Guided Lamb Waves Based Structural Health Monitoring Through a PZT Network System

Carlos SILVA*, Bruno ROCHA**, Afzal SULEMAN***1

*Academia da Força Aérea, Granja do Marquês, Portugal / cbsilva@emfa.pt
**University of Victoria, Victoria BC Canada / bfrocha@uvic.ca
***University of Victoria, Victoria BC Canada / suleman@uvic.ca

Abstract. With the application of newer materials, such as composite materials, and growing complexity and capacity of current aircraft structures, a failure of such a structure will have catastrophic consequences, economically and most probably and importantly in terms of loss of life. Reliably and completely assess the condition of the total structures in real time is then of growing and outmost importance. A Structural Health Monitoring (SHM) system based in Lamb waves is presented. Lamb waves are reflected in material properties and geometric discontinuities, such as damages. Traveling perpendicular to the plate thickness, being guided by the upper and lower plate free boundary surfaces, Lamb waves present advantages for SHM - or global and embedded Non Destructive Testing (NDT) - in terms of low amplitude damping, being able to travel longer distances. A PZT Network based system was developed to be applied to aluminum and composite plates. 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 depicted, 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. A visualization method based concurrently in the statistical methods developed and superposition of the different results obtained from a test set was implemented. Tests executed with multiple damage simulating surface and through thickness holes and cuts are described. These tests conducted to the successful and repeatable detection of 1mm damages in a multiple damaged plate with great confidence. Also loosened rivets and cuts originating from rivets were successfully and repeatedly detected and located.

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. Inspect the aircraft’s structural condition is then of the utmost importance.

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

1 Principal Investigator, IDMEC-IST, Lisbon, PORTUGAL; corresponding author.
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 Fig.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 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 NDE potential technique emerged. The interesting behavior of Lamb waves in evidence is their interference with damages (boundaries and other material or geometry discontinuities), generating reflections that can be detected.

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 waves generation and propagation behavior, and transducers influence on such aspects, applying numerical methods and experimentation, was previously investigated [9]. Lamb wave emission experiments in aluminum 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 (Fig.2 presents the first modes, S₀ and A₀). 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 other important characteristic of Lamb waves is their dispersive behavior – 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 modeled damages are being developed, using Finite Element Analysis (FEA). Specifically, interesting results were attained with simulations based on Spectral Finite Elements [13].

![Fig.2 – First symmetric (S₀) and anti-symmetric (A₀) Lamb wave modes [11].](image)

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].

2.1 Lamb Waves’ Dispersion Curves

For the design of a SHM system, the understanding of Lamb waves’ behavior is fundamental. The most important aspect is their dispersion behavior, i.e., the relationship between propagation velocity and frequency. Fig.3 depicts the calculated dispersion curves for an aluminum 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, which presents challenges in implementing a damage detection method.

![Fig.3 – Lamb waves group dispersion curves.](image)

![Fig. 4 - Modulated sine actuation signal – time and frequency domains.](image)
The selection of an actuation signal centered in a single frequency is then desirable. A Hann window modulation [20] applied to a sine function – Fig. 4 – was selected after analyzing 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 – Fig.5. Moreover, observing Fig. 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 based on the actuation frequency.

![Fig.5 - Lamb waves wavelength vs. frequency.](image)

The SHM system developed was based on $S_0$, due to its higher propagation velocity, with relation to $A_0$. $S_0$ 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 its 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 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.

3. **Experimental Setup**

Experiments were performed with a 2m-side square aluminum plate, 2mm thick. Different boundary conditions were applied, ranging from the plate being totally supported to simply supported and riveted along the edges. 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 PZTs dimensions determined, a scanning frequency of 340 kHz was selected.

Three transducers were bonded to the upper surface of the aluminum plate forming a network. A NI arbitrary waveform generator, capable of 100MS/s and a NI 60MS/s, 8 channels with simultaneous acquisition, oscilloscope were used. These permit a voltage range between ±15V and definitions exceeding 12bits.
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, 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.

4. Damage Detection

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, as follows:

- wave propagation velocities are experimentally determined for the selected actuation frequency 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;
- consecutive scans are then performed using each PZT as an actuator at a time (the others being used as sensors);
- sensors’ 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 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.

Some practical difficulties in the application of this method are related to the small amplitude of damage reflected waves, presenting a corresponding low Signal to Noise Ratio (SNR). This is further compounded by false differences/reflections between damaged and undamaged signals, being generated by noise.

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 to 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 scans repeatedly. To remove off tone noise, sensor signals are analyzed in the frequency domain and afterwards a second order band pass filter is applied, around the scanning frequency.

Besides analyzing 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 analyzed.

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 (based on Fuzzy Logic principles). The final results are presented by plotting a user specified number of the most probable damage locations.

5. Results

During the experiments, the types of damage created included surface and through thickness drilled holes, cuts and semi circular holes, whose dimensions decreased along tests execution from 7mm to 1mm. In order to test the limits of the damage detection system, damages were introduced cumulatively in the same aluminum plate specimen. In Fig.6, two types of damage are shown.

All damages were successfully detected and their position was determined by the current inspection system. The smallest cuts and holes with dimensions of 1mm were repeatedly introduced in different positions of the plates. Cuts were introduced with different orientations.

![Fig.6 - Two of the types of damage created in the plate (a through thickness cut generated from a circular hole on the left and a surface hole on the right).](image)

When cuts were oriented along a radial direction with relation to one of the PZTs, since their thickness was much smaller than 1mm, the reflections generated by those cuts and detected by that particular PZT presented very small amplitudes. These reflections usually fell within noise amplitude range and were not easily detected by that particular transducer. However, since a network was implemented, it is impossible for a cut to be simultaneously aligned with the radial directions of the three transducers in the network – the worst case scenario being that when such cut was aligned with two of the PZTs in the network. Even if in the noise amplitude range, such reflections were usually detected since the software allowed for the consideration of multiple differences determined, i.e., possible reflections, within each sensor signal. This problem was further mitigated through the application of the referred filters and execution of multiple scans. For the same reasons, cuts farther from the network and oriented along a radial direction with respect to its center were also more difficult to detect.

As mentioned before, damages were created and detected in the plate sequentially and cumulatively. The software handled this aspect well. Furthermore, different scans, executed at different points in time, were recorded and could be used as the reference ‘undamaged’ state response signals for subtraction/comparison. This allows for damage growth monitoring and detection of new damages with respect to previously existing ones.
Of course, newer damages created behind existing damages, with relation to the transducers network, are considerably more difficult to detect.

At a later stage, an L aluminum stringer was riveted to the previously damaged aluminum plate specimen. Cuts with increasing dimension, starting in a single rivet hole and then connecting adjacent rivets were introduced. Experiments to detect loosen rivets were also performed. Cuts initiating in rivet holes and also the ones connecting adjacent rivets were successfully detected, as long as they are not beyond the rivets with relation to the network. Particularly, cuts aligned with the network were only detected when their length was over 2mm, due to a minimum required time separation between their reflection and the contiguous rivet hole generated reflection. The positions of these damages were successfully determined, although a lower precision was verified in the determination of the radial position with respect to the network. It was observed that, with the introduction of the stringer, damages that were beyond the stringer were not detected, since their reflections were destroyed (reflected) by the stringer and rivets line.

One of the output screens from the software, showing the determined positioning ellipses and circles is presented in Fig. 7. The corresponding experiment is also depicted in that figure. The damage here considered was a circular surface hole of 1mm of diameter.

Experiments were performed with different boundary conditions raging from fixed, simply supported and riveted boundaries, in a hangar workshop environment. The reliability and accuracy of the method proved indifferent to changes in boundary conditions and exterior noise. Surface and through cuts and holes as small as 1mm were successfully detected with a PoD of 95%.

Experiments were then performed applying the same principles, test setup, damages types and developed system to composite panels. Different laminates were considered. The system feature of determining experimentally the propagation velocities in different directions revealed fundamental for its application to composites. Here, it was no longer possible to use positioning ellipses, but instead possible damage positions were individually determined for each direction with the different propagation velocities. Again, 1mm damages were successfully detected.

6. Conclusions

A SHM system was carefully 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 Fuzzy Logic principles was of the utmost importance to improve damage detection capabilities of the system.

Experiments were performed in a maintenance hangar environment with the plates being subjected to different boundary conditions and with the introduction of damages covering most areas of the plate specimens (both aluminum and composite panels were tested). Damages were simulated by through thickness and surface drilled holes, semi
circular holes and crack simulating cuts with different orientations. Damages of 1mm in dimension, cumulatively introduced in the plates at different locations, were successfully detected with a PoD higher than 95%. The system also proved to be capable of damage growth monitoring and multiple damages detection.

A stringer and corresponding rivets line were also introduced in the test specimens. Cuts originating from rivet holes; connecting adjacent rivet holes and loosen rivets were also detected.

References