Numerical Simulation For ANN Training and validation For Impact Detection

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Abstract—In last decade the presence of composite structures is increased dramatically. Today the composite is present in every field of our life. A lot of objects have a percentage of composites material inside. With the last release of Boeing 787 Dreamliner the composite is become relevant also in aerospace field. Composite materials have a lot of benefit, first of all they can merge high strength and low weight. The life cycle of composite material is far away from metal's one. They need a better monitoring to avoid the delamination problem that is strictly related to objects impact. To help the monitoring and increase the safety of composite structure an artificial neural network has been developed with the task to catch impacts on composite structures and give informations about the integrity status.
Keywords—SHM, composite materials, piezoelectric materials, impact detection, NDT

I. ABSTRACT

Composite structures, today, have a relevant role in our life. The most of the object we use daily are done of composite materials. The recent increase in use of composite materials can be explained if we consider:

* They have great strength;
* They have low weight;

The combination of these two characteristics is the main reason the composite materials are so appreciate in engineering. Every time we need to produce a light structure with high strength composite materials are the good approach to design it. Instead of benefits, composite materials have also some issues. From a structural point of view the most critical is the difficult to monitoring them.

Metal materials integrity is easy to check, the most of the time a visual inspection is enough to detect failures also in early stage. In composite materials, due the way they are maiden, often is impossible detect failures until it is too late to repair them.

The most common problem composite materials have is the delamination. It consists in a detachment of plys inside the material due to an impact on the material itself. From an exterior point of view it is impossible to detect by eye. It suddenly propagates inside the structure inducing failures.

The task of this work is to develop an artificial neural network (ANN) able to detect impacts and restrict the part of structure to monitor looking for damages.

II. Introduction to Structural Health Monitoring (SHM)

A. Introduction

Structural health monitoring (SHM) is a collective term for cutting-edge technologies using permanently attached sensor networks to enable the continuous inspection of the reliability of structures. In the last years there has been an increasing interest in structural health monitoring systems for all kinds of aircraft. Beside the expected enhancement of safety and maintenance performance, also economic aspects play an important role. This regards on the one hand the reduction of unnecessary inspection and repair costs and on the other hand, the possible weight reduction of aircraft parts at the designing phase of an aircraft. The main benefits of SHM are:

* Cost saving by reduction of inspection and repair cost and the possibility to reduce the weight at the design phase;
* Enhancement of safety by much more frequently applied automated inspection;
* Enhancement of passenger throughput by reduction of unnecessary maintenance;

The advantages of a SHM system for aerospace applications is that it enables early identification of damage and consequent reduction in the structural performance. Composite materials can often suffer internal damage which vastly reduces the life of the structure; they are also susceptible to flaws within the material being introduced during the manufacturing stage; both these aspects could substantially reduce the life of a component. Moreover composite materials are highly susceptible to impact damage which leads to delamination of the ply, which is often very difficult to detect externally and can lead to a dramatic reduction of design strength and service life. The introduction of structural health monitoring in routine aircraft maintenance seems to be only a question of time. The obstacles, which have so far prevented the earlier introduction of SHM systems, can be avoided by an integrated approach combining modern technical and organizational principles on a large scale. Moreover, end-users such as manufacturers and operators (airlines) must be convinced that a mature SHM concept ensures complete airworthiness. Projects must provide an essential contribution to these objectives. The development of an effective structural health monitoring system must finally be integrated into a structural health management system where the data on structural integrity are classified and where procedures of maintenance and allocation of resources are organised.

Two fundamental techniques that could be used for a SHM system are Acoustic Emission (AE) and Guided Lamb waves

(GLW).

III. IMPACT DETECTION

The safe use of aircrafts can only be guaranteed when appropriate damage assessment is available. Fiber Composite Materials allow to manufacture large and complex structures with minimum weight at relatively low costs. This is a typical material for e.g. aircraft, boats or rotor blades for wind energy plants. However when compared to metal the fatigue behavior of composite material is more complex. Impacts can cause delamination of the individual laminated layers of fiber composite material. This initial delamination slowly grows when alternating or fluctuating mechanical loads stress the structure. The delamination leads to a loss in stiffness. When a part of the structure is finally to weak to withstand the loads a sudden rupture of the fibers in the remaining cross section occurs. This can lead to a chain reaction destroying the whole structure and damaging the others near it. It is therefore important to detect and monitor damages in high loaded safety components made of fiber composite materials to receive an early warning for a well timed shutdown of the facility respectively landing of the aircraft. This kind of application in our study field is in an experimental phase yet because of two main reasons. Lack of technical maturity the first reason, lack of acceptance by end-users the second one. The lack of acceptance by end-users can be overcome by convincing technical solutions that respond to all the challenges inherent to aircraft operations. The major problem already mentioned in the list above is the difficult interpretation of measured data obtained in complex aircraft components. One possibility to detect “barely visible impact damage (BVID)” after impact in aircraft materials is non-destructive testing (NDT) using ultrasound. The ultrasonic waves are usually excited and received by piezoceramic sensors.

A. *Acoustic Method Detection Based*

There are several structural health monitoring concepts for damage detection in fiber composite materials including fiber brag sensors or modal analysis techniques. The first method provides information only when the damage is near the sensor. Traditional vibration-based monitoring techniques provide only global information about a structure under monitoring by identifying and analyzing specific resonance modes. Due to the low frequencies only large defects can be identified and moreover, cannot be precisely localized in general. For crucial parts of a structure, vibration monitoring can be efficiently supplemented by using elastic waves in the kHz frequency regime. These ultrasonic waves have a shorter range but are more sensitive to smaller defects and thus, can serve as an early-warning system raising an alarm long before critical damage occurs. If the wavelengths are of at least the same size or larger than typical dimensions of the structure, the waves are called “guided waves” [7], [8]. In this case geometrical dispersion cannot be neglected in general. If using elastic waves for structural health monitoring purposes two different approaches are possible, a passive and an active approach. In a passive SHM system only sensors are needed and “natural” sources like impact, ambient vibrations or acoustic emission (AE) caused by crack generation and growth are detected (Fig. 1). The AE events can be localized and characterized and can also be used for imaging purposes using acoustic emission tomography. In an active SHM system the transducers are acting as both, sensors and actuators (Fig. 2).

By using pulse-echo or acoustic signature techniques, scattered waves from inside the structure or changes in acoustic signature response can be detected and used as damage indicator.

A set of transducers spans a so-called “synthetic aperture”. By temporally delayed excitation and detection by individual actuators and sensors, elasto-dynamic wave fields can be focused to specific control volumes of the structure serving as basis for powerful SHM imaging techniques.

The simplest case of guided waves can be found in plate-like structures where so-called plate waves or Lamb waves can propagate. In general symmetric and anti-symmetric wave modes are being distinguished. In most cases, SHM techniques are working in the low-frequency regime below 500 kHz and thus, only the 0th order Lamb waves are of interest for monitoring applications. In addition to the Lamb waves also horizontally polarized shear waves (SH waves) can be used. In contrast to the Lamb waves the 0th order SH wave is non-dispersive. Numerical and experimental investigations show that each wave mode mentioned above shows different sensitivity to specific kinds of damage. For example the antis-ymmetric mode turns out to be well-suited for detection of delamination.

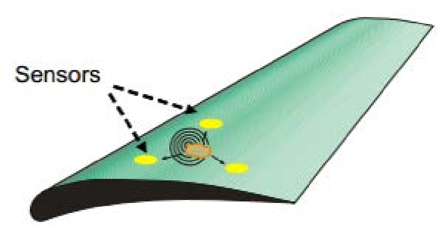


Fig. 1: Passive SHM Approach.

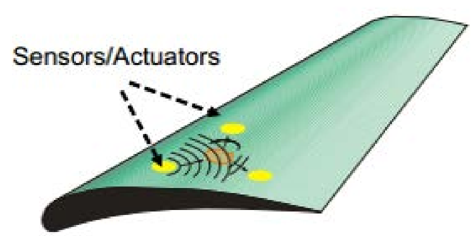


Fig. 2: Active SHM Approach

B. *Fiber Transducer (PZT)*

For the SHM-system piezo transducers made of lead zirconate titanate (PZT) are widely used due to their low thickness. Fig. 3 and Fig. 7 shows the layout of a PZT fiber transducer with corresponding electrode structure. It can be used for both, excitation and detection of elastic waves. The directional characteristic of the PZT fiber transducer depends on its size, the material properties of the structure and the signal frequencies used for monitoring. Therefore, optimized transducers for specific kinds of structures can be designed and applied. Moreover, by using enhanced electrode configurations a wave-mode specific excitation and detection of guided waves is possible. The PZT ceramic is prepared by a special sol-gel process. Gallus PZT-precursors are spun to thin fiber with a diameter of around 30 µm. The endless green fiber is cut into 30 cm long threads to be sintered at 1100 °C in a special gas atmosphere. The sintered piezoceramic fiber threads are embedded in a polymer matrix and electrically connected with silver electrodes in an inter-digital design (Fig. 3). After polarization in an electrical field of 3 kV/mm these thin and flexible transducers (Fig. 5) are ready for use.

Fig. 3: Piezoelectric fiber

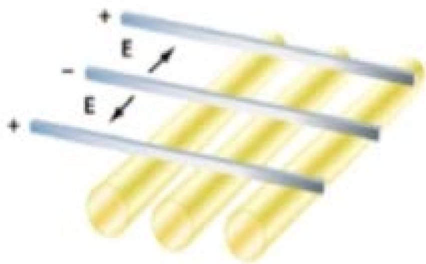


Fig. 4: Inter-digital electrode

Tests on fibre sensors laminated into a glass fiber reinforced plate show a high sensitivity to impact events depending on the orientation of the fibers respectively. For ultrasonic applications the piezoelectric transducers can be manufactured in a special design for frequencies up to more than 10 MHz. Fig. 5 shows a transducer resonance in the impedance spectrum of a piezoelectric fibre composite. The PZT can be simply applied (using an adhesive film) on the plate or embed into the plate. As the material allows the integration of thin transducers in the structure an ideal acoustic coupling can be achieved. The embedded monitoring device is directly bonded to the fibres. However, unlike the applied device, it's really important to study influence of the embedded device on the structural durability of the fibre composite material. Fig. 7 shows an aircraft sandwich-wing with embedded PZT fibre transducers. The SHM system can detect impacts, fibre cracks and delamination in this and similar structures. The typical production process for such structures needs only minor changes to ensure reliable electric contacting of the transducers after curing the fibre composite material.

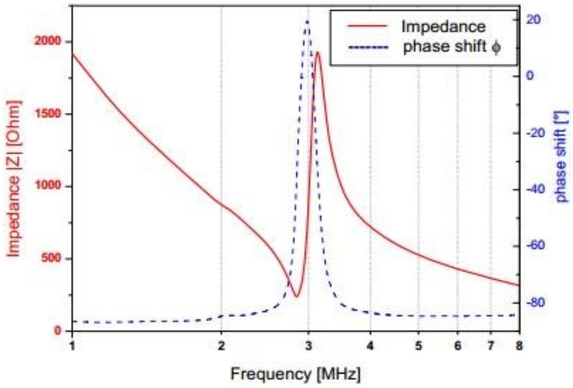


Fig. 5: Resonance phenomena

By avoiding thick adhesive films and using the top and bottom side of the monitoring device a higher acoustic performance can be achieved.

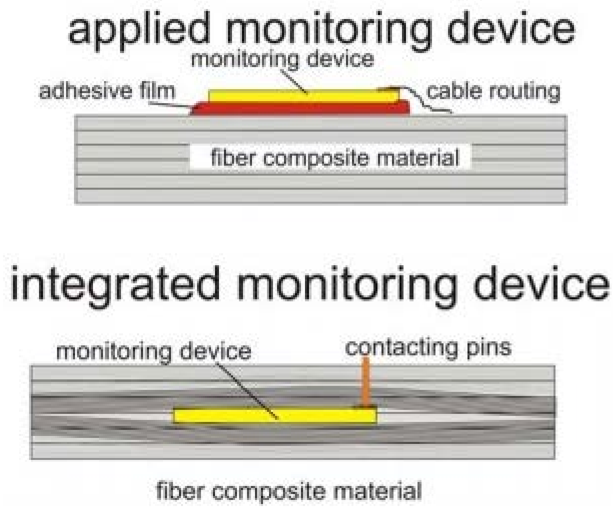


Fig. 6: Applied (up) and integrated (down) device comparison

Fig. 7: Embedded PZT fiber transducer

IV. INTRODUCTION TO NEURAL NETWORK

An artificial neural network attempts to reproduce the functioning of biological neural networks, within the human brain (as well as in many other animals) the resolution of cognitive problems is carried out by neural networks, usually consisting of several hundred of neuronal cells. These networks, the extent and magnitude varies depending on the required task, may also involve different brain areas and their development and formation has been crucial in the evolution of the human species. When we speak of artificial neural networks we refer to information processing systems whose purpose is to simulate the functioning of biological networks within a computer system. Artificial neural networks can be considered as a large computer network made up of several dozen units that play the same role that neurons play within biological networks. Each of these nodes (or artificial neurons) is connected to the other nodes of the network through a dense network of interconnections, which also allow the network to communicate with the outside world. The ultimate goal of a well structured network is to acquire information from the outside world, process it and return a result. The transfer function of the signal in the network is not programmed but is obtained through a learning process based on empirical data. This process can be supervised , unsupervised or for reinforcement. In the first case, the network uses a set of training data thanks to which manages to infer the ties that bind these data and to develop a model "general". This model will later be used to solve problems of the same type. In the case of unsupervised learning process, the system refers to algorithms that attempt to group the input data by typology, identifying representative cluster of data typically making use of topological or probabilistic methods. In the process for reinforcement an algorithm aims to find a modus operandi from a process of observation of the external environment. In this process it is the environment itself guides the algorithm in the learning process.

V. FEM MODEL

To simulate the behavior of a structure a numerical model of a flat plate will be performed. The numerical model will be used for detect the transfer function between some input points to output points in order to train the ANN as shown in next chapter. In the following will be shown the FEM model used for analysis.

A. Geometry

A simple geometry will be considered. A simple flat plate (500x500 mm) is modelled as shown in Fig 9. The plate thickness is set to 1.5 mm.

B. Mesh

The plate has been divided into a regular mesh where just CQUAD4 elements have been used. To guarantee a good discretization of the model the element size is 10 mm. According to mesh size and geometry the plate is divided in a regular grid of 50 by 50 quads. The elements are first order to avoid the model been too complicate. This discretization is good for the purpose of the analysis.

C. FEM Model Data

The task of this work is focused on ANN training and validation so we have simplified the model as mush as we can without neglect any relevant contribute. The model has been developed under the following assumptions:

- A MAT1 material is used instead of a composite material. The material has properties equivalent at the composite one;
- A free - free condition is assumed;

Under these two hypotheses the model is simplified but still really close to the real case.

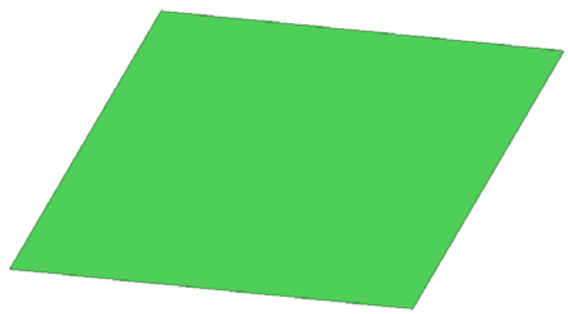


Fig. 9: Plate Geometry

D. Analysis

For the analysis a SOL111 has been performed. The plate was divided in 25 regions (Fig. 10 and Fig. 11) and the center of every region has been excited with a unary force. The response, as function of frequency, has been measured in 5 points simulating the presence of sensors (Fig. 12). Some results are shown in the following Fig. 13.

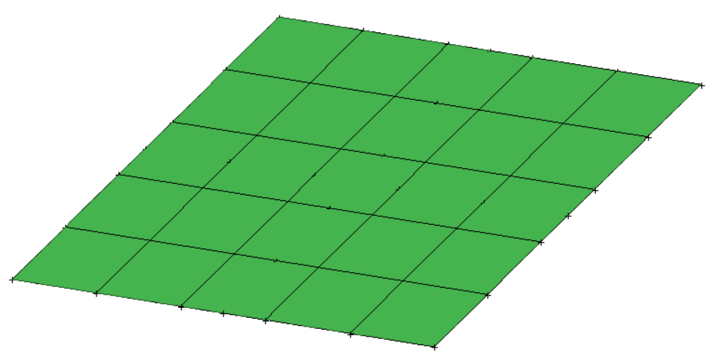


Fig. 10: Surface Mapped in 25 Regions

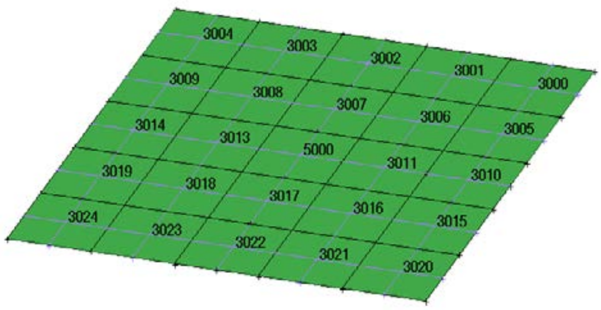


Fig. 11: Surface Mapped and Input Points.

The results displayed in Fig. 13 are the magnitude of translational acceleration in every point due to an unary force in one of the input points shown in Fig. 11. This results will be used as input for the ANN training and, as second step, validation. The Acceleration has been plotted over a frequency range from 100 Hz to 5000 Hz.

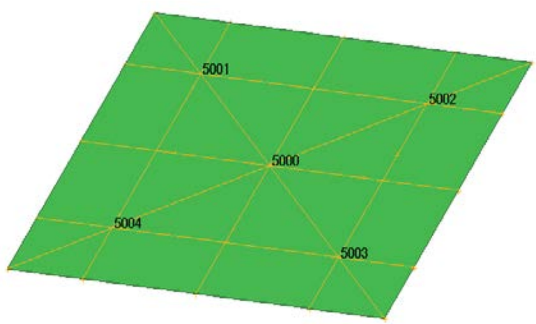


Fig. 12: Response points

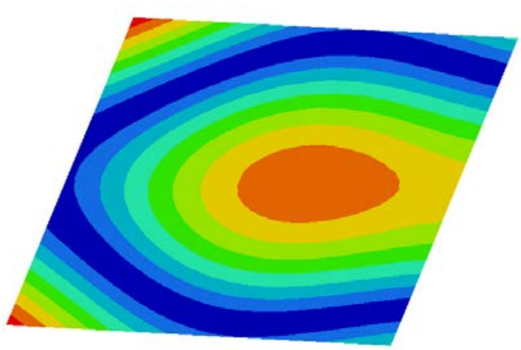


Fig. 13: Translational Acceleration Magnitude for Force in Input Point 3012.

VI. Pattern Recognition Tool

The pattern recognition tool is generally used to connect an input from multiple point to a state of the system. From an abstract point of view it is what we want. The input is the value measured from the 5 piezos (multiple input point) and the state of the system is the region in which the impact occurs.

A. *Input Matrix*

The tool take as input a signal matrix and a system status matrix, coupling them with an ANN can associate every status to a signal value. The limitation of this tool is the fact cannot accept for a certain point a function as input but just a scalar value. From the previously analysis we have for every receiving point a function, an acceleration vs. frequency, and not a scalar number. To use the tool we have transformed the function in a scalar number. At any sensor is assigned the maximum value over the whole range.

The input matrix developed for the tool is a 5 by 25 matrix. Every column is maiden up by the values measured in the receiving point. Given that we have 25 cases and 5 response points the matrix has 25 column (on for every input case) and 5 row (one for every receiving point). This matrix is still not the best we can use for the training phase. As said before the values of the matrix are related calculated for unary force. If the force change the values change themselves. In a numerical model we can always normalize values respect the force but in a real case the impact force is unknown and we cannot normalize the values in the same way. To avoid this problem all the values in the input matrix will be normalized respect the central piezo (numbered 5000 in Fig. 12). This kind of normalization is alway available and is to prefer. In this way also the geometrical relationship between the receiving points is keeped in account. This geometrical relationship depends also from the relative positions of receiving points. An example of Input data is shown in Fig. 14.

B. *Target Matrix*

The target matrix represent the status of the system. The simple status we can represent is the on/off status. This status can be managed with a single value; 0 for off status and 1 for on status. All we need to build up the matrix is a rule for assign the status to the system. The system is composed of 25 regions and, to define the status properly, we have to assign a value to every region. A simple rule we can use is to assign the number 1 to the region in which the impact occurs and 0 to all others. In this case the system is a vector with 24 zeros and only a 1 value if we suppose that no multiple impacts occur at same time. We have to define 25 different states, one for every region in which the impact occurs. The matrix can be rearranged to be a unitary matrix 25 by 25.

C. Build the Network

To configure the network we will use the nntool available in MatLab 2016. It is a fast, simple and transparent way to configure the ANN. For this network we will use a 70% of data for training, a 15% for validation and a 15% for testing. The neural network will be based on two layers with 50 neurons on first one as reported in Fig. 15.

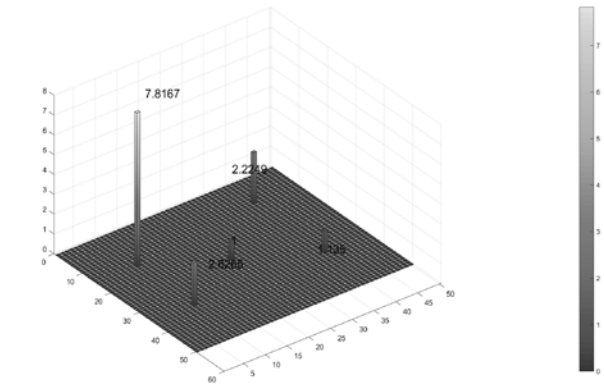


Fig. 14 Normalized Data for Receiving Points due to Input in Point 3005.

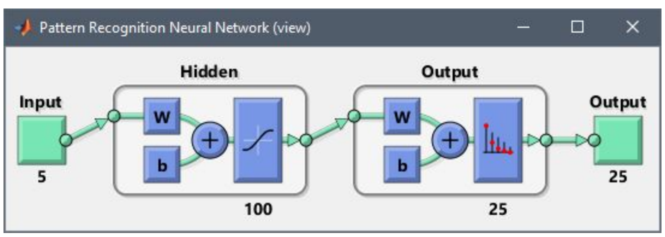


Fig. 15: Neural Network Schematic Form in MatLab 2016

For the training phase the trainscg approach will be used. The algorithm is is a network training function that updates weight and bias values according to the scaled conjugate gradient method. The training algorithm will use a crossentropy performance method. This method is the advantage to maximize the penalty for results far away from the target and low penalty for really close to the target output. In this way if the impact region is missing is really probable a closest region is marked as output instead of a region that is far away from the target.

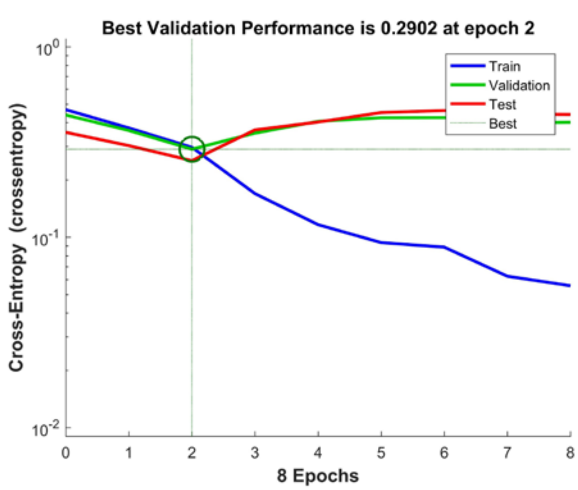


Fig. 16: Best validation performance for ANN

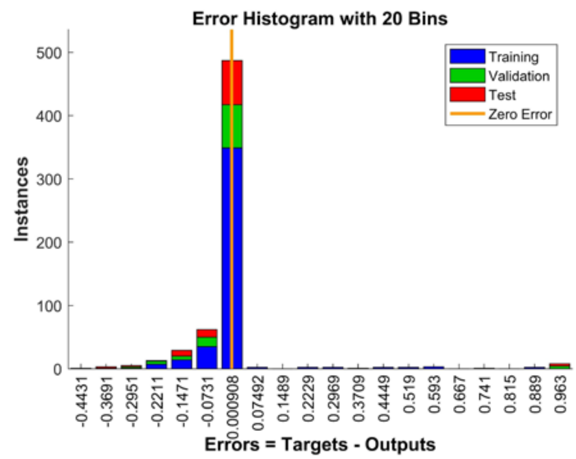


Fig. 17: Histogram Error for ANN Training

VII. Testing the Tool

Last step in this work is the tool validation. To validate the tool a new set of data is needed. Going back to the mesh a new set of points will be choiced randomly. A new analysis will be runned on these points to generate the response in the same points of Fig. 12. The new set of data will be processed with the same ANN to generate an output state that will represent the impact region. In Fig 18 is shown the new set of points generated for tool validation. In Fig. 19 the response for two of points is shown.

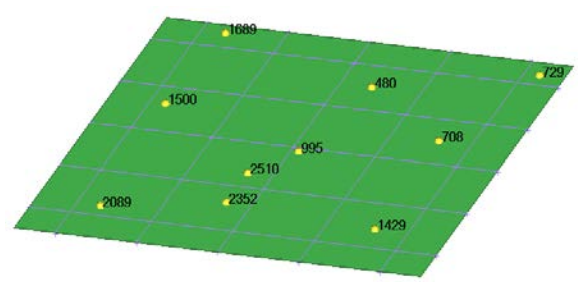
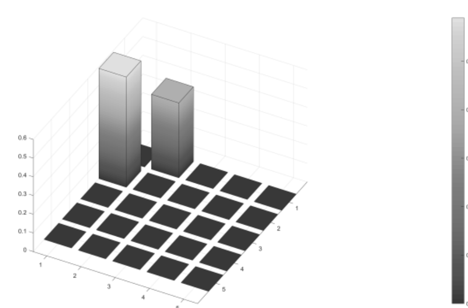


Fig. 18: Randomly Chosen Points on plate.



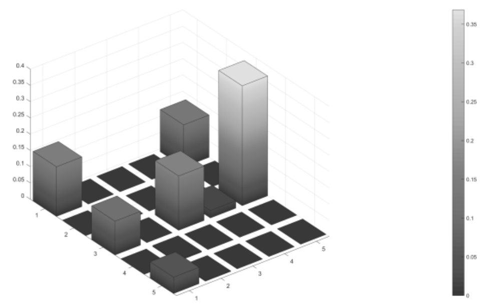


Fig. 19: Output State for Point 1500 (up) and for Point 708 (bottom).

VIII. EXPERIMENTAL TEST ON A COMPOSITE PANEL

In this chapter the test article and the instruments which have been used for the execution of the experimental tests, will be described.

Test article (fig 20) panel's material consisted of carbon fiber whose main features are listed below:

Size	550x550 mm
Thickness	2 mm
LayUp	[02/±45/0/±45]S

The panel was divided in a grid of 253 square of 0.03x0.03mt (fig 21) .

On the test-article 5 piezoelectric patches have been bonded in order to create an array of sensors and placed in squares 52,61,201,207 and 253 (fig 20). In the square 35 an accelerometer used to calibrate the instrument (fig 22) has been bonded.

Fig. 1: Piezoceramic patches bonded on the panel

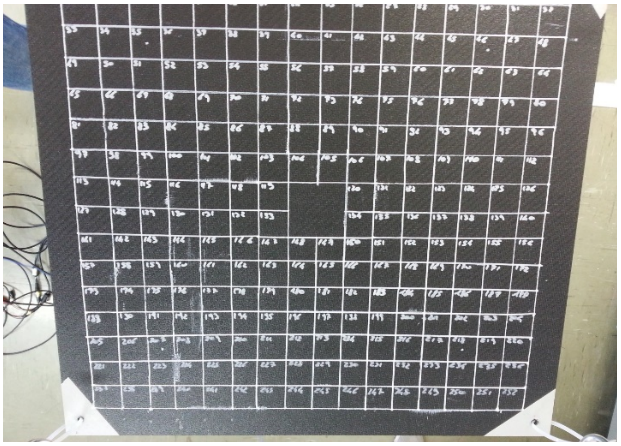


Fig. 2: Test article

Impact signal has been generated by the use of an instrumented hammer, while LMS Test Lab has been used as acquisition environment for simultaneous FRF and PSD function acquisition.

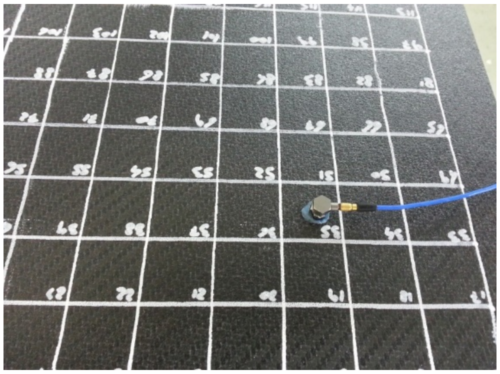


Fig. 3: Detail of Panel and accelerometer

After the definition of panel geometry the setting of acquisition parameters, as defined below, has been fixed.

Bandwidth	2049 Hz
Resolution	1 Hz
Sampling	0.01786 KHz

During the next data acquisition step, each point has been impacted and relative Frequencies Response Functions and the Power Spectral Density, have been acquired . In the specific the sub-script *ij*, hase been addressed to single measurements where *i* represent the relative sensor position (=5 piezo sensors) and *j* represent the impact points (=256 possible impact squared areas).

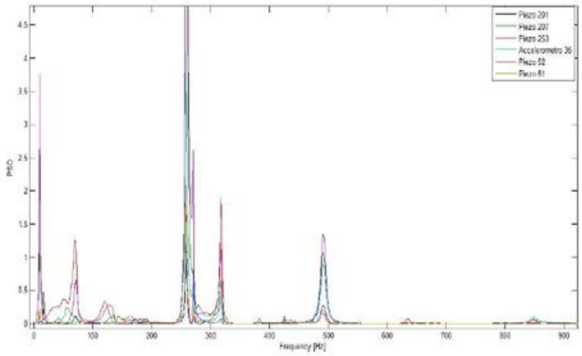


Fig. 43: Examples of acquired FRF

All these data will be in the next stage analyzed using neural networks with the aim to predict the impact location. For this scope, the neural network, needs to be preliminary trained with a set of data as positive examples. During the successive "verification" stage, the network will be able to recognize the similitude of a new response/event with something that has been preliminary recognized or a combination of multiple recognized events.

IX. RESULTS

In the following picture the reconstruction of impact cases have been reported. From the image analysis it can be deduced that, with a good approximation, the impact took place in the range of the cell 132 of the panel because it is in this range that the highest values are concentrated.

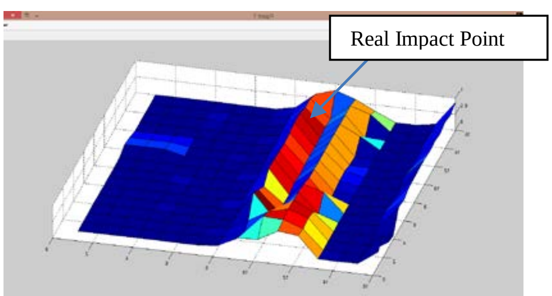


Fig. 5: First case results

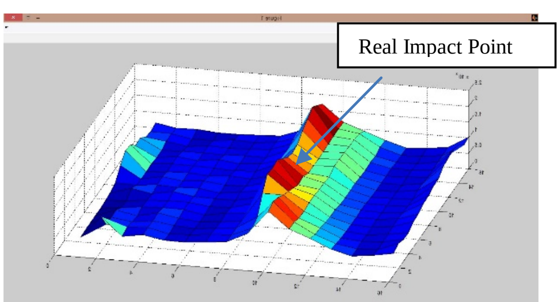


Fig. 25: Second case results

X. CONCLUSIONS

The present work presented an innovative technique for impact detection on composite panel by the use of piezoelectric sensor devices and Artificial Neural Network tool for data processing.

The purpose of the study has been the definition and the verification of the technical feasibility of an impact detection system, that contemporarily could manage the identification of both location and energy related values of a generic impact.

The availability of these information could be of great interest in the direction of more complex SHM techniques set up as well as for predictive numerical models.

The proposed method is based on the acquisition and comparison of the FRFs of the monitored structure for different combination of the impact/sensor point. The focus concept of the method is then based on the idea that a Neural Network tool, once trained, will be able to recognize the real path of an unknown impact and to localize the impact itself.

Preliminary results have confirmed the positive performance of the proposed approach, opening to more extended experimental campaign mainly oriented to the definition of the system precision, possible fault reconstruction and optimization in the data handling and reduction of computational effort.

The next step will be to use a more accurate mapping to stretch the tool for a more accurate impact point detection.

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