration. This is a good point from the damage detection point of view, but nothing can be said about the failure detection. Conversely, in the rectangular configuration case, neither the damage identification nor the sensor failure detection is accomplished.

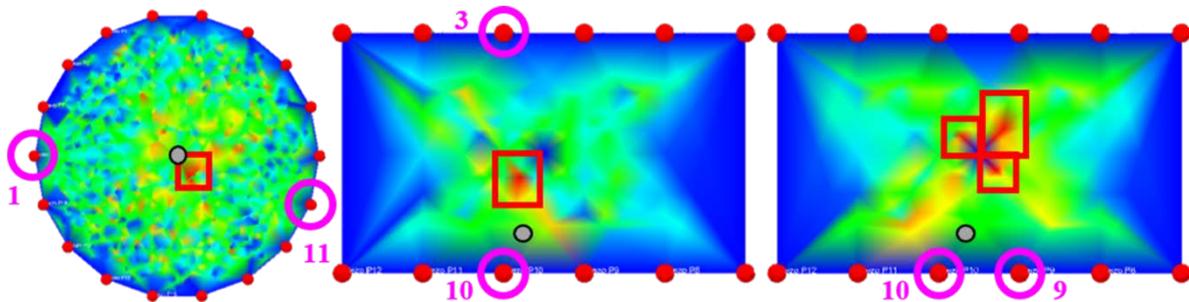


Figure 7. Damage identification results with the transmission factor and the sensor network with a double failure. Flat panel (left): failures on sensor 1 and 11. Stiffened panel: failures on sensor 10 and 3 (middle) and sensor 10 and 9 (right).

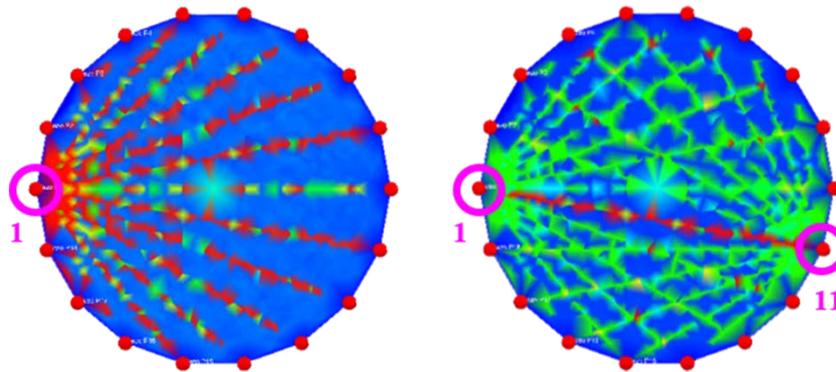


Figure 8. Sensor failure detection with the Pearson coefficient signal feature: flat panel.

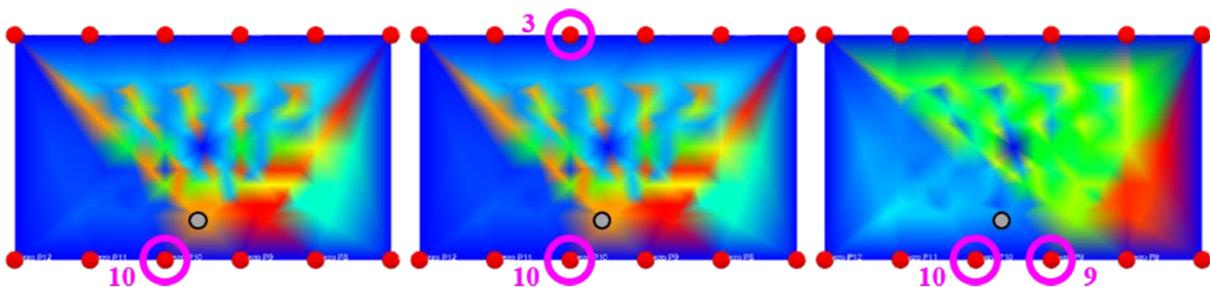


Figure 9. Sensor failure detection with the Pearson coefficient signal feature: stiffened panel.

Fortunately, among the features calculated by the software the Pearson coefficient appears to be promising for sensor failure detection. In the circular configuration, this feature is able to find red lines converging in the failed sensor position or connecting the two failed sensors (see Figure 8). Conversely, the same results are not obtained with the rectangular configuration, where neither the single sensor failure can be clearly detected. However, the Pearson coefficient results highlight the anomaly behaviour of sensors and thus its indication can be integrated in the monitoring process to increase its performances.

5. Conclusions

This work deals with the problem of assessing the performances of a damage identification software under different sensor network conditions. For the software operation, PZT transducers have been installed on two specimens, representative of a composite wing-box. Baseline signals have been acquired before the damage generation, using a drop-weight tower. Then, the signals in damaged conditions have been acquired too. Once the damaged database is available, the EGSS software can be operated, the signal-related features calculated and the graphical representation of the structure health state obtained. The latter is the metric used in combination with three different investigations the software performances, obtaining the following conclusions:

- The transmission factor has been identified as the most promising signal feature.
- Signal averaging analysis: the software and the adopted PZTs showed the ability to correctly operate with a single signal acquisition, meaning no averaging is needed.
- Sensitivity analysis: the software together with the sensor network shapes allowed to define the minimum number of sensors required to obtain a reliable damage identification.
- Sensor failure simulation: the transmission factor failed in detecting the failed sensors, but the Pearson coefficient has been able to detect single and double failures in the circular configuration. The same does not apply for the rectangular configuration.

These findings can be exploited to improve the reliability of the EGSS software, bringing benefits to the development of monitoring technologies. Their integration in vehicles is highly desirable nowadays, for the increase of situation awareness, availability and costs reduction they can bring.

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