Development of a PZT Phased Array and FBG Network for Structural Health Monitoring Based in Guided Lamb Waves

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Abstract. 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.

1. Introduction

Inspections to assess aircraft structures health are of the utmost importance for their safe and efficient operation. Lightweight aircraft structures are submitted to harsh operation conditions, with consequences in case of failure being potentially catastrophic with loss of life and operation. Presently, aircraft structures employ lighter and stronger advanced composite materials, with radically different characteristics with relation to aluminum. To achieve the required lightweight, aircraft structures are also damage tolerant, i.e., they are allowed into operation with known existing damages as long as these are smaller than certain dimensions. Moreover, current aircraft fleets are rapidly ageing, with the aircraft design flight hours of operation being surpassed by much. With this, non predicted damages during the design process of the aircraft and their structures - and the establishment of their design operation load spectrum (surpassed now by much) and consequent scheduled maintenance plan - might exist without being known, or inspected. Additionally, presently used Non Destructive Tests and Evaluations (NDT&E) suffer from localized damage detection capabilities and are not capable of real time and persistent structural inspection.

These aspects are driving required research of Structural Health Monitoring (SHM) techniques, based on embedded, real time and global inspection systems. These will enable: detection of impact or excessive load resultant damages in aircraft structures while in operation; detection of damages in earlier stages of development and then the relaxation of design safety factors; execution of structural inspections, rapidly and briefly, in operation and then conditional maintenance and operation of aircraft. Consequences in decreasing aircraft structural weight and then in increasing available payload or range; or in decreasing required lift, generated drag, required thrust, fuel burn and pollutant emissions are obvious, while assuring higher safety levels of operation.

2. Lamb wave based SHM

In Lamb wave based SHM systems, damage assessment is achieved from the detection of potential damages generated wave reflections in the differences from corresponding sensor signals, obtained from damaged and undamaged conditions.

Lamb wave based SHM systems have been reportedly applied to detect damages in aluminum and composite components [1, 2], with the use of different types of transducers [3, 4] positioned into the components to inspect in both network and array configurations [5, 6]. PZTs and Fiber Bragg Grating (FBG) sensors have been investigated.

Lamb waves present a dispersive behavior, with their propagation velocity being dependent on their frequency and consequently related to their wavelength. The dispersive behavior is represented in Lamb waves' dispersion curves and is dependent on the host structure thickness and on its material mechanical properties, such as Young modulus (in the different directions when an orthotropic material is considered), density and Poisson coefficient. Such dispersive behavior has implications in the selection of transducers dimensions and actuation signal waveform.

Considering SHM systems based in the application of PZT transducers, Giurgiutiu and Bao [7] established that to optimize the activation and sensing of propagating Lamb waves, PZT transducers should have a dimension (in the plate plane) equal to half of the wavelength of Lamb waves activated. Takeda et al. [8] performed experiments to detect delaminations and evaluate their length in composite (Carbon Fiber Reinforced Polymer - CFRP) panels with embedded FBG sensors. In these experiments, FBG sensors with different lengths were applied. The objective was to determine which FBGs (and corresponding lengths) would better sense the propagating Lamb waves. They concluded that Lamb waves were better detected by FBGs with a length equal to 1/7 of their wavelength. With these conclusions, (activation) frequency selection is then inter-related with transducers' dimensions selection.

Regarding actuation signal waveform, as explained in [9], due to the Lamb waves' dispersive behavior, if more than one frequency is excited, different waves with different propagation velocities will be emitted. Lamb waves' propagation pattern will be considerably more complex, as corresponding sensed signals, creating difficulties to the damage detection method. The actuation signal waveform frequency spectrum should then be centered as much as possible around a single frequency. Through the analysis of different possible actuation signals in the frequency domain, a sine wave modulated by a Hann window revealed to be the optimum actuation signal waveform.

Furthermore, multiple Lamb wave modes can be excited by an actuation signal waveform centered in one single frequency. Again Lamb waves' propagation will be more complex, creating difficulties to the damage detection method. Activation frequency should be selected to excite the minimum number of Lamb wave modes.
For lower frequencies, only the first symmetric (S_0) and first anti-symmetric (A_0) Lamb wave modes can be excited. The S_0 wave mode propagates faster and presents consequently higher wavelengths than the A_0 mode, for the same frequency. It is desirable that they have considerably different propagation velocities, to decrease interference in between the two different modes and their reflections. Since A_0 waves present lower velocities than the S_0 waves, being more prone to interference by S_0 reflections, their application poses increased difficulties on the assessment of potential damage reflections in sensors' signals.
It is also possible to tune Lamb wave activation [10]. This consists on selecting an activation frequency such that for a certain actuator PZT dimension the excitation of one of the modes is enhanced (increased resultant amplitude), while the excitation of the other mode is diminished. As referred before, the amplitude of an excited wave is increased when the actuator has a dimension equal to half of its wavelength. The excited wave amplitude is diminished when the PZT has a dimension equal to (or multiple of) its wavelength.
Considering all the aspects referred previously an actuation frequency and transducers dimensions can be selected.

3. Phased Array SHM systems

The application of phased arrays and ultrasonic/sonic waves in NDE&T of structures was developed in parallel with radar and medical applications. [11]. 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.
Due to the difficulties related to actuation of phased array Lamb wave based SHM systems, the majority of reported research involves uniquely the referred phased array principles in sensing. Bao [12] and Purekar [6] studied this approach applied to linear arrays.
Pena et al. [13] and Malinowski et al. [14] reported the successful application of SHM Lamb wave based phased arrays for damage detection. These systems included also dedicated actuation systems developed by the authors. To decrease the complexity of such actuation systems, the authors selected to base the system and damage detection algorithm on the slower A_0 Lamb wave mode.

4. Phased Array development – 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%.

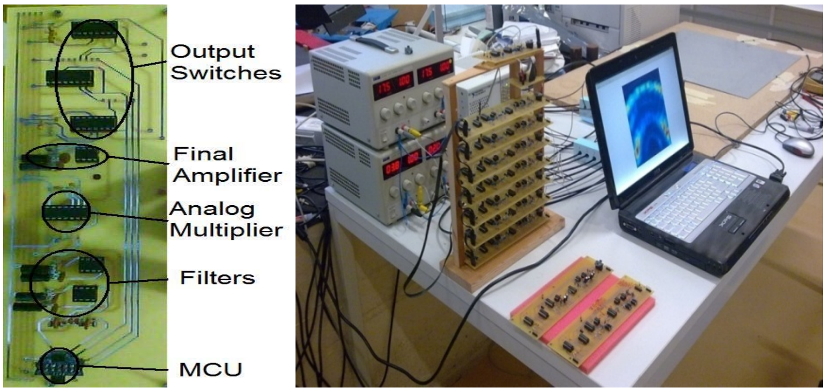

Fig.1 – Slave circuits and complete SHM system.

The slave circuits and the complete SHM system are presented in Fig. 1. 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.

5. Phased Array development – 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 Fig. 2. 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.

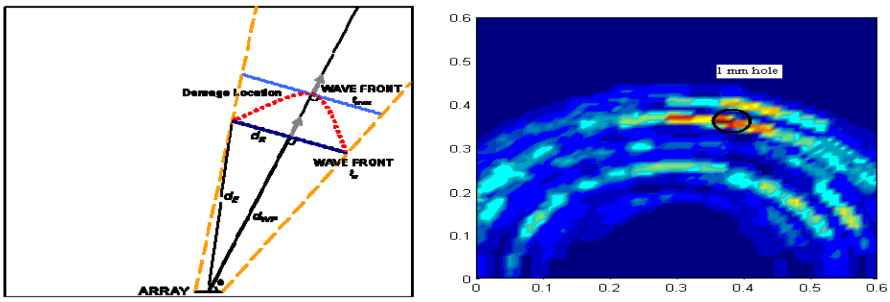

Fig.2 – Damage location algorithm.

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.

6. FBG Network

A network consisting in three sets of FBG sensors was embedded in the GFRP panel in its manufacture. These three sets enable the implementation of triangulation schemes for damage location. Each set consists of two 3mm FBGs in a cross pattern (with its length being 1/7 of the emitted wavelength). By applying these cross patterns, the system is able to detect Lamb waves propagating in any direction. Furthermore, by comparison of sensed strain amplitudes by the two perpendicular sensors (in the same set) the incoming wave propagation direction can be determined. If such wave corresponds to a damage generated reflection, then the intersection of those directions for the three sets of sensors will give the probable damage position.

FBG sensors have different Bragg wavelengths and are printed in the same optical fiber. A single high precision, high power tunable laser, with a well defined narrow peak in its output light wavelength spectrum is used to illuminate the optical fiber and embedded FBG sensors. The opposite end of the optical fiber, with relation to the laser, is connected to a photo-detector, to translate the transmitted light power sensed into an output voltage that is fed to the data acquisition of the SHM system (the same used for the network and phased array systems developed). By using the transmitted light, no circulators are applied with consequent losses in light intensity.

Before each scan the laser output light wavelength is tuned to be close to the Bragg wavelength of one of the FBGs, selected previously. Such wavelength corresponds to the half point in the slope (of one of the sides) of the FBG wavelength spectrum. Consequently the transmitted light intensity will change proportionally to the sensed deformation. It is possible from the output of the photo-detector to reconstruct the propagating wave. Scans are repeated considering all FBGs for each structural health state. This tunable laser enables its control by an external automatic digital system.

With the implementation of this technique, temperature and operational strain effects are removed from sensor signal, since the laser is tuned just before each scan. Furthermore, this technique does not restrict the maximum acquisition frequency. This will instead be limited by the acquisition frequency of the voltage signal acquisition system.

This technique is depicted in Fig. 3. The initial experimental setup and the equipment used for interrogation of the FBGs can be observed. The optical fiber (with all embedded FBGs) can be seen entering and exiting the GFRP panel. At that stage, the phased array was still being bonded to the centre of the panel and at that time only one PZT was bonded. This PZT was being used to execute initial tests for Lamb wave propagation in the panel and to assess the capability of the FBG sensors to detect the propagating Lamb waves.

Fig.3 – FBG system.

With this experimental setup the first symmetric Lamb wave mode (S0) was detected by the system - Fig. 14. To improve signal definition and remove off tone noise, a band pass filter is applied to the FBG signal.

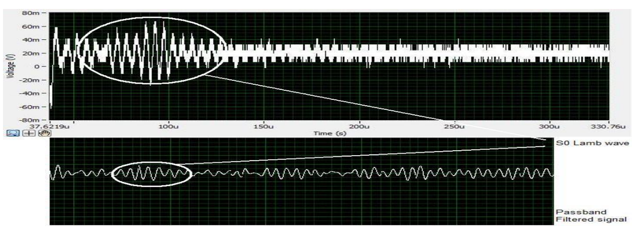

Fig.4 – Detection of S_0 Lamb wave.

The system and its software were completely developed, with the introduction of damage detection and location algorithms specific to the application of the FBGs. The experimental apparatus was also implemented and initial tests are presently being performed with the detection of the activated Lamb waves.

7. Conclusions

This paper describes the development and testing of a PZT phased array SHM system based on S_0 Lamb wave fronts for damage detection and location. 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. Such 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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