MATERIALS CHARACTERISATION AND STRUCTURAL HEALTH MONITORING OF COMPOSITE STRUCTURES USING ULTRASONIC GUIDED WAVE

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Abstract

The ultrasonic guided waves are employed to develop a sensor system that can be permanently attached to the aerospace composite components for the purpose of continuous or intermittent monitoring of the health of the structure. The system is capable of detecting impact and dis-bond damages that occur during the service of the aircraft. The sensor patch design, sensor reliability, low footprint sensor electronics, data processing and evaluation automation, wireless communication, energy requirements, etc. will be discussed in this paper.

***Keywords**: Ultrasonics, Guided Waves, Structural Health Monitoring. Piezo wafer*

Introduction

Structural Health Monitoring (SHM) of is seen as a new paradigm that will reduce maintenance costs and increase safety of aerospace and civil structures. Lamb waves offer a convenient approach to evaluate plate like structures because they can propagate long distances and are sensitive to the in-plane stiffness of laminates. Lamb wave based SHM has been conceived to provide an early warning of the damage extent through array of sensors mounted permanently on the structure. Structural health monitoring of aircraft structures involves the evaluation of plate-like components, using transducer arrays located suitably on the structure. These plates are anisotropic, with wave propagation properties varying with direction. Ultrasonic piezo wafer arrays have been shown before to have the ability to locally characterize the stiffness properties of a composite material with anisotropy. The guided ultrasonic Lamb waves are used where the central piezoelectric wafer-active sensor (PWAS) emits the guided waves, and the other PWAS sensors receive the Lamb wave signals. In the current work, this technique has been extended to the determination of global elastic moduli using the Lamb wave S_0 and A_0 mode signals that are reflected from features in the structure such as edge of the plate, bolt holes, etc. that are known apriori using STMR array and then reconstruct the unknown defects present on the structure using the same sensor array. The reconstruction of elastic moduli is accomplished using a Genetic Algorithm (GA) based inversion algorithm that optimizes an objective function for a particular configuration of the STMR array and the elastic moduli of the component. The solution to this inversion is the global elastic moduli of the composite which is then used to determine the unknown defects in the test component. Simulations were carried out using S_0 and A_0. The low footprint electronics has also been developed that is compatible with some of the commercial wireless communication protocols. One of the major obstacles preventing the widespread adoption of Lamb wave-based SHM is that availability of portable low power, low mode velocity data for composite layups such as unidirectional, cross-ply, and quasi-isotropic graphite-epoxy composite layups. The inversion algorithm was tested using the simulated edge reflector data and found to agree well with the expected values. Experimental validation has been performed on 3.15 mm quasi-isotropic graphite-epoxy composite.

The low footprint electronics has also been developed that is compatible with some of the commercial wireless communication protocols. One of the major obstacles preventing the widespread adoption of Lamb wave-based SHM is that availability of portable low power, low cost instrumentation operating in 50 kHz to 1 MHz region of interest. Permanently mounted piezo wafer active sensors (PWAS) has evolved as a de-facto sensor for Lamb wave based SHM. Pulser-Receiver is fundamental building blocks for excitation and reception of signal from piezoelectric sensor. Conventional Pulser-Receiver is not suited for integration in SHM Circuits due to physical size, power and nature of the pulse. This paper has attempted to use Commercial off-the-shelf video amplifiers for development of a practical, compact, low power, low cost Pulser-Receiver Module using PWAS sensors for SHM Applications. A simple experiment demonstrates the developed unit at a conceptual stage along with its performance and application.

Sensor Array Design and Development

Piezoelectric wafer-active sensor(PWAS) are small size, light weight, low cost and consuming less power compared to conventional transducers yet able to excite and receive lamb waves efficiently. PWAS has evolved as a de-facto sensor for Lamb wave based SHM. PWAS can act as passive and active sensors which can monitor the health of the structure over time. In the present investigation Circular PWAS sensors having radial mode of vibration is used. PWAS are brittle and cannot withstand small bending. This brittleness imposes difficulties in handling and bonding of the PWAS on the structure being monitored. Also the sensors used in SHM should have long term durability, survivability, and operation performance over extended time periods and in a wide variety of varying environmental conditions. Flexible printed circuits on polyester films are used when applications need light weight and to conform to certain contours or fit into small spaces. Embedding PWAS sensor in polyester patches aids handling and noise free data acquisition of permanently fixed array of sensor. The compact nature of flexible circuits results in considerable weight and space savings.

A method earlier developed by Somashekar et al. [1] to fabricate Smart Flexible Piezo Sensor patches (SFPS) for Structural Health Monitoring System was used here. The thickness of the screen-printed conductive material is approximately 140 μm on the sensor side (lower layer) and the electrode (upper layer) side. The conductive traces were covered by screen-printing a top coat. The dimensions of the conducting lines are 1.0 mm wide. Several flexible patch were prepared by sandwiching PWAS between the two layers of the thin film of Polyester film. First, the PWAS was bonded on to the lower layer of flexible patch as shown in Fig.1, with a thin layer of conductive silver-epoxy paste. Then the upper layer having the positive electrode also coated with silver-epoxy paste is then placed on the lower layer and the sides are bonded with Anabond.

Low Foot Print Electronics

This section will describe the development of a small low powered tone burst excitation and reception pulser-receiver unit using PWAS sensors which can be used as standalone for Lamb wave applications for SHM systems. The low voltage and low power custom pulser receiver is capable of generating a variable cycle pulses. For e.g. a 5 cycle square wave of 250 kHz having 20 usec pulse width generated by this unit. The pulser receiver unit with its different components is shown in Fig.2(a). The PWAS sensors having radial resonance frequency of 250 kHz 10 mm diameter and 0.2 thick are assembled on smart patch and then stuck on the structure with Anabond super glue. There is small shift and broadening of the resonance frequency peak of PWAS when they are stuck on the structure. But this shift is marginal and does affect the frequency of excitation of PWAS. An experimental test is then performed to validate the custom made low voltage pulser receiver unit using different thickness of aluminium and composite plates as a test structure to generate and receive Lamb waves and the setup is shown in Fig.2(b). Lamb wave experiments are carried out in pitch catch and pulse echo mode using the custom made pulser receiver and signals received after amplification from the pulser receiver are collected by a digital oscilloscope as shown in Fig.3(a) and its FFT in Fig.3(b).

Lamb Wave Reconstruction Algorithm

There are different techniques [2-8] for SHM, such as single-transmitter multiple-receiver (STMR) array and multiple- transmitter multiple-receiver (MTMR) array, for isotropic [2-5] and anisotropic [6-7] structures. All the above algorithms require prior knowledge of elastic moduli in order to compute the anisotropy in the material, and to calculate dispersion properties along different propagation direction, which will be used in the phased addition algorithm [8] to remove the dispersion effect from the measured signals. But, in all the above works, the elastic moduli correspond to the virgin sample were used for the calculation. It is well known that elastic moduli of the sample may undergo time-dependent degradation, or it may change due to the introduction of defects and/or due to heat damage. Hence it is necessary to evaluate the global elastic moduli of the composite plate before carrying SHM of the structure. Phased addition reconstruction algorithm maps the positions of the reflectors (edges, defects and other discontinuities) in the area which is scanned. Given the elastic properties of the plates, velocity information evaluated using dispersion algorithms [9], the defect or edge reflectors on the plate can be imaged. Schematic of the sensor array patch is shown in Fig.4. Phased reconstruction algorithms work on the basis that at the point of the defect or the edge reflector, the time shifted signal, time shift estimated using Equation (1), from each receiver add constructively and the resultant signal will resemble the transmitted signal.

$$t_j = OD/v_{1_f} + DR_j/v_{2_f} \tag{1}$$

$$A_{(r,\theta)}(f) = \sum_{i} S_j(f) \times \exp(i\,2\,\pi f t_j) \tag{2}$$

In other words, there is constructive phase addition at that point which produces a strong signal while at any other point, where there is no reflector, the addition is less constructive, which will diminish the phase added amplitude for the point. The inversion is carried out through a genetic algorithm (GA) by maximizing the peak in amplitude function in the above Equations (1) and (2) is illustrated in Fig.5.

Materials Characterisation Using Structural Features

Full-ring STMR SHM array was attached to 3.15 mm graphite - epoxy composite plate with honey as adhesive. The genetic algorithm was used for optimizing an objective function that maximizes the reconstructed signals at the structural features such as the edges that should provide reflected ultrasonic guided wave modes [10,11]. The reconstructed elastic moduli are as shown in the Table-1. The elastic moduli reconstruction was done using both S_0 mode and A_0 mode phase velocity information. As seen from the Table-1, the error in reconstruction the elastic moduli was limited to less than 10%.

SHM of Composites

The reconstructed elastic moduli from Table-1 were used to reconstruct the edges and delaminations present on the structure as shown in Fig.6. The SHM based reconstruction of the data on the composite material shows (a) the edges that are reconstructed well in the three sides. It also images a very subtle defect (indicated by the dotted circle in the figure below) that was introduced using a 7 Joule impact that was approximately 5 mm x 5 mm.

Table-1 : Shows the Reconstructed Elastic Moduli for 3.15 mm Graphite Epoxy Quasi Isotropic Composite

	Reconstructed Elastic Moduli		Effective Moduli	Actual Moduli	Error %
	S_0 Mode	A_0 Mode			
C11	64.67	56.51	64.67	65.77	-1.67
C12	23.28	22.36	23.28	22.57	3.13
C13	6.50	6.42	6.50	5.87	10.79
C22	49.09	52.78	49.09	48.35	1.53
C23	5.50	5.59	5.50	5.75	-4.29
C33	11.68	12.24	10.68	12.43	-6.04
C44	4.57	4.36	4.36	4.15	5.06
C55	4.57	4.54	4.54	4.36	4.13
C66	21.15	22.88	21.15	21.33	-0.83

Summary

A new sensor array for in-situ assessment of elastic moduli, has been developed. The advantage of using a single STMR array to reconstruct elastic moduli and to image the edges and defects present on the structure is demonstrated. Reconstruction of elastic moduli of graphite - epoxy quasi isotropic composite plate has been carried out by a Genetic Algorithm - based inversion method using S_0 and A_0 mode velocities measured in various directions. Full-ring STMR SHM array along with phased addition reconstruction algorithm was successfully used for imaging reflectors (edges, defects) present on the anisotropic plate - like structure. The algorithm takes into account the anisotropy in the material and performs phased addition using appropriate dispersion data depending on the direction of wave propagation. It is shown that the phased addition reconstruction algorithm can image defects accurately in the near-field as well as far-field region of the plate. The algorithm is generalized for reconstructing images using any array configuration and for any customized domain discretization.

The Stamp Size Pulser-Receiver unit was designed and built to send and receive Lamb wave at very low voltages. The key features of the test system are low voltage which considerably reduces system complexity and the use of relatively low cost off- the- shelf a low-noise, high gain wide bandwidth amplifiers. Attention is also paid to discussing selection of circuit components. Signals produced by this board were comparable to those generated by a commercial Function generator and were found have to have sufficient receiver voltages for further processing. This pulser-receiver unit is portable, low cost feasible alternative to commercial function generator for SHM experiments using PWAS sensors. This pulser receiver board concepts should be of great potential for development of new sensor boards for commercial Wireless Sensor Network for Lamb wave based SHM of aerospace and civil applications. Further improvement is presently being performed to increasing gain of the signal and control and reduces the power consumption of the components. Future refinements could be made to investigate low voltage multiplexed pulser receiver unit useful for multiple sensor transduction.

Acknowledgement

The author thanks Aeronautical Development Agency (ADA), Bangalore for the funding of the work over many years through the DISMAS and NPMASS programs. The author would like to acknowledge that the results presented here were based on the hard work of several students at CNDE that includes B. Somashekar, J. Vishnu Vardhan, V. Rajesh and Ajith Muralidharan.

References

1. Somasekhar, B.V., Balasubramaniam, K. and Krishnamurthy, C.V., Bruce Maxfield, "Algorithm for Health Monitoring of Anisotropic Plates Using Flexible Ultrasonic Patches", Review of Progress in Quantitative Non-destructive Evaluation, No.27, 2007, pp.1501-1508.

2. Wilcox, P.D., Lowe, M. and Cawley, P., "Lamb SH Wave Transducer Arrays for the Inspection of Large Areas Of Thick Plates", Review of Progress In Quantitative Non-destructive Evaluation, Melville, NY, USA, American Institute of Physics, No.19A, 1999, pp.1049-1056.

3. Wilcox, P.D., "Guided Wave Beam Steering from Omni Directional Transducer Arrays", Review of Progress in Quantitative Non-destructive Evaluation, Melville, NY, USA, American Institute of Physics, No.22, 2002, pp.761-768.

4. Wilcox, P.D., "Omni Directional Guided Wave Transducer Arrays for the Rapid Inspection of Large Areas of Plate Structures", IEEE Trans Ultrason. Ferroelectr. Freq Control, No.50(6), 2003, pp.699-709.

5. Jagannathan, R., Balasubramaniam, K. and Krishnamurthy, C.V., "A Single Transmitter Multi-receiver (STMR) PZT Array for Guided Ultrasonic Wave Based Structural Health Monitoring of Large Isotropic Plate Structures", Smart Mater. Struct., No.15(5), 2006, pp.1190-1196.

6. Jagannathan, R., Balasubramaniam. K. and Krishnamurthy, C.V., "A Phase Reconstruction Algorithm for Lamb Wave Based Structural Health Monitoring of anisotropic multilayered composite plates", J. Acoust. Soc. Am., No.119(2), 2005, pp.872-878.

7. Vishnuvardhan, J., Muralidharan Ajith., Krishnamurthy, C.V. and Balasubramaniam, K., "SHM of Anisotropic Plates Through an Ultrasonic Guided Wave STMR Array Patch", 2nd Advanced Non-destructive Evaluation, 2007.

8. Muralidharan Ajith., Balasubramaniam, K. and Krishnamurthy, C.V., "A Migration Based Reconstruction Algorithm for the Imaging of Defects in a Plate Using a Compact Array", Smart. Struct. Syst., No.4(4), 2008, pp.449-464.

9. Nayfeh, A.H., "Wave Propagation in Layered Anisotropic Media with Application to Composite", Amsterdam, Elsevier Publication, 1995.

10. Vishnuvardhan, J., Krishnamurthy, C.V. and Balasubramaniam, K., "Genetic Algorithm Based Reconstruction of the Elastic Moduli of Orthotropic Plates Using an Ultrasonic Guided Wave Single-Transmitter-Multiple-Receiver SHM Array", Smart Mater. Struct., No.16, 2007, pp.1639-1650.

11. Vishnuvardhan, J., Krishnamurthy, C.V. and Balasubramaniam, K., "Blind Inversion Method Using Lamb waves for the Complete Elastic Property Characterization of Anisotropic Plates", J. Acoust. Soc. Am., accepted, in Press.

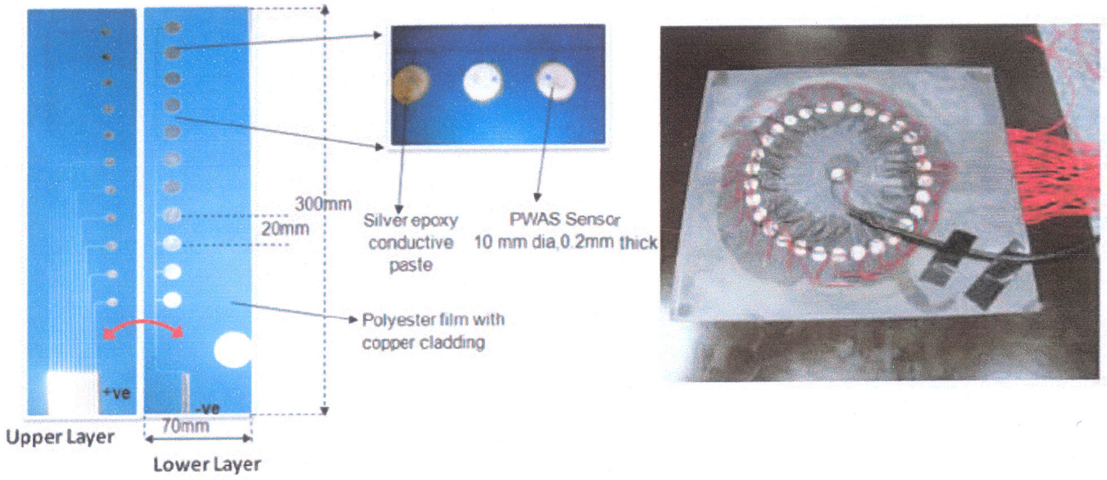
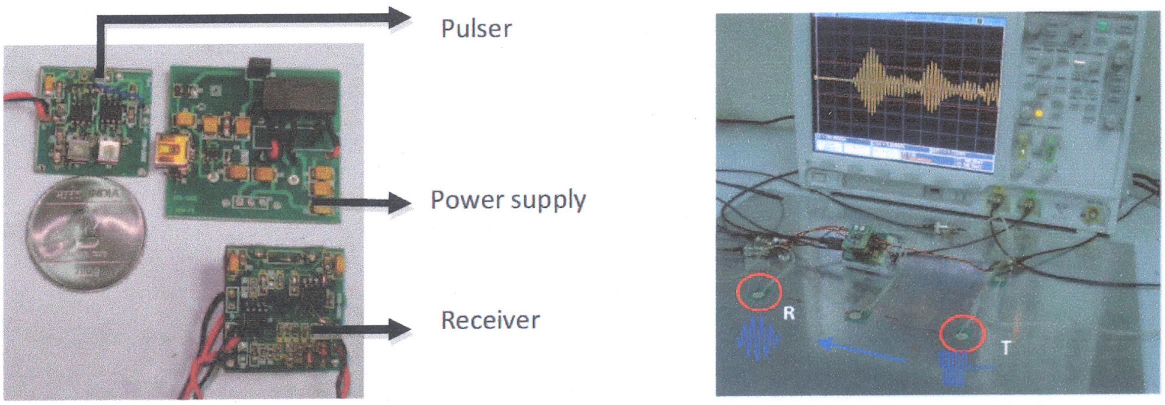
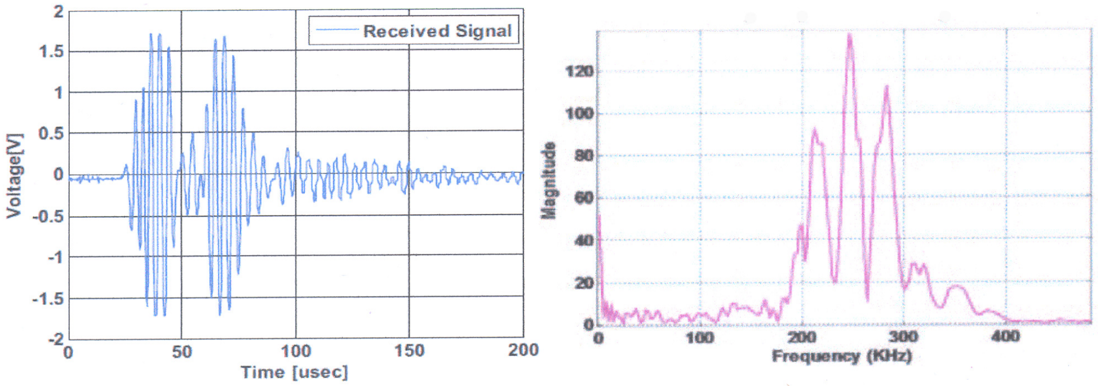


Fig.1 Shows Construction of Smart Flexible Piezo Sensor (SFPS) Patches



(a) (b)

Fig.2 (a) Printed Circuit Board of Sensor Electronics and (b) Lamp Wave Experimental Setup



(a) (b)

Fig.3 (a) Received signal when PWAS is excited with a square-wave burst in a A1 plate having sensor placed at an distance of 150mm separation and (b) FFT of the received signal

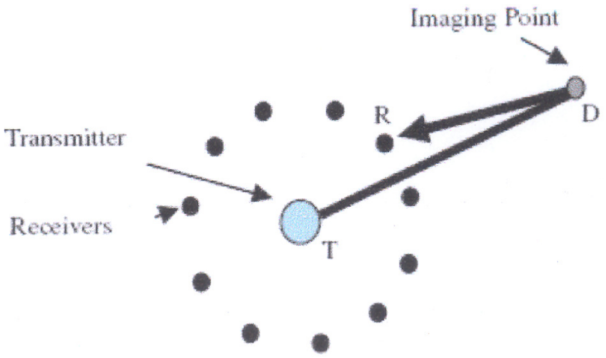


Fig.4 Schematic of Single Transmitter Multiple Receiver (STMR) Array System

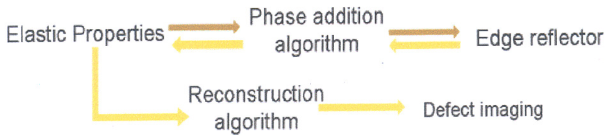


Fig.5 Received signal when PWAS is excited with a square-wave burst in A1 plate having 150mm sensor distance and its FFT

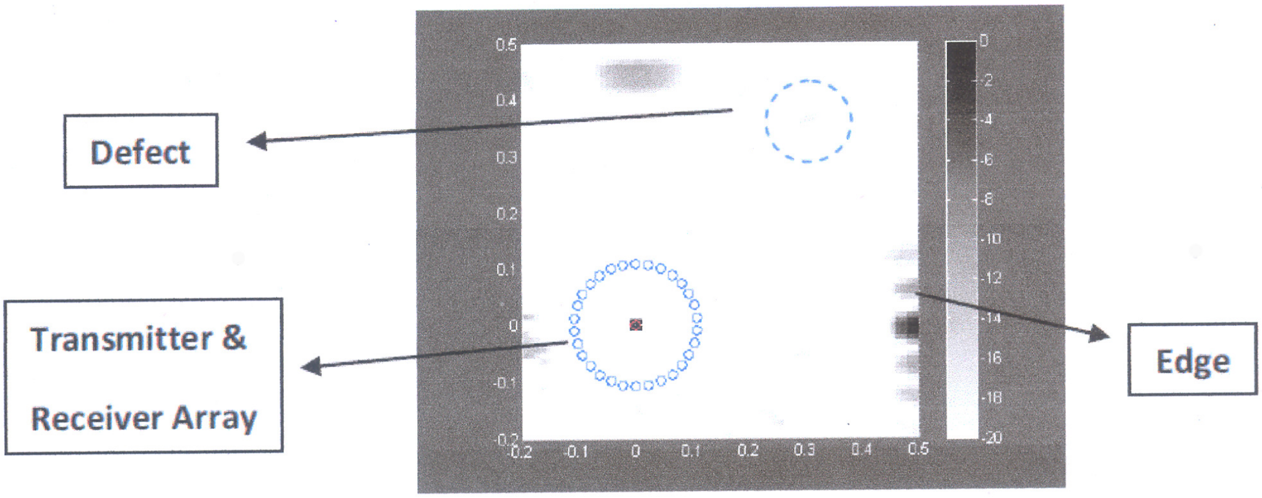


Fig.6 Reconstructed Image Using the Reconstructed Elastic Moduli