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Damage Detection in Composites by LAI-PZT Transducer

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ABSTRACT

Composite structures are known for being susceptible to manufacturing defects and in-service damage. Since damage in composites is not always visually apparent, Non-Destructive Techniques (NDT) such as ultrasonic imaging are often employed to detect and quantify damage [1]. Materials such as carbon-epoxy and fiberglass-epoxy plates are frequently used as structural elements in the both the civil and aerospace industry. Structure made of these materials display high acoustic impedances along the direction of the fibers but behave as Low Acoustic Impedance (LAI) materials in the transverse direction (i.e., through the composite's thickness). It follows that LAI acoustic transducer are generally more appropriate to scan and detect damage/defects through the thickness in various types of anisotropic structures. When transducers are coupled in a direction orthogonal to the resonant mode they display significantly lower characteristic impedance than if coupled in the same direction. In some cases, this feature can eliminate the need for intermediate "matching" films and makes LAI transducer desirable for acoustic imaging applications. In this paper we introduce the use of low-cost, low effective impedance PZT transducer for damage detection in LAI structures. This manuscript also describes results from both numerical modeling and damage detection testing performed using a prototype transducer. In the future simple and economical transducers resonated in their transverse mode rather than the thickness mode could be used to detect damage such as matrix cracking and delamination of the composite structure.

INTRODUCTION

In recent decades, composite structures have been playing a more significant role in modern aerospace, civil, and medical industries. One outstanding example in the usage of composites is the Boeing 787 aircraft whose body accounts for approximately 50% by weight of composite components [2].

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Composite materials also have numerous applications in the medical field; beside some well-developed applications in prosthetic body parts, composites materials are also used in key components of medical resonance imaging devices [3]. Since the number of applications for composite material is steadily growing, the development of affordable and accurate inspection and damage prognosis techniques is extremely valuable. Structural Health Monitoring (SHM) includes damage detection and interpretation that will lead to higher degree of reliability and safety, whereas a lower inspection and maintenance cost is required. SHM has been defined as "acquisition, validation and analysis of technical data to facilitate life-cycle management decisions." [4]

The life-cycle cost in a structure represents one of the key points of life-cycle management, including key items such as inspection and maintenance cost. In the aerospace industry, about 27% of aircraft life-cycle costs are related to maintenance and inspection [5]; clearly any innovation and optimization of damage detection techniques will greatly impact the structure life-cycle cost directly. Acoustic techniques have been an inseparable part of NDTs in defect prognosis and interpretation [6]. Piezoelectric ceramics such as lead-zirconate-titanate (PZT) are often used in acoustic imaging transducers. PZT materials have desirable characteristics such as high electro-mechanical coupling and low internal losses. Nonetheless, the acoustic impedance of PZT ceramics is approximately one order of magnitude higher than biological tissue, polymers, and most fluids [7][8]. Large acoustic mismatch between the sensor and the coupled medium is expected to result in poor signal transmission. Often times to improve signal transmission, when PZT transducers are coupled to polymeric composite matrix or other LAI materials, one or multiple thin intermediate "matching" films with specific characteristic acoustic impedances are deposited on the transmitting face of the transducer. The function of these "impedance matching" layers is to maximize the energy transmitted into the area to be imaged.

Transducers resonated transversely display significantly lower characteristic impedance compared to when resonated through the thickness. This feature eliminates the need for intermediate "matching" films making low characteristic impedance transducer more appropriate for LAI applications. In this paper we will present both results from numerical modeling and damage detection testing conducted using low-cost, high effective impedance PZT transducers. In the future simple and economical transducers resonated in their transverse mode rather than the thickness mode could be used to detect damage such as matrix cracking and delamination of the composite plate.

LAI IMAGING

Traditionally acoustic transducers are designed to operate at frequencies corresponding to the thickness mode's resonant frequency. Nonetheless, at the operational frequency, these type of transducers display high characteristic acoustic impedance. For the case of piezoelectric ceramic transducers, the characteristic impedance of the material is at least one order of magnitude higher than the acoustic impedance of fluids and polymeric matrix materials. To improve energy transmission, transducers often utilize various intermediate layers designed to reduce the effective mechanical impedance. The efficiency of this type of transducer depends, among other factors, on the precision of the manufacturing process.

The impedance of a transducer transmitting in a direction orthogonal to the resonant direction is considerably lower than the characteristic impedance, $c{\cdot}\rho$ of the material itself. The effective impedance of the actuator coupled in a direction transverse to the resonating frequency can be significantly less than its thickness mode counterpart and it could be tuned by changing the aspect ratio between the actuator's thickness and its length. Some examples of acoustic imaging by resonating sensors radially can be found in Dugnani et al. [9,10] and Dugnani [11].

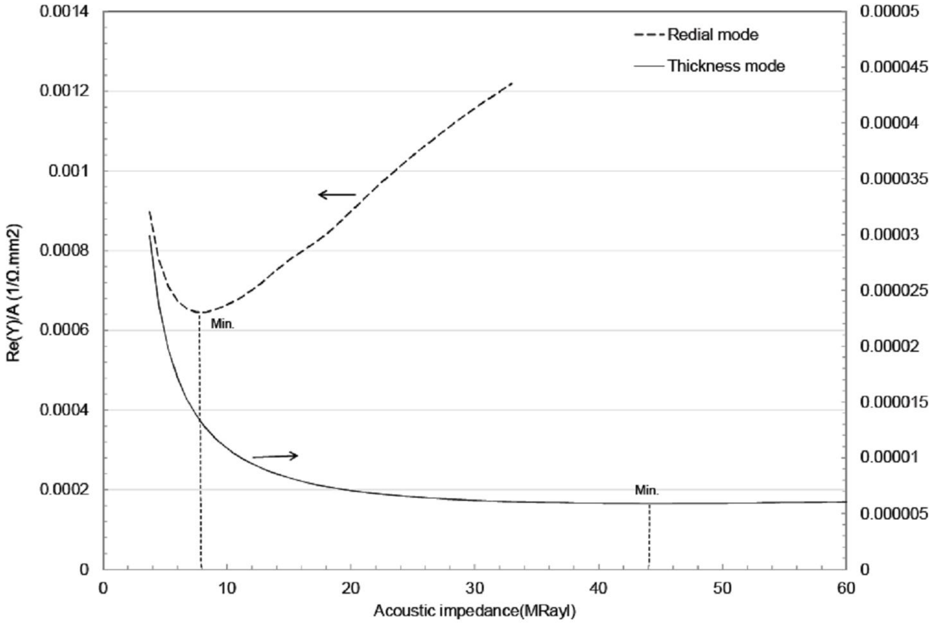

Figure 1. Real part of admittance, *Y*, for transducer resonated in the thickness, and radial mode.

Figure 1 shows plot of the real part of the admittence, *Y*, as a function of the media's acoustic impedance for both a transducer resonated in the thickness mode and for a trasducer resonated in the radial mode. The plot was obtained from various numerical simulation obtained by placing a sensor in contact with a semi-infinite surface displaying a given characteristic impedance. The dimensions of the transducers where chosen so that the resonant frequency of both transducers was the same for the thickness and radial modes. The minimum value for the real part of the admittance in each curve corresponds to the maximum energy dissipated by the transducer, and hence the maximum energy trasferred into the structure. As expected the maximum energy transferred for the transducer resonated in the radial mode occurs for much lower values of the medium acoustic impedance compared to the one resonated in the thickness mode. This indicates that transducer resonated radially transfer energy more effectively than sensors resonated in their thickness mode when LAI materials are utilized. In his work, Dugnani [13] shows similar results.

TEST SETUP

The setup for the acoustic imaging is shown in Figure 2. The setup consists of a laptop computer with data analyzer software, one testing circuit to perform impedance measurements, and a ceramic PZT transducer. The PZT transducer was connected to the AD5933 board (Analog Device Corporation) by short cables and coupled to the structure using hair gel.

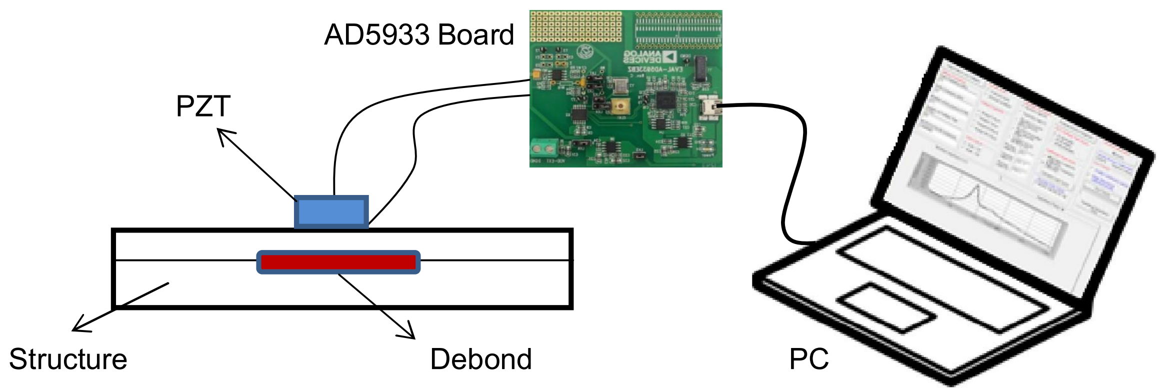

Figure 2. LAI imaging test set-up.

AD5933 Testing Board

Impedance Analyzers, such as HP 4292, are often used for efficient electrical impedance measurements of electrical components. Although highly accurate, these types of devices are expensive, often costing in the range of tens of thousands of dollars. In our work, we used the AD5933 evaluation board (Analog Device Corporation) to measure the electromechanical response of a PZT transducer in the KHz range. The AD5933 has programming capacity of frequency sweeping and peak excitation to higher frequencies than 100 KHz [12].

LAI Transducer

A PZT-5A (American Piezo Ceramics, APC850) piezoelectric sensor of 0.95 *cm* diameter and 0.32 *cm* thickness was used in the experiments described in the manuscript. To ensure flatness on the sensing side, a flat aluminum foil was glued to the PZT sensor by means of conductive epoxy on the sensing side. A second wire was solder on the opposite side. Microscope imaging of the cross sectioned transducer (Figure 3), indicated that both the aluminum foil electrode and the silver conductive epoxy's thicknesses were approximately 30 μm thick.

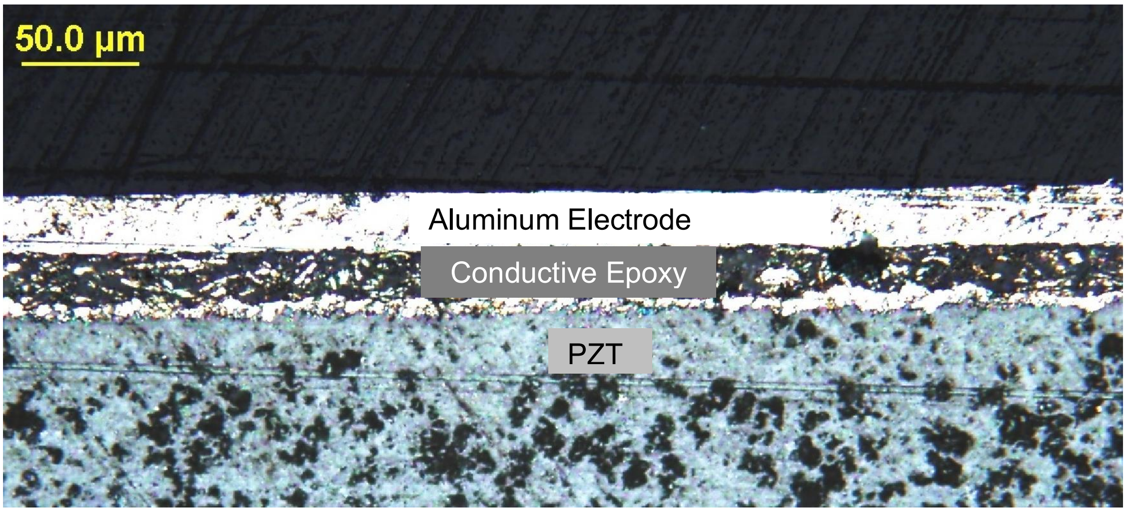

Figure 3. Cross section of electrode area showing aluminum electrode (top), silver epoxy, tin electrode (not labeled), and PZT substrate (bottom).

Test Samples

A debond defect was artificially created by joining two sheets of Polymethyl methacrylate (PMMA) material while leaving the central portion of the two plates unglued. Both plates were 8 *cm* long and the overall thickness of the plates was 0.75 *cm*. The upper plate had a thickness of 0.25 cm, whereas the bottom plate had an overall thickness of 0.5 *cm*. The debond section was located in central contact portion of the sandwich structure and it was approximately 2 *cm* long and 50 μm high.

TESTING

The purpose of the experiments conducted was to determine how accurately the system could detect debonding within a polymeric sandwich structure mimicking debonding in a composite plate. The experiments were conducted by resonating the PZT transducers at various locations on the surface of the PMMA plate and concurrently measuring its electrical impedance. Figure 4 shows an example of the Impedance phase angle for the transducer both as it is resonated in air and coupled with the polymeric structure. In the case of all the experiment conducted, the actuator was resonated at frequencies near the first radial resonant mode. Phase measurements rather than the real part of the impedance where used as the signal from the circuit utilized appeared clearer for these cases.

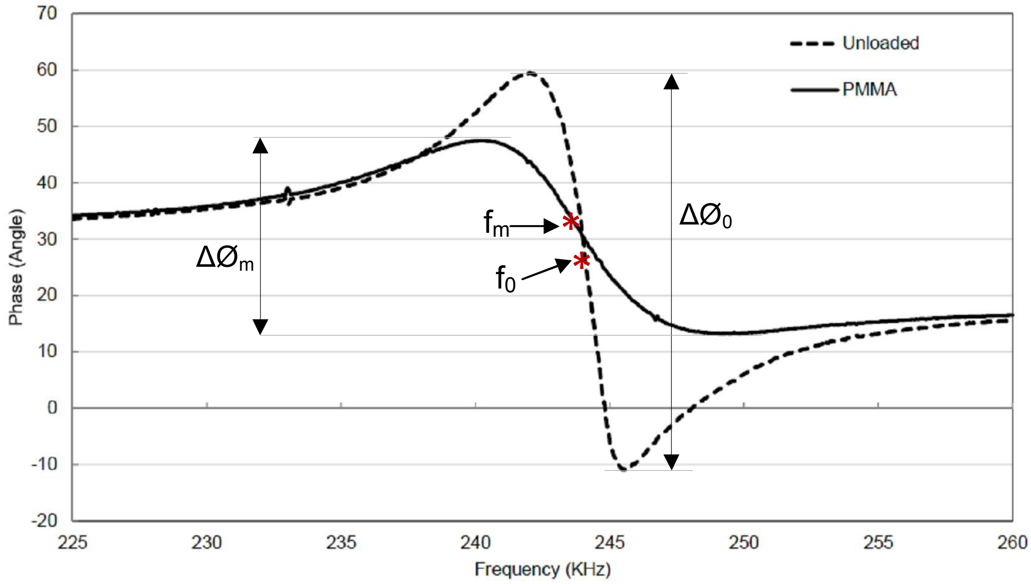

Figure 4. Examples of Impedance phase angle for the transducer (air and against PMMA structure).

Numerical Simulations

In addition to the testing, numerical simulations were running by using a commercially available finite element code. The numerical model was strictly two dimensional (2D) and the geometry of the PMMA plates tested was as described in the experimental section above. In the numerical simulation, the PZT-5A transducer was moved across the PMMA sheet at 0.50 *cm* incremental steps and its electromechanical impedance computed. 'Free Quad' meshing was utilized in the numerical simulations. The model consisted of 12,550 elements and 72,004 degrees of freedom. A Schematic view of the mesh is shown in Figure 5.

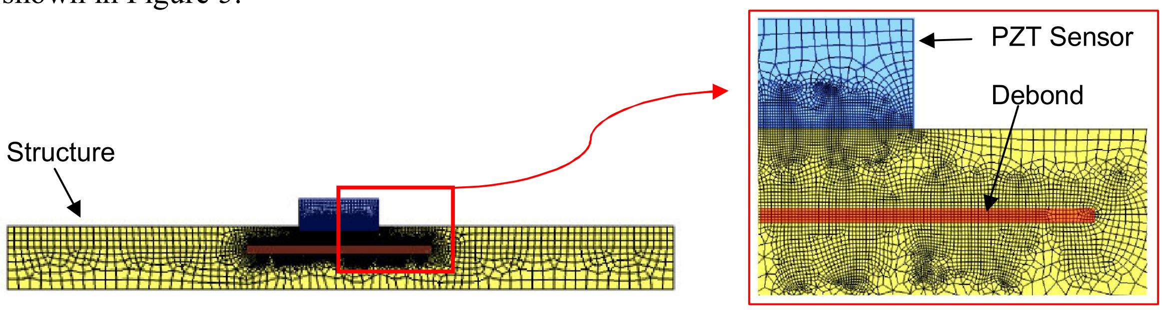

Figure 5. Example of meshing of the actuator on the PMMA plate, including the debond

RESULTS

Both experimental and numerical techniques have been implemented to verify the validity of damage detection method. The diagnostic technique consists in analyzing the changes in the admittance complex values and resonance frequency for various locations of the transducer. It has been observed that defect's presence causes significant resonance frequency and phase change in the case of measured values.

Experimental results

The AD5933 evaluation board was used to measure the complex admittance of the PZT transducer. The electromechanical response of the sensor was measured at various locations on the plate. To estimate the repeatability of the setup, measurements were run in quintuplets and average values obtained. For each location considered, values for the phase amplitude and resonant frequency for the transducer were obtained and compared to the correspondent values obtained for the case of the sensor resonated in air. Normalized values were obtained by dividing the measured resonance frequency, f_m, and phase values, ϕ_m, by the resonance frequency and phase values for the unloaded transducer (i.e., f_o and ϕ_0). To obtain the shift in resonant frequency the voltage signal for the unloaded transducer (baseline, V_0) was mathematically cross-correlated with the data at each location on the plate (V_m):

$$xcorr(f) = (V_0 * V_m)(f) \tag{1}$$

The shift in the peak value of the *xcorr(f)* function and the autocorrelation function was assumed to correspond to the shift in the peak frequency for the data. Figure 6 shows average values for the normalized frequency versus the location of transducer and Figure 7 shows the normalized phase amplitude versus the location of the transducer. Experimental measurements show small standard deviation in all cases, especially for the normalized frequency with deviation less than 2%. Deviation for the phase amplitude was a bit larger as the data showed some degree of noise (deviation 5%). For the geometry analyzed, the measured normalized resonant frequency of the sensor increased while the resonance phase decreased in debonded region.

Numerical results

Commercially available FE software was utilized to simulate the electro-mechanical behavior of the PZT sensor. The model characteristic properties have been chosen based on real test sample, except the actual test utilized a disc-shaped transducer, while the numerical testing used a two dimensional model. The size of the transducer was slightly reduced compared to the diameter of the sensor used in the experiments to ensure that resonant frequency matched the value of the experimental case for the unloaded sensor. Similarly to the experimental case, values of the normalized phase amplitude and the normalized phase frequency were obtained for various locations of the sensor. Figure 6 and Figure 7 show the results from the numerical model compared to the experimental results. Noticeably trends are similar for both cases. Figure 8 also shows a snapshot of the acoustic pressure distribution through the structure for both the cases where the transducer is place away and above the debonded area. It's clear that a portion of propagated acoustic waves are reflected in defect region.

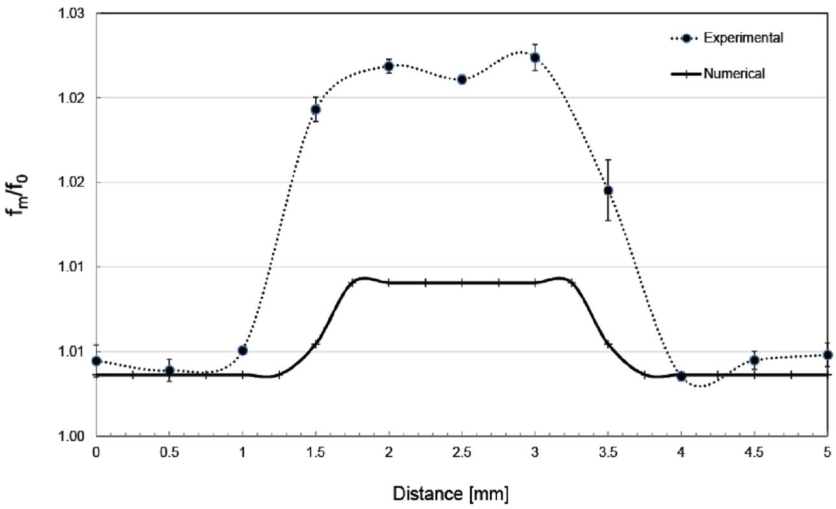

Figure 6. Normalized resonant frequency for transducer (Experimental and Numerical) vs. transducer location.

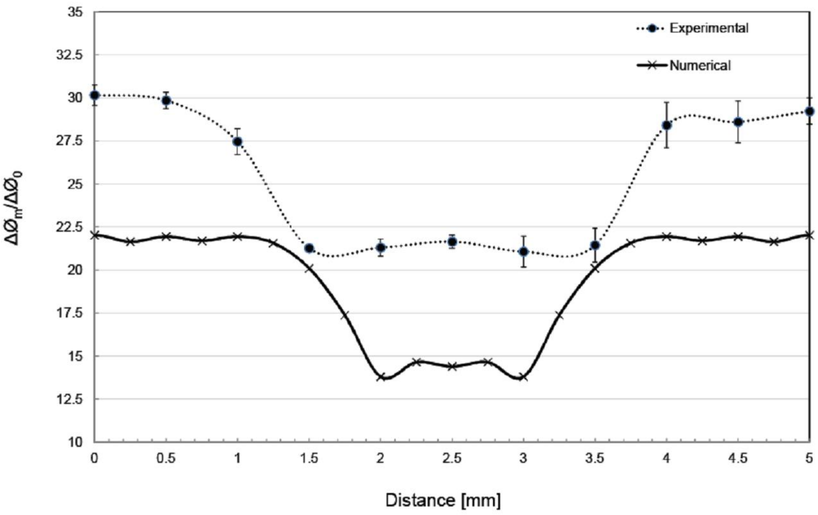

Figure 7. Normalized phase amplitude for transducer (Experimental and Numerical) vs. transducer location.

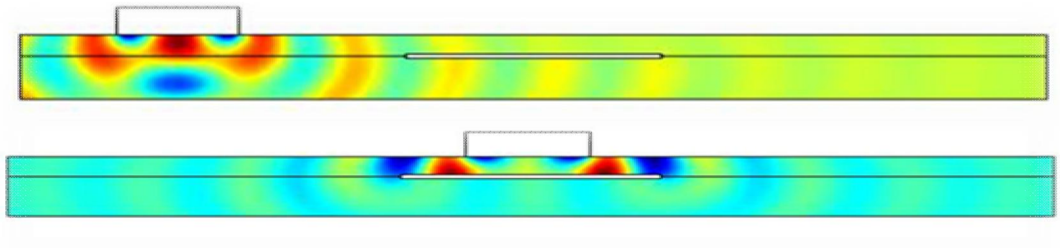

Figure 8. Acoustic pressure distribution through the structure away from the debonded region (top image) and at the debonded region (lower image).

DISCUSSION AND CONCLUSIONS

In this paper we introduced the use of low-cost, low effective impedance PZT transducer for damage detection in LAI structures. Signatures at different locations in the structure were studies by cross-correlation of the electromechanical response of a novel low-cost impedance analyzer. Both the numerical modeling and the testing conducted on PMMA plates showed similar trends. In particular clear, distinguishable signatures were recognizable at the debond area. Experimental testing also indicated that the testing using LAI-PZT technique were very repeatable with relatively low experimental variations.

Although trends were found to be consistent, noticeable amplitude differences were apparent in the normalized phase amplitude and frequency between the numerical and experimental results (Figure 6 and Figure 7). The reason for the differences between the numerical and the experimental results are unclear and currently under investigation.

LAI-PZT based diagnostic techniques show high potential in low impedance structures including wide range of composites, organic materials, and polymers. The effects of the shape of the transducers (i.e., aspect ratio and geometry) need also to be investigated. Damage detection on more complex composite structures and organic tissues using LAI-PZT diagnostics will be performed in the future using similar sensor. Finally, a more compact version of the transducer with embedded electronics is planned for the future.

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