PZT Network and Phased Array Lamb Wave Based SHM Systems

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Abstract. With the application of newer materials, such as composite materials, and growing complexity and capacity of current aircraft structures, reliably and completely assess the condition of the total structures in real time is then of growing and utmost importance. PZT Network and Phased Array, Lamb wave based Structural Health Monitoring (SHM) systems were developed to be applied to thin panels. The selection of transducers, their size and selected locations for their installation are described. The development and selection of the signal generation and data acquisition systems is also presented in detail. The requirements conducing to the development and selection of these systems are laid and particularly the selection of the actuation signal applied is justified. The development of a damage detection algorithm based in the comparison of the current structural state to a reference state is described, to detect damage reflected Lamb waves. Such method was implemented in software and integrated in the SHM system developed. Subsequently the detection algorithm, based in discrete signals correlation, was further improved by incorporating statistical methods. For phased arrays, a novel damage location algorithm is presented based on the individual sensors response. A visualization method based concurrently in the statistical methods developed and superposition of the different results obtained from a test set was implemented. These tests conducted to the successful and repeatable detection of 1mm damages in a multiple damaged plate with great confidence. Finally, a brief comparison and a hybrid system implementation is presented.

1. Introduction

Failure of a primary aircraft structure usually results in catastrophic consequences, economically and most probably and importantly in terms of loss of life. The harsh operation conditions; the evolution in aircraft structural design philosophy to the most needed light weight damage tolerant aircraft structures; ageing fleets; and use of composite materials emphasizes the need for the application of different types of Non Destructive Tests and Evaluations (NDT&E). There are several inspection methods presently applied to assess the health of structures in service, namely: Visual Inspections; Penetrant Liquids; Magnetic based Inspections; Eddy Currents; Radiography; Ultrasonic Testing, etc. Typical Probability of Detection (PoD) of different defect dimensions, for the methods previously referred, is presented in figure 1.
A competitive SHM inspection technique should be able to detect defects of 1 to 2mm with a PoD of 80% or higher. Additionally, such technique will be embedded to the structure enabling real time, persistent and global monitoring of structural condition, as opposed to external conventional NDT&E. Some of the drawbacks of the application of conventional NDT&E that will be assessed by such system are: scheduled based maintenance; extensive disassembling and inspection operations (to have access to parts to inspect); safety of operation in between inspections; increased design safety factors and consequently structural reinforcements and increase in weight to account for unpredicted damage growth (due to excessive loads, impacts, etc., and possibly in unpredicted non inspected locations) between maintenances – restricting performance, payload, fuel burnt and pollution; consequent operation costs, etc.

2. Lamb Waves

In 1917, Horace Lamb [2] predicted analytically the existence of a particular type of acoustic waves in solids, later named after him - Lamb waves. His study was based in the theory of Rayleigh waves – mechanical elastic deformation waves in solids, near a free boundary [3]. Lamb waves exist in thin plate like, or low curvature shell like structural components, and are guided by the two parallel free boundaries. Due to the low damping imposed by the free boundaries, Lamb waves can propagate to long distances with minor amplitude damping. It is also interesting to realize that most of aircraft structural components can be decomposed into several plate or shell like cross sections. In 1950, Mindlin [4] completed a theoretical approach to this type of waves. In 1961, Worlton [5] suggested the potential of applying Lamb waves for structural inspection and damage detection, and a new NDT&E potential technique emerged. The interesting behaviour of Lamb waves in evidence is their interference with damages (boundaries and other material or geometry discontinuities), generating scattering and/or mode conversion, which can be detected. Hence, information about damage is present in scattered Lamb waves.

The prospective damage types prone to be detected by this kind of inspection were summarized by Rose [6]. Worden et al. [7] established the axioms for every SHM system. The first one refers that every damage assessment is based on a comparative analysis, between damage and undamaged states.

Important aspects that must be considered in the development of a Lamb wave based inspection method are: the wave propagation characteristics in the host medium; the types of transducers to be employed and how they are applied into the structure; the actuation type; and finally, the type of signal processing and evaluation to be applied [8].

Research is being performed in different aspects of this problematic. Lamb wave generation and propagation behaviour, and transducer influence on such aspects, applying numerical methods and experimentation, has been investigated [9]. Lamb wave emission experiments in aluminium plates proved that these high frequency waves were sensitive to damage presence, especially when small distances between damage and probe were considered [10].

Furthermore, a given frequency of actuation can excite multiple Lamb wave modes. These can be divided into symmetric and anti-symmetric modes [11], according to deformation patterns (figures 2
and 3 present the first modes, $S_0$ and $A_0$). The symmetric modes essentially produce compression and traction, while the anti-symmetric modes produce movement in the normal direction with respect to the propagation direction.

One important characteristic of Lamb waves is their dispersive behaviour – dependence of propagation velocity to their frequency. As an example, experimental results were attained using 2D Fast Fourier Transform on data collected by a vibrometer [12].

Numerical models for wave propagation and their interference with modelled damages are being developed, using Finite Element Analysis (FEA). Specifically, interesting results were attained with simulations based on Spectral Finite Elements [13].

![First symmetric (S$_0$) mode](image1)

![First anti-symmetric (A$_0$) mode](image2)

Piezoelectric transducers have been selected in most cases to generate Lamb waves [14]. They have the capability to work at high frequencies, both as actuators and sensors. Their size, shape and location must be carefully selected [15].

The potential of Lamb wave based SHM methodologies to monitor large metallic aircraft surfaces was previously presented by Dalton et al. [16]. More recently, imaging signal processing techniques to detect damage position have also been developed [17]. Moreover, an aircraft fuselage panel was also successfully tested using two strips of PZTs, by Ihn and Chang [18]. Besides networks, beam forming approaches were also implemented on a wing panel with satisfying results [19].

For composite materials, the interaction of Lamb waves with delamination has been studied by Su and Ye [20]. Mode conversion is observed upon Lamb waves encountering structural damage.

### 2.1. Lamb Waves' Dispersion Curves

For the design of a SHM system, the understanding of Lamb waves' behaviour is fundamental and specifically their dispersion behaviour, i.e., the relationship between propagation velocity and frequency. Figure 4 depicts the calculated group dispersion curves for an aluminium plate 2mm thick, for frequencies up to 1MHz, where only the first modes are excited.

Dispersion curves are of paramount importance in the selection of actuation signal and transducers to be applied, their material and size. In terms of actuation, if multiple excitation frequencies are applied in wave generation, groups of waves with different propagation velocities will be generated. The latter introduces noise and added complexity in wave propagation patterns and their consecutive assessment. Sensor signals will be more intricate with the superposition of multiple waves with different velocities, which presents challenges in implementing a damage detection method.
The selection of an actuation signal centred in a single frequency is then desirable. A Hann window modulation [20] applied to a sine function – figure 5 - was selected after analysing different actuation signals in the frequency domain. The frequency of the sine function, i.e., the frequency of actuation, is equal to the frequency of the generated waves.

Furthermore, for higher actuation frequencies, secondary modes may be excited. In this case, the generated waves will be a combination of different modes with different propagation velocities and deformation patterns, again raising problems in the evaluation of sensors’ signals. Through the observation of dispersion curves, a frequency range for actuation can be established. Also, a clear difference in $S_0$ and $A_0$ propagation velocities is advantageous, since their corresponding sensed signals will be well separated in time.

Based on dispersion curves, i.e. the relationship between scanning frequency and corresponding wave propagation velocity, it is possible to establish the relation between wavelength of the emitted wave and its frequency - figure 6. Moreover, observing figure 2, actuation and sensing can be optimized when transducers present a characteristic dimension equal to half of the emitted wavelength. Then, the selection of PZTs’ dimensions is related with the selection of the actuation frequency and excited Lamb waves’ wavelength (and their propagation velocity).
Figure 6. Lamb waves’ wavelength vs. frequency.

The SHM systems developed were based on the $S_0$ Lamb wave mode, due to its higher propagation velocity, with relation to the $A_0$ mode. The $S_0$ wave will then appear first in sensor signals. Therefore $S_0$ and its first reflections, including a possible damage reflection, are then less prone to interference by $A_0$ and corresponding reflections. Also, due to their morphology, $S_0$ waves are more sensitive to internal damages, while $A_0$ wave modes are more sensitive to surface damages. The previously presented characteristics and the fact that $S_0$ waves present smaller propagation amplitude damping were deemed more important than the fact that $A_0$ presents a smaller wavelength than the $S_0$ mode for the same frequency, theoretically meaning that it is more sensitive to smaller damages.

A similar approach can be adopted for quasi-isotropic composite plates. In this case the different wave propagation velocities and wavelengths in the different directions must be considered. Transducers can be selected now to optimize the generation of the different wavelengths and actuation frequencies can be tuned for the different directions. Furthermore, in the practical application of an SHM system, it can be considered an initial measurement of the propagation velocities in different directions, to tune the method and correct initial predictions. However, since composite plates are more prone to mode conversion and/or coupling, the damage detection complexity may increase.

3. Experimental Setup

Experiments were performed with a 0.6m-side square aluminum plate, 2mm thick, simply supported. According to the previous considerations, 8mm diameter PZT discs, 1mm thick, were selected. These transducers had the piezoelectric material oriented so that its principal actuation direction ($d_{33}$) is along the thickness (to maintain the same planar radial characteristics). Simultaneously, with the PZT dimensions determined, a scanning frequency of 340 kHz was selected for the networks technique, according to the relation to the emitted waves’ wavelength.

3.1. PZT Networks

Four transducers were bonded to the upper surface of the aluminium plate forming a network. A National Instruments (NI) Arbitrary Waveform Generator, capable of 100MS/s in a single channel output, and a NI 60MS/s, 8 channels with simultaneous acquisition, oscilloscope were used. These permit a voltage range between ±15V and a minimum of 12 bit definition.

Since each PZT can be used as an actuator or as a sensor, a circuit was designed to direct the actuation signal to the desired PZT in the network. Additionally, in order to avoid cross-talk between actuator and sensor channels for the same PZT, such circuit employs a system of switches to cut the connection between the actuation channel and the PZT immediately after actuation. The actuator PZT is also used as a sensor upon actuation. This setup can be seen in figure 7.
3.2. Phased Arrays
As the name implies, a phased array system is comprised of a set of transducers. Each transducer is individually controlled in order to achieve the desired phased actuation. With such phased actuation, it is possible to promote constructive interference between the different waves being generated by the several elements in the array - beamforming. Through the formation of a wavefront is possible to increase the amplitude of generated and consecutively of reflected waves, increasing Signal to Noise Ratio (SNR). Thus each transducer has its own control structure. In order to manage the independent elements in the array, there is a hardware master circuit whose function is to trigger each individual slave system, at a pre-programmed time to form a coherent beam. By changing the relative time delays in actuation, it is possible to steer the wavefront and then the inspection region/direction.

The developed array consists of a linear array of seven sensors, accounting for the array aperture. A linear array configuration was selected for the initial tests and development of the system, as the basis for the future development of arrays with different shapes (crosses, stars, etc). To avoid the problematic of the propagation of two generated wavefronts in opposite directions by a linear array, the array was positioned near one of the edges of the plate. The PZTs used have a diameter of 8mm, applied with a spacing of 3mm. To avoid the generation of side lobes, the pitch of the array must be smaller than half-wavelength of the generated wave. Thus, the excited wavelength should be equal or higher than 22mm. The actuation frequency was then selected to be 250kHz.

The same plate was used for the application of both the network and array techniques. The setup can be seen in figure 8, and in figure 9 the transducer array is depicted.

4. Damage Detection
4.1. PZT Networks
Through the execution of a frequency sweep, it was confirmed that 340kHz is indeed the optimum actuation frequency, enhancing the amplitude of the $S_0$ waves generated. The fully automated damage detection scheme was implemented in LabView® and Matlab®, as follows:
wave propagation velocities are experimentally determined for the selected actuation frequencies and for the different directions, based on the Time of Flight (ToF) of the activated wave, while propagating between actuator and sensors, and the ToF of boundary reflections. These velocities are subsequently compared with the ones obtained from dispersion curves. With such information, if needed the actuation frequency can be further tuned. Also, this step can be used to assess the different wave propagation velocities in the different directions in a composite plate;

- consecutive scans are then performed using each PZT as an actuator at a time (with the remaining PZTs in the network being used as sensors);
- sensor signals are assumed to be the baseline signals, or undamaged state signals and are therefore saved for future reference;
- scans may then be repeated at a future time, when the plate might have sustained damage, i.e., whenever is desired. For the potentially damaged plate, recorded sensors’ signals are adjusted in terms of the origin of times and amplitudes, and then subtracted from baseline signals (for the undamaged state). The resulting differences are examined to assess the existence of damage generated reflection waves. In the presence of these waves, damage detection is confirmed (or suspected) and the ToF of those waves is determined for each sensor signal. By knowing the propagation velocity, the distance travelled by the reflected wave is determined, for each PZT;
- for each actuator and sensor pair, an ellipse is defined, with those PZT positions as the two foci of that ellipse;
- the intersection points of the different ellipses are determined as being the potential damage locations.

4.2. Phased Arrays

When using phased arrays, a number of PZTs are being actuated in a predetermined and synchronized way. The lag between each individual actuation, along with the velocity of propagation will determine the wavefront propagation direction. These delays in actuation were previously calculated accounting for the array aperture and to achieve a certain superposition of inspection regions. Those delays are computed and then established by the actuation system (program), which also sets the actuation signal, its frequency and, consequently, the wave propagation velocity. A dedicated, automatic actuation system was developed. The imposed delays are also calculated and confirmed through the acquired data, automatically by the data acquisition system, so that the entire SHM system is tuned to the inspection direction. The fully automated damage detection scheme was implemented in LabView®. For each inspection direction, it can be described in the following manner:

- scans are performed using each PZT (as an actuator and) as a sensor for every inspection direction;
- sensor signals are assumed to be the baseline signals, or undamaged state signals and are therefore saved for future reference;
- scans may then be repeated at a future time, when the plate might have sustained damage, i.e., whenever desired. For the potentially damaged plate, recorded sensor signals are adjusted in terms of the origin of times and amplitudes, and then subtracted from baseline signals (for the undamaged state). The resulting differences are examined to assess the existence of damage generated reflection waves. In the presence of these waves, damage detection is suspected and the ToF of those waves is determined for each sensor signal. By knowing the wavefront velocity and its propagation direction, the distance travelled by the reflected wave is determined, for each PZT;
- for each actuator a probable damage location region is defined. There will be as many of these regions as transducers in the array.
Some practical difficulties in the application of this method, for both techniques, are related to the small amplitude of damage reflected waves, presenting a corresponding low SNR. This is further compounded by false differences/reflections between damaged and undamaged signals, being generated by noise. Networks are more prone to present this problem rather than arrays.

The duration of a single scan (including a pausing time after its execution to allow for the damping of all wave reflections propagating in the plate) is less than 1ms. Also, the computation and storage capabilities required by the method are in the range of what is available presently in a PC. The first obvious solution to decrease noise (random) influence and to obtain a better definition in damage detection and location is to perform each scan repeatedly. To remove off tone noise, sensor signals are analysed in the frequency domain and afterwards a second order band pass filter is applied, around the scanning frequency.

Besides analysing directly the filtered signals, several statistical methods are applied concurrently, including averaging of signals, determination of average maximums and minimums at all times and the determination of signal bands, or thresholds. In this case, no longer differences between damaged and undamaged correspondent signals are performed. Instead it is examined when the damaged corresponding signal band leaves the undamaged signal band.

Despite all these corrections, "ghost" damages may still exist. To avoid eliminating a true damage reflection, in each scan, the determination of multiple possible differences (potential damage reflections of different damages) is allowed - thus including the true damage and false positives. All the combinations based on all the different potential differences are analysed.

For networks, the locations surrounded by the most intersection points (an uncertainty area of 5mm radius is considered) are saved and plotted, being considered as possible damage positions. After plotting the probable damage sites the code allows for the user to interactively discard false positives. Alternatively, the program can operate in a fully automated mode, where it performs a probability analysis on all possible damage locations. The final results are presented by plotting a user specified number of the most probable damage locations.

Furthermore, for phased arrays, probable damage locations found for each direction are simultaneously plotted. Based on the amplitude of the reflected wave, the damage can be located.

5. Results
Damages were simulated by the cumulatively introduction in the plates of surface and through the thickness drilled holes, cuts and semi-circular holes, whose dimensions decreased along test execution from 7mm to 1mm. All damages were successfully detected and their position was determined by the inspection system mentioned for networks.

One of the output screens from the software, for the transducer network damage location method, showing the determined positioning ellipses and circles is presented in figure 10. In the contour plot, the superposition of curves allows for a better visual representation of the possible damage locations. In this case a 1mm through the thickness hole was drilled in the plate, in the position pointed by the system and depicted in the figure.

This damaged plate was then used for the array technique testing. After the array installation, data was acquired and considered as undamaged or as the baseline, reference signals. This means that the original plate had a discontinuity at the 1mm damage location. In order to execute tests with the array, the hole was enlarged by 1 mm to simulate damage growth. Figure 11 shows the contour plot, where the damage is successfully pinpointed indicating the damage position, as calculated by the software.
6. Conclusions
Network and phased array, Lamb wave based SHM systems were developed with the integration of an automatic damage detection algorithm, implemented in software. Scan repetition and the application of combined statistical and probability methods based on a nondeterministic approach was of the utmost importance to improve damage detection capabilities of the system.

Experiments were performed in a maintenance hangar environment with the same plate being subjected to different boundary conditions and with the introduction of different damage types. Damages were successfully detected using both techniques.

Based on the experiments, a comparative study was carried out between the sensor network and phased array architectures. The main advantage of phased arrays is that signal processing is simpler (high SNR). They are nevertheless limited by their inability to avoid blind spots in the array vicinity and behind existing damages, with relation to the phased array position. Also, damages with a small dimension perpendicular to the wavefront propagation direction, even if presenting a considerable dimension along such direction, are more difficult to detect. Sensor networks are simpler to implement, however, signal processing complexity (poor SNR) is a disadvantage. The lower precision of phased arrays in terms of damage location is outweighed by their relatively simpler processing requirements.

A hybrid solution, combining the capabilities of networks and phased arrays enhances the damage detection capability while minimizing the shortcomings of each system.

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