ON THE DEVELOPMENT OF METHODS AND TECHNIQUES FOR AIRCRAFT STRUCTURAL HEALTH MONITORING

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Abstract

A workgroup from Technical University of Lisbon, University of Victoria and Portuguese Air Force, is developing methods and techniques for application on aircraft Structural Health Monitoring, allowing continuous usage monitoring and particularly diagnosis and prognostic of aircraft's structural health. As a result, aircraft safety, reliability and operation readiness will increase. Operational costs and need of preventive and corrective maintenance actions will decrease.

This paper describes developed systems, methods and techniques. Some results from computational and experimental results are also presented. Experimental results

1 Introduction

Safety and reliability of a structural component depend on factors that are initially associated to design criteria and quality requirements of the material and manufacturing processes. During its operational usage, safety and reliability of civil or military aircraft's structural components depend on prompt detection and immediate damage repair before critical dimensions, at which catastrophic failure occurs, are reached. The crack growth in a structural element depends primarily on the loads that are acting on the structural element. This is in fact the damage tolerance analysis concept.

Adopted techniques and methodologies for aircraft structural integrity assessment, based on the damage tolerance concept, involve the measurement of flight parameters which, with other additional information, allow the prognosis of the aircraft structural health. Maintenance procedures are then planned and applied, involving the diagnosis of the aircraft structural health by inspection of structural components, in order to detect and evaluate existing flaws, using Nondestructive Evaluation (NDE) methods [1]. These maintenance and inspection actions are expensive and involve larges periods of immobilization.

With the development of integrated systems on structural components, allowing automated usage monitoring – prognostic, inspection, damage detection and analysis - diagnosis will result in the automation of all structural health prognostic and diagnosis actions. With the adoption of these methods and techniques will result: an increase on aircraft safety and reliability; a reduction of preventive and corrective maintenance actions; an increase in the aircraft operation readiness; a reduction of the operational costs.

1.1 Aircraft Structural Integrity Assessment

Aiming the structural integrity assessment of several Portuguese Air Force (PoAF) aircraft fleets, collaborative projects have been conducted [2-4] applying the damage tolerance concept. With the application of these methods and techniques results: the optimization of maintenance procedures; the safe and rational use of the aircraft fleet; the expansion of its operational life.

Applied methodology allows the prognosis of the aircraft structural health, and is generally referred as flight loads monitoring [3]. This concept involves the measurement of several flight parameters, as for instance the loads applied on the various structural components and locations, namely those defined as critical, based on data supplied by the airframe manufacturer, on historical records and on data supplied by other users of that kind of aircraft. This knowledge is complemented with additional information allowing characterization of the mission type related with each flight and the establishment of a relationship between the applied loads and the flight manoeuvres. The instrumentation systems used on flight loads monitoring include airborne and additional ground components. These systems allow simultaneous measurement of several parameters and therefore are also called multi-channel instrumentation systems. The number and characteristics of the several measured parameters depend on the particular objectives of each application project. Usually the measured parameters list includes:

- indicated or true airspeed;
- altitude;
- vertical acceleration on the centre of gravity or load factor;
- microstrains resulting from mechanical stresses applied on components and critical locations of the airframe.

These microstrains are normally measured by full resistive strain gauge bridges, in order to minimize the temperature effects and to achieve the best measurement sensibility [5]. Strain gauges are surface bonded on previously defined location of the critical structural components.

Maintenance actions are then planned according to the experimental results of the flight loads monitoring process. These maintenance procedures involve the diagnosis of the aircraft structural health by inspection of several structural components, in order to detect and evaluate existing flaws, using Nondestructive Evaluation (NDE) methods [1].

Since structural areas which are not easily accessible imply complex and thus time-consuming disassembly and assembly operations, these inspection methods are complicated, expensive and require normally the aircraft immobilization by a large period of time. Also, nowadays, passive safety measures are used to assure aircraft safety, consisting on the application of safety factors and redundancy. In structural design that implies added weight, and so added fuel consumption, with increasing costs, pollution and again a further increase in weight.

1.2 Structural Health Monitoring Concept

With the development of Structural Health Monitoring (SHM) methods and techniques, systems allowing usage monitoring, inspection of structural components, damage detection and analysis will be integrated in the structural components. All mentioned actions are automatically executed and particularly the prognostic and diagnosis of the aircraft structural health could be continuously performed, dramatically reducing the time period necessary for the inspections and allowing its realization during the normal immobilization of the aircraft. From the application of the SHM concept will result: increase on aircraft safety and reliability; reduction of preventive and corrective maintenance actions; increase in the aircraft operation readiness; reduction of the operational costs; eventual increase of aircraft production costs as new systems will be integrated. On the other hand, by applying these active safety improvement methods, passive measures can be decreased, resulting in a decrease on the overall weight, as the increase on weight due to the use of new integrated systems will be largely compensated by the decrease due to reduction of safety factors and redundancy. Again, a reduction on the operational costs will result.

2 Structural Health Monitoring Methods and Techniques

SHM methods and techniques emerged from the field of smart structures, integrating several disciplines such as: microelectronics; sensors and actuators; signal acquisition and processing; structural dynamics; materials and structures; fatigue and fracture; NDE. Two methods were considered. The first one is based on changes on frequency response, which occurs as results of the mass and rigidity changes due to the structural damages. The second one is based on changes on wave propagation. Due to an applied excitation, the resulting wave propagation parameters in the structure depend on its health condition.

2.1 Frequency Response Based Methods

As stated before, this method is based on the natural frequencies that every single structure possesses. Generally, these frequencies depend on the mass and on the rigidity of the structure. A damaged structure can be seen as one that has its mass and rigidity altered, hence with different natural frequencies. This conclusion can also be applied for free frequency response, i.e., differences will emerge when responses from the same structure, with and without damage, to the same external excitation are compared.

Consecutively, 2D computational models were developed on NASTRAN (and ANSYS, to compare) to study this theory. Both isotropic and orthotropic materials were investigated. Those models consisted on rectangular shaped plates, with one clamped edge and the remaining free, as seen on Figures 1 and 2. Several tests were run, starting from an undamaged structured and then placing damages on different locations to access the (changes) on natural frequencies and modes of vibration.

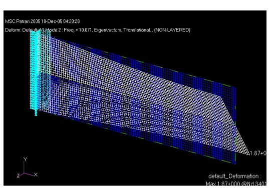

Fig. 1. Computational analysis of an aluminium plate

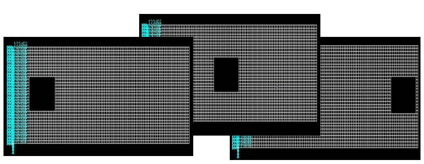

Fig. 2. Imposed damages to the plates

Damages were simulated using mass/rigidity reduction, by removing certain finite elements.

Preliminary tests revealed that 10% differences, in 1st natural frequency, can be observed starting from 5% of elements/mass/area reduction. Damages near the clamped edge induce mainly a decrease in the rigidity, resulting in a decrease of the first natural frequency of 12,75%. While damages far from this edge, have as preponderant effect the decrease of mass, resulting in an increase of the first natural frequency of 9,25%. The damage in the middle of the plate produced only a slight variation of 2,7%.

From this study, a limitation of this method can be retained: significant frequency variation occurs only for high values of mass/area reduction, which corresponds to large structural defects.

This method can be applied using low frequencies, what represents an advantage. Also, damages far or near clamped boundaries are better detected.

2.2 Wave Propagation Based Methods

Ultrasonic testing is one method used in NDE. Current ultrasonic inspection of thin wall structures is a time consuming operation. One method to increase the efficiency is to use guided waves, like Lamb waves, instead of the conventional pressure waves. Guided waves propagate along the mid-surface of thin-wall plates and shallow shells. They can travel at relatively large distances with very little amplitude loss and offer the advantage of large-area coverage with a minimum of installed sensors. Guided Lamb waves have opened new opportunities for cost-effective detection of damage in aircraft structures.

Initially, 1D analytical model were studied, based on multiple spring/mass systems. This study permitted to fully understand the behavior of 1D elastic medium and the influence of boundary conditions. As a starting point, this type of solution can be used for application frequency response SHM methods, since it allows calculating modes and response of the system to external excitation, with and without damage. Damage can be modeled by local mass or/and spring rigidity increase/decrease. Considering the dynamic response of each mass, their respective displacement amplitude at a certain time and the elapsed time between two consecutive masses reaching their maximum displacement, strain wave propagation can be modeled. Considering the differences between that propagation (and boundary reflections), with or without damage, and resulting damage reflections, damage can be assessed (wave propagation method).

Furthermore, 2D analytical models were developed from this 1D system. 2D computational models based on rectangular shaped isotropic plates, with different sets of boundary conditions, were developed on NASTRAN, ANSYS and MATLAB to study this theory. Several tests were run, starting from an undamaged structure and then placing damages on different positions. Structural response/wave propagation to different strain impulses and step excitations in one or more nodes of the structure was investigated. Some results are shown on Figure 3, including the response from an undamaged plate, the same plate with a central damage and the difference between both cases.

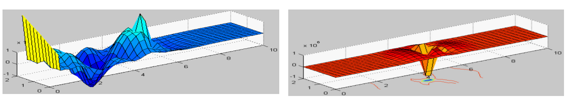

Fig. 3. Elastic deformation – Lamb waves propagation

On left, wave longitudinal propagation in an undamaged plate is easily seen, as the lateral boundaries reflections/interference. On right are shown differences for a plate with a central damage. The strain concentration in the damage location and its consequent propagation are also seen.

Results obtained from the MATLAB code developed to assist the development and implementation of phased array actuators (3.5) can be used to analyze the propagation behavior, reflections and interactions between the different waves. As an example, Figure 4 shows the results of the radial propagation with only one actuator, before (left) and after (right) reflections.

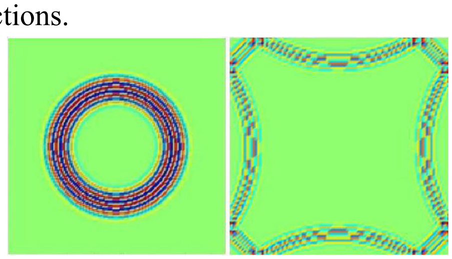

Fig. 4. Radial propagation of the signal

3 Structural Health Monitoring Based on Lamb Wave Propagation

Studies have been conducted to access the feasibility of SHM methods and techniques based on the propagation of Lamb wave for damage detection. Since structural flaws represent changes in effective thickness and local material properties, measurements of variations in Lamb wave propagation can be employed to assess the structural integrity of these structures.

3.1 Lamb Waves

Lamb waves [6] are elastic waves that propagate across thickness of thin wall structures with free boundaries parallel to the mid-surface. Lamb waves can be either symmetric (compression) or anti-symmetric (bending/shear) across the material thickness. These waves present high propagation velocities, with dispersion characteristics with frequency, and the ability to propagate through considerable distances without significant decrease in their amplitude.

The entire thickness of the plate can also be interrogated by various Lamb modes, affording the possibility of detecting internal damage as well as that on surface. As referred, since the wave speed varies with frequency, the propagation of Lamb waves is essentially dispersive. For a given frequency multiple modes can exist and therefore the received signals are a complex mixture from different modes and difficult to evaluate. The analytical dispersion curves give an idea of the various existing modes and its velocities for each frequency of excitation. Then, it becomes necessary to plot the dispersion curves for each case to choose the optimal frequency excitation.

3.2 Dispersion Curves

As mentioned before, Lamb waves present a dispersion behavior. This particular characteristic was analyzed through a Phonon approach and through the Rayleigh-Lamb equation for plates [7-10]. It was created a simple code in MATLAB to compute such dispersive behavior, which results, for a 2mm thick aluminum plate, are presented on Figure 5.

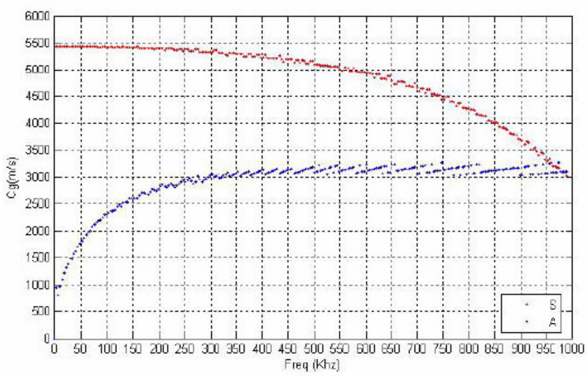

Fig. 5. Lamb waves dispersion curves

These results show the dependency of the group velocity with the frequency. The Group frequency represents the speed with which Lamb wave packs are sent and received along the thin-wall plate. These results shows that if the frequency is well know the velocity of the waves is also well defined and then the distance from the actuator to the sensor, including reflections on boundaries and defects, can be determined by the knowledge of the propagation time. But the good definition of the actuation signal on frequency implies a bad definition on time and vice-versa. Then we need a good balance between the definition of the actuation signal in time and in frequency. Several signals have been studied. Some of them are presented on Figure 6.

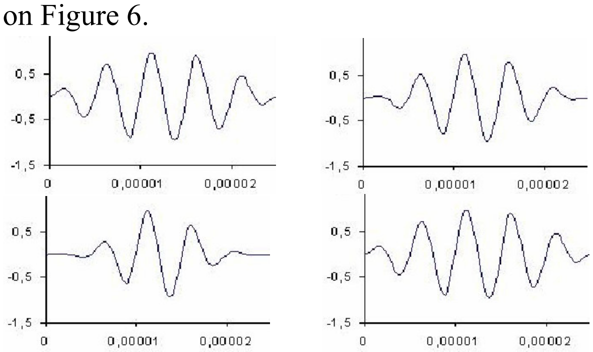

Fig. 6. Studied excitation signals

The wavelength of the produced waves, as function of the propagation velocity and frequency, is related to the dimension of the actuators, in order to obtain the correct generation of the waves in the host material. Actuators must have dimensions inferior to the wavelength of the waves to be generated. As it was observed in the experiments executed, also the amplitude of the generated waves depends on the dimensions of the actuators. Higher amplitudes are obtained when the wavelength of the excited wave is close to the dimensions of the actuators (or are multiples of those dimensions), i.e, when certain local modes of the structure – host material and actuators – are excited. Another important consideration, not expressed on graphs but verified experimentally, is that, since the actuation is applied on the plate surface, for frequencies bellow 250 KHz, shear waves amplitude is enhanced with relation to compression waves.

When selecting the PZT actuators, besides what was previously referred, care must be taken to work in frequencies well bellow the resonance frequencies of the actuators, while selecting the actuators with significant d_{33} and d_{31} characteristics. Also the excitation of structural natural frequencies should be avoided, if they are characterized by low damping coefficients.

3.3 Lamb Waves Generation and Detection

The methods being study, developed and presented involves the use of Lead Zirconate Titanate (PZT) piezoelectric components acting as actuators but also as sensors. Piezoelectric materials convert electrical energy to mechanical energy and vice versa. The practical implication is that an applied voltage produces mechanical displacement (actuator) and conversely, applied mechanical strain produces a voltage between its ends (sensor). PZT piezoelectric components are nowadays already reliable for industrial applications and can be easily introduced in systems. They have the advantage of their application being easily achieved, independently of the base material, since for instance they can be bonded (surface glued or embedded) to metal, carbon, composite, etc. This type of coupling, which is parallel to the material surface, is significantly more efficient for the excitation and reception of Lamb waves than that of the conventional ultrasonic transducers, which can only impinge normal to the material surface. PZT piezoelectric components work well in a wide frequency range, needed for vibration control (low frequencies) and for SHM (high frequencies when wave propagation methods are considered).

3.4 Use of Phase-Array Actuators

With a phased array actuator, several single actuators are combined to produce a directional or steering actuation signal, resulting from the interference of the individual actuation signals.

Again in this case, the wavelength of the produced waves, related to the propagation velocity and frequency, will define the distance between the actuators, in order to obtain the correct generation of the waves.

Another application was developed in MATLAB to simulate and study the behavior of such phase array actuators. Using several actuators, the steering effect can be achieved by changing the phase of the actuation signal applied to each individual actuator. Figure 7 show results with different interspaces (left - 5mm; centre – 20mm; right – 40mm), for a phased array of 7 actuators and with a central excitation frequency of 150 kHz. Figure 8 show results from the change on the relative actuation signal phase (left – 60º; centre – 100º; right – 150º).

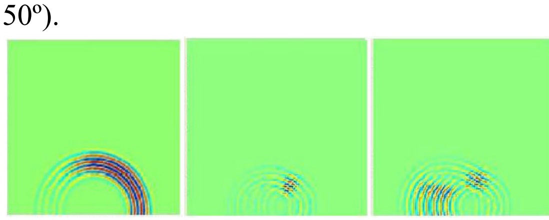

Fig. 7. Phased array – effect of interspace

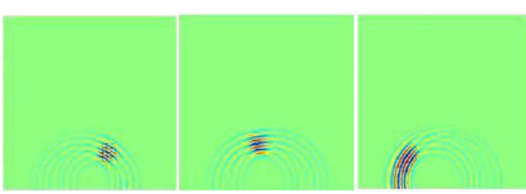

Fig. 8. Phased array – effect of phase

3.5 Damage Detection

The principle to detect and locate a damage is then very simple. If multiple sensors, in different locations, are utilized to detect the original generated Lamb waves and their reflections by the damage, knowing their velocity of propagation and the difference in time of detection from those different sensors, by triangulation is possible to detect their source location, i.e., the damage. This method is presently referred as Time Of Flight Displacement (TOFD) and is illustrated on Figure 9. The analysis of the sensor signal consist of an inverse problem that may be solved by a series of different proposed methods, applied on time, frequency or both.

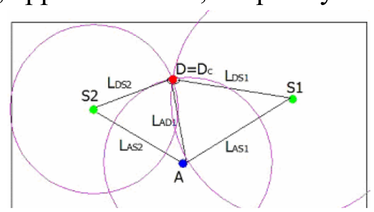

Fig. 9. TODF damage detection method

The two different first modes of Lamb waves, S_0 and A_0, are prone to detect different types of damages. Symmetrical/compression (S_0) Lamb waves allow a better detection of failures along thickness, for instance cracks, while anti symmetrical/bending/shear (A_0) waves allow a better detection of failures like surface discontinuities, for instance in mass/density, and/or surface defects. Besides, the amplitude of reflected waves is proportional to damage dimension and dependant on damage orientation. Damages oriented perpendicular to the local propagation direction of the Lamb waves (parallel to wave front, perpendicular to a radius centered in the origin of Lamb waves) are better detected than those angled, being the extreme and more difficult case to detect when the damage is oriented along the propagation direction of the Lamb waves.

Besides the location of an existing damage, knowing that the amplitudes of damage reflecting waves are higher when the principal dimension of such damage is perpendicular to the wave front, by actuating different transducers in space and by so creating waves with different wave front directions, the geometry of the damage may be assessed. The dimension of the damage is related to the amplitudes of the reflected waves and a Distance Amplitude Correlation (DAC) is possible to be determined experimentally.

3.5 Use of Fiber Bragg Grating Sensors

Preliminary studies on the usage of Fiber Bragg Grating (FBG) sensors [11] are promising. FBG sensors, as optical fiber sensors, have reached a level of maturity that has already led to real applications in the civil engineering area, allowing stresses and temperature monitoring. Recent advances in optical fiber sensor systems have led to: an increase in the number of sensors, in the same fiber, increasing the number of monitored parameters; an increase on the bandwidth, allowing the detection of high frequency events.

5 Experimental Results

Intensive experimental testing is presently being conducted in an acoustic uncontrolled environment, i. e., subjected to noise, as shown on Figure 10. As stated before, different sensor configurations and techniques, such as TODF and phased arrays actuators are being tested for assessment of its performance on damage detection and characterization. Experimental results are also used for validation of analytical and numerical simulations.

Various square aluminum plate of 1.5m and 2mm thick where instrumented and used to simulate an aircraft wing panel. For signal generation, a National Instruments NI 5421 was used. The data acquisition was performed with a National Acquisition module NI 5105. Both modules are installed in a National Instruments NI 1333 PXI chassis connected to a Laptop.

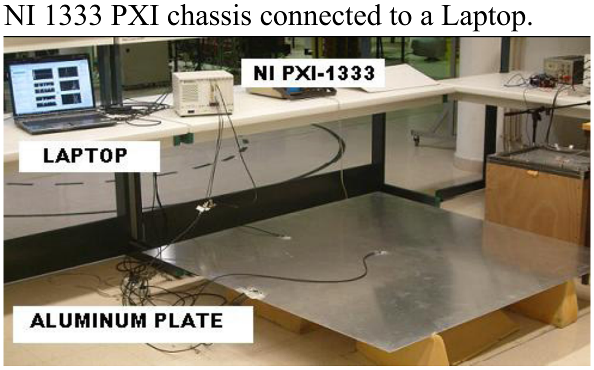

Fig. 10. First experimental setup

Different boundary conditions were tested, ranging from simply supported to fixed boundaries and starting with the configuration shown. Also different damage types were imposed to the plate: added local masses and artificially produced cuts and cracks. Figure 11 shows two of used PZT actuators/sensors configurations.

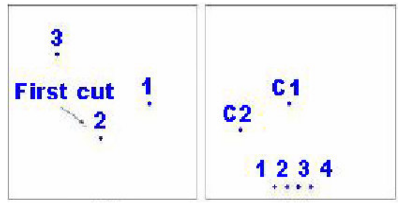

Fig. 11. Examples of PZT actuators/sensors configurations

On Figure 12, the actuation, hamming sine wave, and one sensor signals are shown. The data presented results of the repetition of the different experiments and subsequent statistical treatment, applying the mean average and uncertainty of the different experimental results. This data will be used afterwards to teach the system and for comparison with undamaged and different damage conditions.

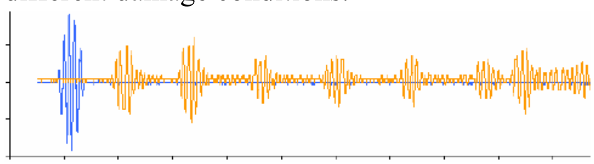

Fig. 12. Actuation (blue) and sensor (orange) signals

Figure 13 shows the results of a experimental evaluation on the influence of the central frequency used for actuation. These results shows that the high sensor sensivity is obtained with central frequencies ranging from 100 to 200 kHz. Other experimental evaluation revealed that the high sensibility obtained at 150 kHz is directly related to a natural mode of the plate, with 143 kHz of natural frequency and low damping. This fact implies that the response has high amplitudes and low damping, difficult the identification of the TOFD.

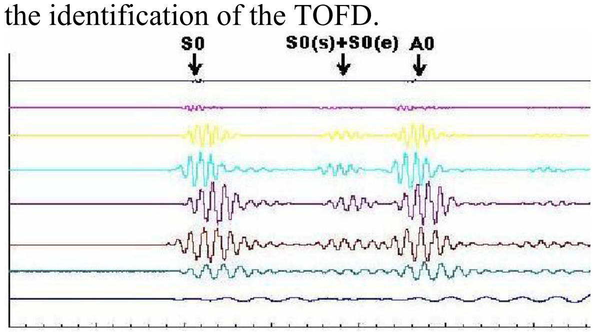

Fig. 13. Influence of the actuation central frequency on sensed signals, from 50 kHz (bottom) to 400 kHz (top)

Before imposing damages, the undamaged response of the system was obtained and the wave propagation behavior in the plate was characterized, namely identifying the generated S_0 and A_0 waves and the reflections from plate boundaries and other transducers bonded to the plate. Results obtained on two different sensors for the same excitation signal are presented on Figure 14.

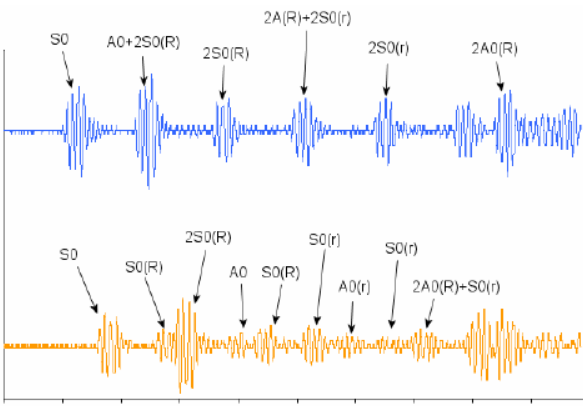

Fig.14. A_0, S_0 waves and boundary reflections

Afterwards, damages were imposed and experiments were repeatably executed. On Figure 15 sensed data on an undamaged and on a damage conditions are depicted.

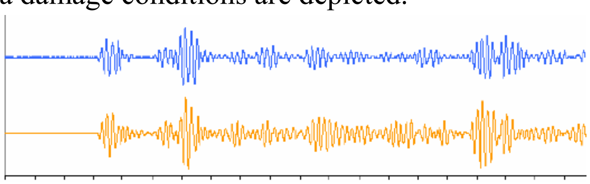

Fig. 15. Undamaged (blue) and damaged (orange) conditions sensed signals

After applying a statistical treatment to the raw data, analyzing and comparing both responses of the system was possible to successfully identify damage reflections (in an acoustic uncontrolled environment). Applying the method described previously damages were successfully located, with limitations stated before and related to the sensibility when the actuation signal is perpendicular to the damage orientation. On Figure 16 a typical example of damage reflections identification is shown.

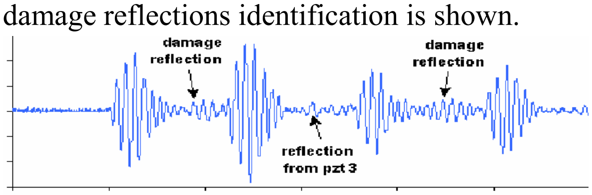

Fig. 16. Identification of damage reflections

Presently are being performed experiments to assess damage characterization, identify the minimum damage dimension identifiable, verify the response of the system to different damage morphologies and their relation with the system characteristics, mainly concerning generation frequency and transducer characteristics.

The experimental evaluation of the developed tools for simulations and analysis of phase array actuators was also performed. Figure 17 shows an implemented array of four PZT actuators. Figure 18 shows the results of the simulations for several actuators/sensors configurations. Figure 19 shows the corresponding experimental results, which are very similar to those produced by the phased array simulator.

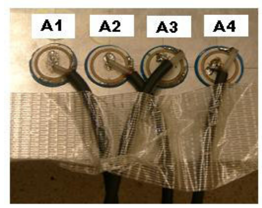

Fig. 17. Implemented phased array actuator

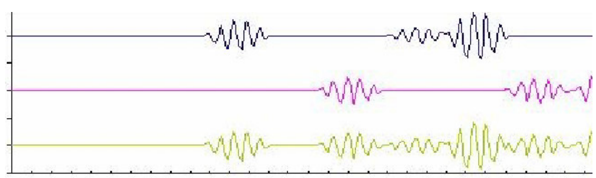

Fig. 18. Simulated sensed results for several actuator configurations

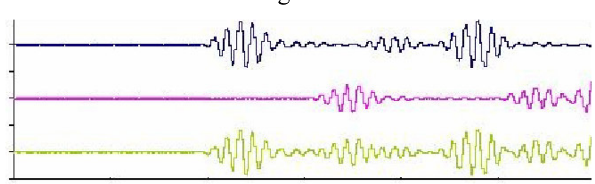

Fig. 19. Experimental sensed results for several actuator configurations

To allow the usage of FBG sensor on SHM, a FBGinstrumentation system (light source, filter, circulator and photo-detector) is being developed to suite specifically to the high frequencies associated with wave propagation SHM methods. The developed prototype is not yet able to deal with these high frequencies. For this reason, this system was used on the study and characterization of the FBG sensors, namely regarding its future usage on aircraft flight loads monitoring. Several experimental comparisons between FBG sensors and usual resistive strain gauge sensors have show that the first ones have good metrological performances, very good immunity to electromagnetic noise, are more flexible and its installation is similar. Additionally, FBG sensors can be integrated on structural composite components. One application project is now starting aiming to study this integration.

7 Conclusions

The work presented in this paper shows a contribution to the development of methods and techniques for aircraft SHM.

The design of a simple SHM system using a PZT actuators/sensors network was depicted. This system was used to validate and demonstrate some developed techniques and methods, namely by the ability to apply wave propagation SHM methods to detect damages in an aluminum plate similar to a wing skin panel. The experimental testing was performed in a sound uncontrolled environment, for instance similar to a maintenance hangar environment, putting further noise and difficulties for the system to overcome. Different boundary conditions on the plate edges were assessed.

Presently a high speed voltage amplifier is being developed specifically adapted to the use in our system. With such amplifier it is predicted that by reducing noise influence, the sensibility and precision of the system will be significantly increased.

To allow the future application of phased array actuators, also aiming the increase on the resulting sensibility, one application was developed and validated, numerically and experimentally.

An FBG instrumentation system is on development, aiming the application of FBG sensors with wave propagation SHM methods. Until now, the instrumentation system under development has permitted the successful evaluation of FGB sensors for usage on flight loads monitoring. Additional work will be devoted to the analysis of the integration of FBG sensors on structural composite components.

The presented results where the result of a large workgroup with members from the Technical University of Lisbon, in Portugal, the University of Victoria, in Canada, and the Portuguese Air Force. We would like to thank the important collaboration of our colleagues Cap. Carlos Silva of the PoAF Academy, Eng. Joana Capinha and Eng. Veerle Van Doorsselaere.

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