# Structural Health Monitoring Using Lamb Wave Based Piezoelectric Networks and Phased Array Solutions

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## *ABSTRACT*

*Lamb wave based structural health monitoring shows a lot of potential for damage detection of composite structures however, currently there is no agreed upon optimal network arrangement or detection algorithm. The objective of this research is to develop a sparse network that can be expanded to detect damage over a large area. To achieve this, a novel technique based on damage progression history has been developed. This technique gives an amplification factor to data along actuator-sensor paths that show a steady reduction in transmitted power as induced damage progresses and is implemented with the reconstruction algorithm for probabilistic inspection of damage (RAPID) technique. Two damage metrics are used with the algorithm and a comparison is made to the more commonly used signal difference coefficient (SDC) metric. Best case results show that damage is detected within 12mm. The algorithm is also run on a more sparse network with no damage detection therefore indicating that the selected arrangement is the most sparse arrangement with this configuration. Finally, a phased-array solution is also proposed to detect and locate damage on a plate with piezoelectric transducers.*

## 1.0 INTRODUCTION

To achieve lighter aerospace structures, damage is allowed to exist during operation as long as it is within safe, predetermined specifications; aircraft structures are designed according to a damage tolerant philosophy. In more recent years composite materials are being used to build aerospace structures because they are lightweight, still and have excellent fatigue and corrosion resistance. The down side to composites however, lies in their damage mechanisms. Composites may fail or become damaged in a number of ways that are very different from traditional metallic materials. Defects may arise during manufacture due to voids/porosity, ply misalignment or inclusion of foreign objects that show no evidence to the naked eye. Composites suffer from low velocity impacts that can damage the internal structure of a laminate while leaving no visible evidence on the surface.

Maintenance and inspection of aircraft is of the utmost importance for safe and efficient operation. Aircraft structures operate in harsh conditions sustaining high loads, fatigue cycles and extreme temperature differentials. Failure of these structures is not acceptable due to the possibility of loss of life and assets. To ensure aircraft structures are in safe operational condition, costly inspection involving aircraft down time and often disassembly of major components is routinely performed. The cost of inspection is about 30% of the total cost of acquiring and operating composite structures [1]. Currently, damage detection is performed with techniques referred to as non-destructive testing (NDT) or non-destructive inspection (NDI) to locate and quantify damage.

To reduce operational cost and improve reliability and performance, a common goal of researchers, designers and manufacturers is to develop a real time inspection system that is permanently installed or embedded within the structure. This technique is commonly referred to as structural health monitoring (SMH) [2, 3]. Such systems typically consist of a network of transducers that are used to sense physical parameters that indicate the presence of damage with an interrogation technique or algorithm.

In 1917, Horace Lamb published his classic analysis and description of acoustic waves, which included the first consideration of Lamb waves [4]. In 1961, Worlton, D.C. [5] proposed the use of Lamb waves for damage detection and a new NDE potential emerged. In 1962, Frederik, C.L. et al [6] conducted the first experimental study. Beginning in the 1990s Hutchins, D.A. et al [7, 8, 9] and Nagata, Y. et al [10] applied Lamb waves to NDE using medical imaging and seismic tomography techniques to both metallic and composite materials. Their systems utilized pairs of transducers that were positioned across the material at various locations in order to obtain a dense collection of pitch-catch signals in order to reconstruct a tomogram. While the techniques produced reasonable results the methods were time consuming, requiring a lot of repositioning of the transducers and in some cases requiring the specimen to be placed in a water bath. Prasad, S.M. et al [11] implemented an SHM system for composites using surface bonded piezoelectric transducers. Since the transducers were permanently bonded in place the system could be operated in real time without any repositioning. Gao, H. et al [12] introduced the reconstruction algorithm for probabilistic inspection of damage (RAPID). Michaels, J.E. [13] later investigated the application of tomography algorithms to sparse networks.

Other research efforts were made to use the Lamb wave mode propagation characteristics in order to detect damage; specifically the attenuation and arrival time of the first two wave modes. In 1993 Guo, N. et al [14] studied the interaction of Lamb waves with delaminations in composite materials both numerically and experimentally. Keilers, C.H. et al [15] later proposed a built-in damage detection system using an array of piezoelectric transducers. Giurgiutiu, V. et al [16] discussed the pulse-echo analysis technique and subtracting baseline data from damaged data to detect damage.

These Lecture Series notes present the details and results of a study on the implementation of a sparse piezoelectric transducer network for damage detection in composite materials. Here, the objective is to develop a sparse network that can be expanded to detect damage over a large area. To achieve this, a novel technique based on damage progression history has been developed. Also, the development of a phased-array actuation system is presented.

## 2.0 THEORY AND IMPLEMENTATION

Lamb waves are elastic, guided waves that propagate parallel to the surface in thin structures with free boundaries. Plates are the best example. However, Lamb waves can also propagate in structures with a shallow curvature. The most advantageous characteristics of these waves are their susceptibility to interferences caused by damages or boundaries (the features of interest) and low amplitude loss. To implement a Lamb wave based damage detection technique some important properties must be determined. When Lamb waves propagate they travel in one of two possible ways with respect to the plate's mid plane. If the motion is symmetric about the mid-plane (the peaks and troughs of the waves are in phase) then it is a symmetric mode and if the motion is not symmetric (the peaks and troughs are 180_ out of phase) it is an anti-symmetric mode. An infinite number of modes exist, each mode is referred to as an A mode or S mode if it is anti-symmetric or symmetric respectively, with a subscript indicating its order. For example the lowest order/frequency symmetric mode is referred to as an $S_0$ mode while the second lowest order/frequency symmetric mode is referred to as an $A_1$ mode. Each mode exists at a different frequency depending on the properties of the material. At lower frequency-thickness values less modes exist. It is advantageous to operate in a frequency-thickness range where only the $S_0$ and $A_0$ modes exist. This is generally below 1.5MHz-mm.

### 2.1 Implementation

To employ Lamb waves for damage detection, a system to send and receive Lamb waves must be developed and a number of parameters must be selected to tune the system such as the transducer type, size and arrangement, actuation signal and data acquisition.

Piezoelectric transducers are commonly used in SHM systems. They are inherently simple devices consisting of simply a piezoelectric material with two conductive surfaces. When a voltage is applied across the surfaces the material expands or contracts (depending on polarity) proportional to the magnitude of voltage applied. Conversely, when the material is deformed a voltage difference is seen between the surfaces. This property leads to the greatest benefit of piezoelectric transducers: their ability to both send and receive signals. Piezoelectric transducers are small and light and can be bonded to or embedded within a structure with little effect. Signals are voltage based and therefore easy to generate and acquire with common hardware. Lead zirconate titanate (PZT) is the most commonly used material in piezoelectric transducers. They offer excellent performance for both generation and acquisition, have excellent mechanical strength, wide frequency responses, low power consumption and can be obtained at a low cost [17].

When actuating Lamb waves it is desirable to actuate the least number of modes possible (preferably only the $S_0$ and $A_0$) so that signal interpretation is simplified. As mentioned earlier, this usually occurs below 1.5MHz-mm. This range is also beneficial because there is low dispersion, which means that if the frequency changes as the wave propagates through the material, its velocity will remain relatively constant, therefore simplifying signal interpretation. It is desirable to send out a single pulse so that the propagation of the wave groups can be analyzed. The challenge then lies in producing an instantaneous pulse that can be controlled and actuated at a desired frequency. There is no control over a frequency generated by a simple impulse, therefore a short burst must be emitted. If a simple sine wave composed of a few cycles is emitted then the desired frequency can be actuated however, the frequency domain of such a signal shows small secondary peaks in the frequency domain that are present at other at other frequencies. To eliminate these peaks the signal can be modulated with a window function to slowly increase and decrease the magnitude of the signal [18]. A commonly used signal that provides a good compromise between number of cycles and ramp up rate consists of five sine peaks modulated by a Hann window. A signal with an odd number of peaks is used so that there is a clear maximum peak that can be used for signal processing (if an even number of peaks were used then there would be two peaks with the same maximum amplitude).

## 2.2 Damage Location Algorithm

Once data is collected in undamaged and various damaged states, a technique must be implemented to locate the damage. Various techniques have been developed; each relies on a difference between the damaged and undamaged state. Such techniques include: delay-and-sum beam-forming [19], the time-difference-of-arrival method [20], the energy arrival method [21] and the filtered back-projection method [22]. To implement the proposed sparse hex network an algorithm was developed that incorporates damage progression information. This algorithm can be incorporated with existing algorithms to increase their accuracy.

The algorithm selected for this research was the reconstruction algorithm for probabilistic inspection of damage (RAPID) [12]. It was developed for networks based on 8-16 transducers and has inherently good signal-to-mean-noise ratios [13], it can accept various input parameters and produces reasonably accurate results [22]. Changes in the transmitted Lamb wave signal are related to a change in the material properties (i.e. damage) between two sensors. The probability of defect presence at a certain point can be reconstructed from the severity of the signal change and its relative position to the actuator/sensor pair [12]. The RAPID algorithm is based on two assumptions: i) all effects from every possible actuator/sensor pair can be expressed as a linear summation across the entire inspection region, ii) information from a specific actuator/sensor pair contributes to the defect distribution estimation of a sub-region is the vicinity of the path between the pair.

Equation (1) describes the RAPID algorithm:

$$P(x,y) = \sum_{k=1}^{N} p_k(x,y) = \sum_{k=1}^{N} A_k \left(\frac{\beta - R}{\beta - 1}\right) \tag{1}$$

where P(x,y) is the probability of the existence of a defect at position (x,y), the Cartesian coordinate of a point in the inspection area, $A_k$ is the damage metric as described below, $\beta$ is a scaling factor that defines the sub-region where the actuator/sensor pair has an effect on (essentially an ellipse with the actuator and sensor at its foci) and R(x,y) is described in Equation 2 as:

$$R(x,y,x_{1k},y_{1k},x_{2k},y_{2k}) = \frac{\sqrt{(x-x_{1k})^2+(y-y_{1k})^2}+\sqrt{(x-x_{2k})^2+(y-y_{2k})^2}}{\sqrt{(x_{1k}-x_{2k})^2+(y_{1k}-y_{2k})^2}} \quad (2)$$

where ($x_{1k}$, $y_{1k}$) is the Cartesian coordinate of the actuator and ($x_{2k}$, $y_{2k}$) is the Cartesian coordinate of the sensor. In this work a value of 1.05 was selected for $\beta$ as it is the commonly used value [22, 23, 24].

$A_k$ is a damage metric that is extracted from the Lamb wave signals. It can be based on various phenomenon such as a reduction in transmitted power, reduction in magnitude of waves or delay in arrival time. More recently Moustafa, A. et al [25] used the fractal dimension with a modified box-counting algorithm. The fractal dimension is a metric used to compare two curves and is calculated as the Hausdorff dimension. The most commonly used metric is the signal difference coefficient (SDC) used by various researchers [22, 23, 24]. This metric will be used as a baseline to compare results with the proposed algorithm. The signal difference coefficient between two data sets is defined as:

$$SDC = 1 - |\rho_{ab}| \quad (3)$$

where:

$$\rho_{ab} = \frac{1}{S}\frac{\sum_{i=1}^{S}(a_i-\mu_a)(b_i-\mu_b)}{\sqrt{\left\{\sum_{i=1}^{S}(a_i-\mu_a)^2\right\}\left\{\sum_{i=1}^{S}(b_i-\mu_b)^2\right\}}} \quad (4)$$

and S is the total number of samples, $a_i$ and $b_i$ are the initial data and damaged data, respectively at sample i and $\mu_a$ and $\mu_b$ are the arithmetic mean value of the initial data set and damaged data set, respectively. Most damage detection systems rely solely on detecting damage as it occurs, i.e. by comparing the change in the damaged state with the undamaged state. In reality however, damage often begins as a small aw that slowly increases in size while in service. As the damage grows, information can be collected that can be used to locate the damage before it is large enough to be detected by algorithms without this information. In this work, a novel technique is developed that incorporates information from the damage progression into the RAPID algorithm to increase the effectiveness and enable its use in sparse networks where it may otherwise not be applicable.

To incorporate damage progression information, the magnitude of power from the transmitted Lamb waves is compared with that from the previous state (the previous hole size in the case of this study). If the power is less then there is the possibility that either damage is progressing in that path or external noise has caused a decrease in the signal. A history of the progression is recorded and if the power consistently drops across a particular path the probability of damage in that location is multiplied by an amplification factor. This is done in order to differentiate between noise and damage progression. Naturally, the initial damage states will not accurately show a damage progression however, as the trend continues across more damage states the accuracy increases and the results become more reliable. In this study an amplification factor of 1.10 (a 10% increase) was selected.

# 3.0 SPARSE HEXAGONAL NETWORK USING DAMAGE PROGRESSION TRENDS

To investigate the potential of the proposed network, experiments were conducted on a composite panel with a single unit cell of 12 transducers arranged in a hexagonal pattern as in Figure 1a. Reference data was collected while the material was in pristine condition and again with incrementally greater induced damage in the form of a through hole. The data was processed using the RAPID algorithm in order to determine the location of the damage.

## 3.1 Proposed Network Technique

The technique developed in this research aims to provide a practical, modular network that is sparse and can be expanded to cover a large area. Generally, tomography requires a dense network of transducers that cannot be easily expanded to cover a larger inspection area. The proposed technique makes use of a hexagonal arrangement, which is modular in the sense that it uses a 'unit cell' that can be repeated to expand the network to cover a large inspection area. The unit cell consists of 12 transducers in a hexagonal arrangement as shown in Figure 1a. The network can be expanded by simply increasing the number of unit cells as shown in Figure 1b. A further benefit is that two unit cells can share three transducers, which means that another unit cell only requires nine new transducers.

Each transducer can act as both an actuator and a sensor. Inspection begins by actuating one transducer to send Lamb waves through the material and recording the signals with the remaining transducers. This is then repeated 11 times such that each transducer acts as an actuator once. Since there is one actuator and 11 sensors, there are 11 actuator-sensor pairs per transducer with direct paths between them as shown in Figure 1a.

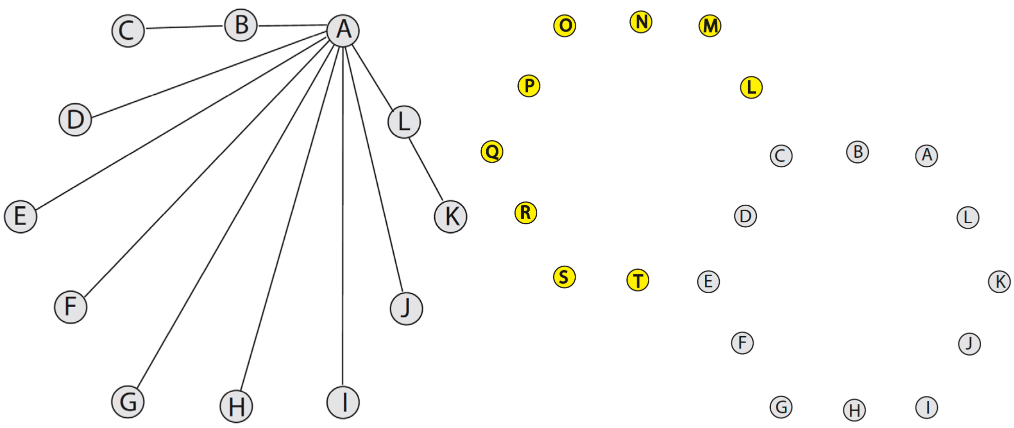


**Figure 1: a) Hexagonal network showing actuator-sensor paths from transducer A (left), and b) expansion of a single unit cell (right).**

## 3.2 Experimental Setup

A 420mm x 420mm panel, composed of eight plys of 139gsm, unidirectional T700 carbon fiber with West System 105/206 epoxy was laminated in a [0/90/+/-45]s orientation to produce a 1.23mm thick quasi-isotropic composite. A jig was machined to locate and bond 12, 1mm thick, 7.56mm diameter PZT transducers to the panel in a 75mm circumradius hexagonal array. The panel and network are shown in Figure 2a, while a close up of the network showing the damage location is shown in Figure 2b. Each transducer was assigned a letter for reference as seen in Figures 1 and 2. The coordinates of the transducers are: A: (247.50, 274.95), B: (210.00, 274.95), C: (172.50, 274.95), D: (153.75, 242.48), E: (135.00, 210.00), F: (153.75,177.53), G: (172.50, 145.05), H: (210.00, 145.05), I: (247.50, 145.05), J:(266.25, 177.53), K: (285.00, 210.00) and L: (266.25, 242.48) in mm from the lower left corner of the panel. Damage was induced at: (228.75, 241.85).

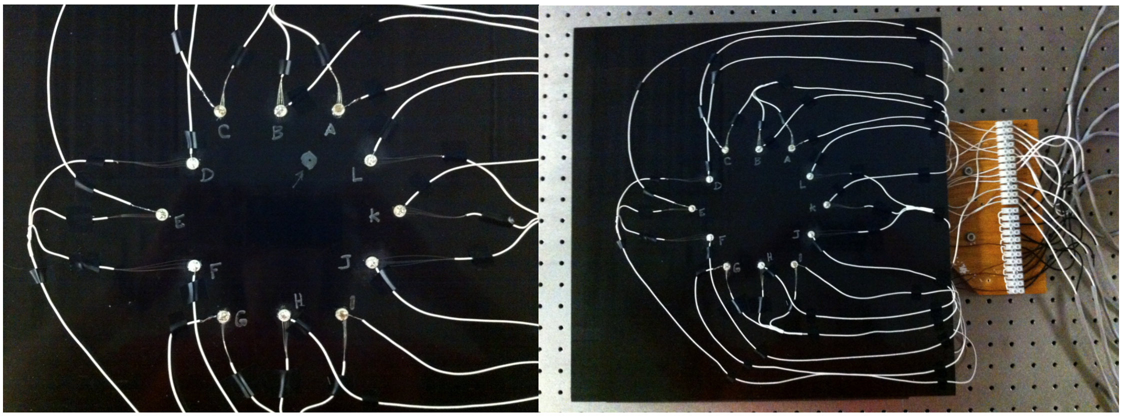


**Figure 2: a) Composite panel with hex network (left), b) hex network with induced damage (right).**

A National Instruments NI PXI-5421 arbitrary waveform generator was used to generate a signal while a NI PXI-5105 digitizer/oscilloscope was used to acquire the signal. Both units were installed in a NI PXI-1033 chassis and controlled with a custom National Instruments LabView program. A model A-303 amplifier from A.A. Labs Ltd. was used to amplify the generated signal.

## 3.3 Signal Generation and Acquisition

An actuation signal consisting of a sine wave with five peaks modulated by a Hann window was employed. An amplitude of +/-8V was produced by the waveform generator and amplified by a factor of 20 before it was sent to the actuator resulting in a maximum amplitude of +/-160V. The actuation frequency was selected based on a number of criteria. In order to only actuate the $S_0$ and $A_0$ modes the frequency-thickness product was kept below 1.5MHz-mm. A frequency scan from 100kHz to 400kHz was performed to determine the frequency that transmitted the greatest amplitude. It was found that the frequency range of 260-270kHz transmitted the greatest amplitude, therefore 265kHz was used for the experiments.

With these properties selected, the waveform generator was programmed to output the actuation signal at 100MHz. Data was acquired at 60MHz for $30\times10^3$ samples (500μs). An ASCII text file was written after each run and saved for data processing.

## 3.4 Experimental Procedure

Once the experimental apparatus was setup as described above, a number of experiments were performed under various damage conditions. Each experiment consists of actuating one transducer and sensing the other eleven, then actuating the adjacent transducer and sensing with the remaining eleven. This process is repeated until all 12 transducers have actuated the system once. At this point the damage is increased and the process is repeated.

Initially the experiment was conducted on the panel in pristine condition before damage was inflicted in the form of a hole drilled through the panel at a location such that it intersected the paths between PZT pairs A-G and C-K as shown in Figure 2b. The initial diameter of the hole was 1.59mm, which was increased to 2.38mm, 3.18mm, 4.00mm, 4.76mm and finally 6.35mm.

The main objective of this work is to develop a modular sparse network. To achieve this an algorithm that uses damage progression information is introduced. With this algorithm, two damage metrics were implemented. The first is based on the SDC in order to compare the proposed algorithm to a conventional metric (SDC). The second damage metric is based on the transmitted power of the signal from an FFT analysis. For both metrics, a comparison between the results with and without the damage progression algorithm is made to assess the effectiveness. A third case was also considered that neglected information from every second sensor, essentially creating a more sparse network of six transducers however, this did not produce any reasonable results therefore implying that minimum of 12 transducers are required in this situation.

Figure 3a presents an example of the received $S_0$ and $A_0$ waveforms actuated by transducer A and received by transducer G. All damage states are plotted together on the same chart with their peaks marked with an asterisk (*). Figure 3b shows a close up of the $A_0$ peak; a consistent decrease in amplitude due to damage is clearly seen. Signals like these from all paths are processed to determine if a decreasing trend exists.

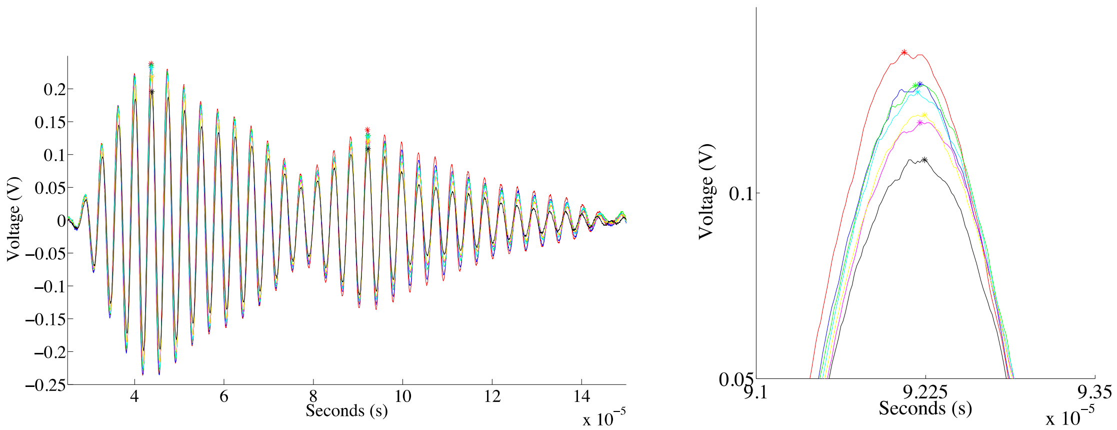


**Figure 3: a) Received Lamb wave signals at all seven damage states along path A-G (left), and b) close up of A0 wave (right).**

To benchmark the results, the SDC was calculated for each actuator-sensor path and implemented in the RAPID algorithm. A contour plot indicating the probability of damage is presented in Figure 4a. The damage location is indicated with the yellow cross and circle. With this information no damage could be detected. This is reasonable according to Michaels, J.E. [13] who reported that the technique was not highly effective on large, sparse arrays. The aforementioned damage progression information was also implemented with the SDC metric. The results are shown in Figure 4b. While the algorithm was not able to detect the exact location of the damage it did locate a region close to the general area of the damage therefore showing a marked increase in accuracy by using damage progression information.

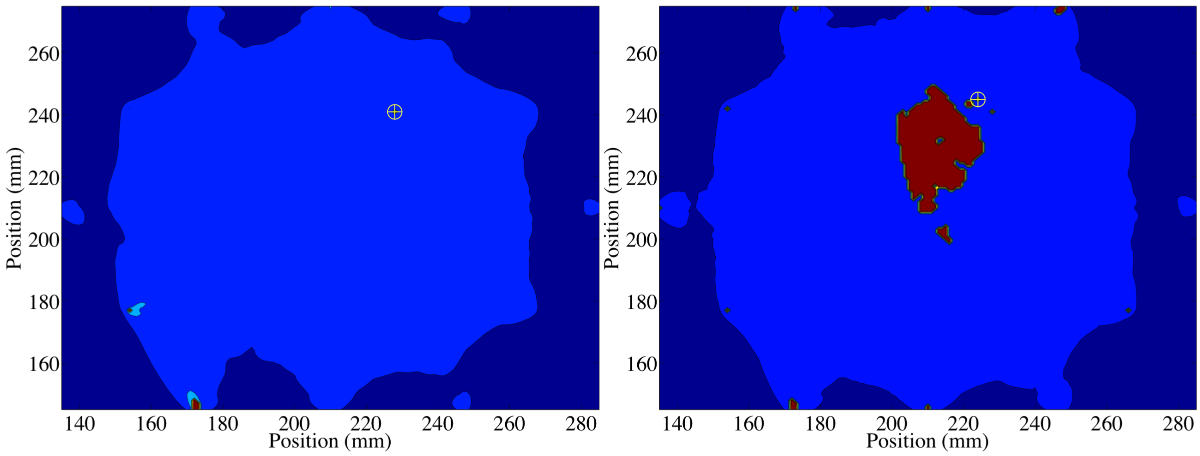


**Figure 4: a) SDC results with no damage progression factor (left), b) SDC results with damage progression factor of 1.10 (right) *Damage location indicated by yellow cross.**

In the second implementation the transmitted power was used as the damage metric. An FFT analysis was performed on data from every actuator-sensor path to extract the magnitude of transmitted power. The RAPID algorithm was implemented and the results are shown in Figure 5a. At this point the algorithm has located three possible damage locations compared to zero locations with the SDC metric. The algorithm was implemented with the damage progression information as shown in Figure 5b. With this information the algorithm has located a small region of damage roughly the same size within a 12mm radius. While these results are not highly accurate they do demonstrate that the use of information from the damage progression does increase the probability of damage detection and allows a large, sparse network to be used.

Many similar research efforts focus on aluminum rather than composite making it difficult to compare results. The results from the experiments performed here are an improvement over the work on an aluminum panel by Hay, T.R. et al [22] as a larger spaced array is implemented with fewer transducer with results comparable to Liu, Y. et al [26] who were able to detect a 30mm x 30mm delamination to within 10.2mm using an array of four transducer pairs arranged in a square with sides of 225mm in length. In general, this technique allows for a larger spaced array with a lower density of transducers.

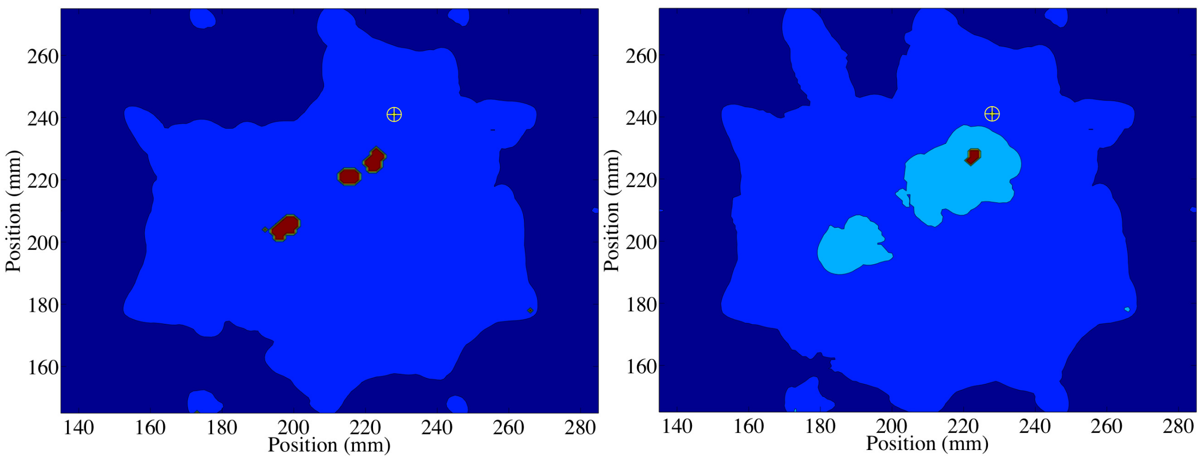


**Figure 5: a) Power amplitude results with no damage progression factor (left), b) Power amplitude results with damage progression factor 1.10 (right) *Damage location indicated by yellow cross.**

In real world structures, the effects of temperature and material anisotropy would have an effect on the signals used in this algorithm and could possibly create inaccurate results. In the case of anisotropy, this would be known a priori as the laminate schedule and material properties of the structure are known. It could be taken into account by normalizing the signals to compare all sensor-actuator pairs if needed. Since this technique relies on signals that travel in a straight line between sensor-actuator pair that are compared to the same signal from a previous damage state, the effect of anisotropy would not have an influence because it remains constant (aside from the effects of damage). Temperature however, can change drastically during service. As the temperature of a carbon fiber/epoxy laminate increases, the modulus of elasticity decreases and therefore the magnitude of the signal that it transmits decreases. To address this, a temperature sensor could be used to measure the temperature of the laminate in the region being monitored and with the effect of temperature on signal transmission known, the effects of temperature could be accounted for in the algorithm.

### 3.5 Discussion

A novel sparse network that can be expanded to cover any size area has been proposed along with a novel technique for incorporating information on the progression of damage to improve the accuracy of existing algorithms. The network consists of a unit cell of 12 piezoelectric transducers arranged in a hexagonal pattern as shown in Figure 1a. The network is easily expanded by adding nine more transducers to the existing 12 as shown in Figure 1b (two unit cells). The hexagonal arrangement allows for efficient stacking of unit cells that would not be otherwise possible with a circular array.

Damage progression information was implemented in the form of a 10% increase in signal magnitude if the actuator-sensor path showed a consistent decrease in power across each damage state (i.e. if the power was consistently less than the previous state). The results presented in Figure 4 show that incorporating the damage progression information increases the chance of detection with SDC as a damage metric. When the power of the transmitted wave is used as a damage metric some potential damage locations appear as shown in Figure 5a. When the damage progression information is incorporated the accuracy is increased, locating a potential damage site that is within 12mm of the actual damage as shown in Figure 5b. While the results do not directly pinpoint the damage location they do show that an improvement over the existing RAPID algorithm can be made by incorporating damage progression information with the use of a larger area sparse network on a carbon fiber composite material.

## 4.0 PZT PHASED ARRAY SYSTEM

The development of a Structural Health Monitoring (SHM) strategy based on a PZT phased array system is proposed. The objective is to increase the low Signal to Noise Ratio (SNR) compared to PZT networks for Lamb wave based SHM systems. This is achieved by constructive interference – beamforming – of the different waves generated by the different transducers in the array. By carefully choosing and changing the delays in between actuation of consecutive transducers in the array, the wave front can be steered to different selected directions in the plate plane. By increasing the amplitude of generated waves, through beamforming, potential damage reflected waves present also an increased amplitude and higher SNR, facilitating their assessment in sensor signal and consequently damage detection. The developed system was designed based on the use of the fast propagating first symmetric Lamb wave mode ($S_0$). The accuracy of the method is strongly dependant on a precise multiple actuation system and particularly in the accuracy at which the diminutive time delays are introduced in between actuation of the different array elements. This problem was addressed by developing a dedicated multiple actuation system. Tests were performed with the successful and repeatable detection of 1mm damages applied cumulatively into both aluminium and composite plates, subjected to different boundary conditions. Damages were simulated by surface and through thickness holes and cuts with different orientations. Finally, a network and phased array were also applied to a more complex composite panel with embedded Fiber Bragg Grating (FBG) optical sensors. An FBG interrogation technique, based in a tunable laser and photo-detector, was developed. The laser is tuned just before test execution and it is not changed during scans. With no moving components, this technique does not impose a maximum sampling frequency. At the same time temperature and operational induced strains (both static and due to low frequency vibration) influences are eliminated.

The application of phased arrays and ultrasonic/sonic waves in NDE&T of structures was developed in parallel with radar and medical applications. The objective of a phased array SHM system to excite Lamb waves is to increase Signal to Noise Ratio (SNR) with relation to the implementation of transducers networks, while maintaining the capability to inspect an entire structural component. Phased arrays also present the advantage of focusing the inspection effort into different areas of the component at a time. This is achieved by constructive interference – beamforming - of the different waves generated by the different transducers in the array. By carefully selecting and changing the delays in between actuation of consecutive transducers in the array, the wave front can be steered to different directions in the plate plane. Increasing the amplitude of generated waves, through beamforming, potential damage reflected waves present also an increased amplitude and higher SNR, facilitating their assessment in sensors' signal and consequently damage detection. Detectable damage size might then be reduced. Even more importantly, the difficulties created due to damping of propagating waves, particularly when structural reinforcements exist, can be diminished.

Also the multiple sensor signals available in an array can be used to increase the accuracy of detection, by "steering" sensing capabilities into a determined direction. This can be achieved by gathering the sensed signals from the different transducers after the execution of a scan (with an actuation either introduced by the phased array, or by any single actuator) and shifting neighboring sensor signals by a certain time delay. This time delay is equal to the difference in times at which an incoming wave from the selected direction would reach two consecutive transducers in the array. With this procedure, the reflection from a potential damage existing in that particular direction will appear in all sensor signals at the same time. Afterwards, the shifted sensor signals are added, so that the potential damage reflection in the scanned direction will be enhanced with relation to the remaining sensor signal. Particularly, the detected reflection will be enhanced with relation to noise and other reflections, for instance from other damages in other directions, or boundaries. The difficulty in the application of phased arrays to SHM, involving Lamb waves generation, is mainly related with the required phased actuation system. Due to the high propagation velocities of Lamb waves, such system must be capable of reliably and accurately introduce diminutive time delays involved in the phased array approach. Simultaneously, all the requirements related to Lamb wave generation must be considered. Particularly more complex generation signals are involved with required significant amplitude, time and specifically frequency definition. Such accuracy is even more important when the fast propagating $S_0$ wave is selected as the mode of interest to be activated by the phased array and to base the damage detection system.

## 4.1 Actuation System

One important aspect that must be considered in the development of a phased array system for activation of a Lamb wave front is that the array pitch should be less than half of wavelength of the waves to be excited, so that undesirable side lobes do not exist. The tuning of such system should now be performed with relation to the array pitch and no longer with relation to the PZT element dimensions. The PZT transducer dimension should be as close as possible to the phased array pitch, reducing spacing in between consecutive elements to a minimum. Nonetheless, neighbouring elements should not be in contact.

To be able to inspect an entire component, scans performed by a phased array must be repeated, steering the wave front into different directions in the component. Consequently, different time delays must be applied in between the actuation of consecutive array elements. To define the directions (and related time delays) that must be considered, the aperture of the generated wave fronts must be taken into account.

The development of the Lamb wave based phased array SHM system performed in this work stemmed from the previous implementation of a Lamb wave based PZT network SHM system [9]. Such system was successfully tested in aluminum and composite panels, subjected to different boundary conditions and with the inclusion of stringers and rivets. Tests were performed in an aircraft maintenance workshop environment and concluded with the detection of 1mm damages. This system was based in the $S_0$ Lamb wave mode.

The phased array system uses the same PZT transducers as before and the same data acquisition module. The principles referred previously and the ones applied in the development of the previous system and their derivations were fundamental in the implementation of the phased array, here reported. The same test setup was implemented with the use of aluminum and Glass Fiber Reinforced Polymer (GFRP) panels, subjected to different boundary conditions. The aluminum plate was similar in dimensions to the ones used previously. The GFRP panels were manufactured in a dedicated Resin Transfer Molding (RTM) apparatus, developed in house for that purpose. They had the maximum planar dimensions enabled by such apparatus (305mm x 610mm) and a thickness of 1.6mm. These quasi isotropic panels were manufactured with a 200g/m$^2$ E-glass fiber in a $[0, 90, +45, -45]_S$ layup. Furthermore fiber optic sensors were embedded in those panels during their manufacture to demonstrate their potential future use for SHM.

A linear phased array was applied to the panels, consisting in seven PZT elements, with a 1mm spacing in between consecutive transducers. Regarding the phased array actuation system, a configuration based in a master circuit controlling the phased activation of different slave circuits was implemented. Each slave circuit, when activated by the master, generates the actuation signal to one PZT transducer in the array. The master circuit consists in a simple Micro Controller Unit (MCU). This was selected considering its processing speed, its output frequency and number of output pins (number of slave channels that one MCU is able to control). The processing speed and the maximum MCU output frequency determine the minimum time delays and the precision that the MCU is capable to apply for phased activation. A MCU with 16MHz of clock frequency, 4MHz of output frequency and two output ports, with eight and two pins respectively, was selected.

For the design of the slave circuits, it was considered a similar MCU to generate the digital signal corresponding to the actuation waveform. With the designed technique to generate the actuation signal, the MCU is capable to generate signals with frequencies up to 2MHz (half of its maximum achievable output frequency of 4MHz).

The slave MCUs generate and output the bit trail in two different pins, one for the generation of the inner sine function and the other to generate the modulation window. These signals are filtered in a developed amplifier based Digital to Analog (D2A) circuit.

Afterwards, both signals are multiplied, by an analog multiplier, and its output is amplified to the desired voltage range output (±18V). The actuation signal is passed then by a switch, which is only closed during actuation. This solves the usual impedance mismatch problems in between actuator and signal acquisition circuits In experiments performed to compare the amplitude of acquired signals with and without the use of the output switch, the first ones presented an increase of over 600%.

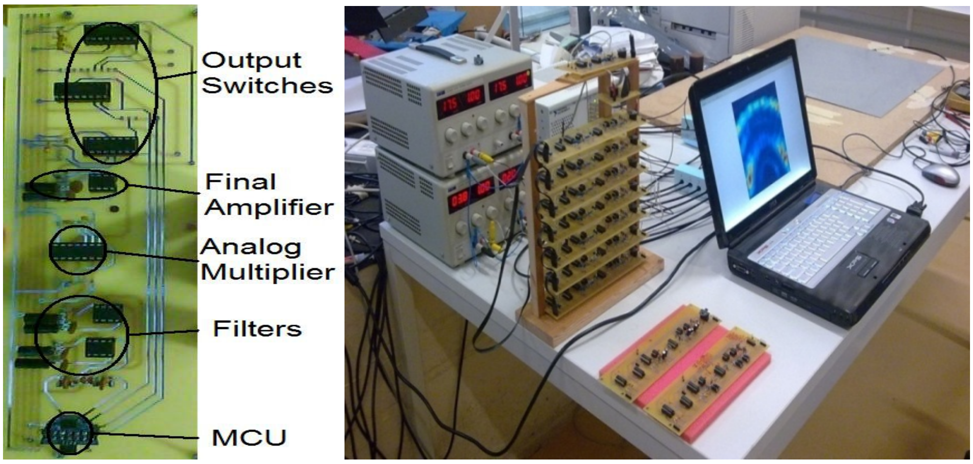


**Figure 6: Slave circuits and complete actuation system.**

The slave circuits and the complete SHM system are presented in Figure 6. The complete actuation system was tested, with relative errors in amplitude, time and frequency being inferior to 3%. The experiments to assess the correct generation of the wave front and its steering were performed in the aluminum plate, with the linear phased array implemented near and parallel to one of its edges (in its middle). For these experiments, it was used a network of three PZT transducers bonded near the other three plate edges (also in the middle). The sensors' signals corresponding to scans executed with the wave fronts steered to each one of the network elements and adjacent directions were analyzed. It was concluded that wave fronts were successfully generated and steered.

Through the wave front Time of Flight (ToF), between generation and arrival to each one of the network sensors, the propagating velocity of the $S_0$ wave fronts was confirmed with the initially calculated values from dispersion curves. With these tests the desirable actuation frequency for the array pitch was confirmed to be 250kHz for the aluminum plate. The aperture of the array was also confirmed. Finally the amplitudes of the network sensors' signals corresponding to the propagating wave front generated by the phased array were assessed. It was verified that the sensed amplitudes for the wave front were ten times higher than the ones obtained for a single wave generation.

## 4.2 Damage Detection and Location

Following actuation, PZT transducers in the array are used as sensors. In terms of damage detection and location, the phased array sensing principle for the scan direction was applied to enhance the detection of potential damage generated wave reflections in the sensors signals. To enhance the precision of damage location, the same principles developed in the application of the previous implemented PZT network Lamb wave base SHM system were applied. Particularly the successive repetition of scans in the same direction (for all scan directions considered in the plate) was implemented. Statistical methods were applied to data in the same fashion as before with the determination of signal bands, averages, deviations, maximum and minimum average values for all times, etc. Damage location was considerably enhanced by the parallel application of the scheme depicted in Figure 7. In the application of this location scheme all possible damage detected reflections in sensor signals are considered (including the true damage reflection and "ghost" damages generated by noise). These signals are also analyzed in the frequency domain and after the application of a band pass filter centered in the actuation frequency.

Particularly for the application to the GFRP panel (and to composite components in general) the system enables, initially, the experimental determination of propagation velocities for the different scanning directions. Specifically for the quasi isotropic GFRP panel used, wave front propagation velocities for different directions do not present significant variations. For the array pitch implemented it was verified that the average optimum actuation frequency was 148kHz, corresponding to an average wavelength of 21mm. To note that the phased array was implemented in the center of the GFRP panel, instead of near one of its edges as in the aluminum plate, for its use for subsequent experiments using the optical fiber embedded sensors in that panel.

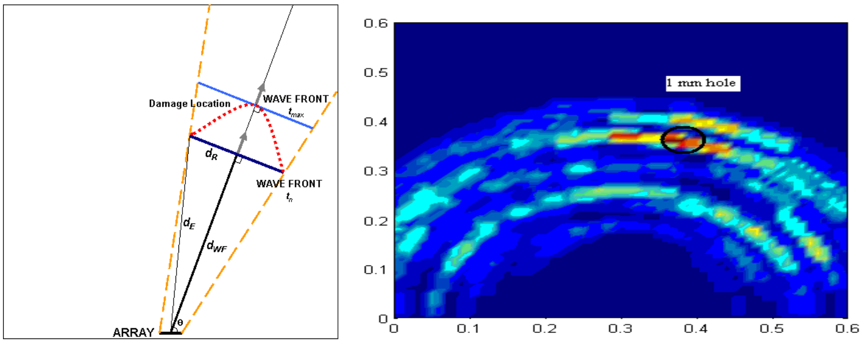


**Figure 7: Damage location algorithm.**

The phased array system was then experimentally tested in the plates with the introduction (cumulatively) of surface and through the thickness circular holes and cuts (with different orientations), with a maximum dimension not exceeding 1mm. The simulated damages were successfully detected. The only exceptions were damages created behind other damages previously introduced, with relation to the phased array. The software for automated inspection developed for networks was adapted for the phased array system.

### 4.3 Discussion

The development and testing of a PZT phased array SHM system based on $S_0$ Lamb wave fronts for damage detection and location has been presented. The phased array generates fast propagating wave fronts. Tests performed in aluminum and GFRP panels subjected to different boundary conditions resulted in the successful detection of 1mm damages. These were simulated with surface and through the thickness holes and cuts. Next, a FBG interrogation technique, based in a tunable laser and photo-detector, was implemented to enable the use of the FBGs embedded in the GFRP panel. Thus temperature, operational strains and vibration effects are eliminated. The interrogation technique also does not limit by itself the acquisition/scanning frequency and speed – limitations are imposed instead by the frequency of the digitizer. This is important to enable the high speed acquisition required to assess the fast propagating Lamb waves. The initial experiments proved the ability of the FBG sensor and interrogation technique to detect and assess the fast propagating Lamb waves.

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