NUMERICAL AND EXPERIMENTAL STUDIES USING AIR-COUPLED SINGLE-SIDED L-SCAN FOR DELAMINATION SIZE DETECTION IN COMPOSITE STRUCTURES: LIMITATIONS AND RECOMMENDATIONS

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ABSTRACT

This paper describes applications of air-coupled ultrasonic imaging method based on Lamb waves for identification of delamination in flat composite laminates using single sided L-scan (Lamb wave scan). The air-coupled wave propagation problem in through transmission normal and oblique incidence methods is first studied numerically with FE model. The numerical observations were validated using experiments. The second part of the experimental study presents an imaging of delamination with single sided L-scan approach using fundamental A_0 mode. The limitations of L-scan method are discussed and recommendations to improve L-scan results are listed. A simple expression was derived to get actual size of the delaminations for L-scan images.

Keywords: Composites, Lamb waves, delamination

INTRODUCTION

Air coupled ultrasonics imaging (AUI) is emerging NDE technique for composite structures which works without need of mechanical contact, liquid coupling or without any surface preparation and hence is an excellent alternative for replacing current squirter based inspection system. Advances in piezocomposites transducer technology have further improved signal-to-noise ratios of air-coupled transducers leading to highly efficient transducer designs. In actual in-service applications most of composite structures have only single-sided access for inspection. Inspections by AUI currently make use of both side access and employs bulk waves. It is therefore of practical importance to develop methods for in-service inspection of defects in composite structures such as delamination using single sided inspections.

Air-coupled ultrasonic NDT using through transmission employing bulk waves have been widely investigated. Testing of very thin metal plate with air-coupled ultrasonic lamb waves was first described [1]. Using broad capacitive aircoupled ultrasonic transducer [2] far greater thickness plates can be inspected if exciting frequency of transducer matches the through thickness resonance plates. There is larger impedance mismatch between air and most solid materials in normal incidence through transmission compared to oblique incidence method through transmission. Hence recently oblique incidence has been employed in the inspection and imaging of composite has been demonstrated experimentally [3,4]. In a previous work of (Kundu et al., Chimenti D E et al.) have used single sided inspection of multilayered composites by immersion based $S_{0}$ mode Lamb wave scan. Castaings M and Cawely et al. were one of the first to address singled sided inspection of composites employing aircoupled transducers using $A_{0}$, lamb wave mode and the results were also validated with finite element (FE) model. Interaction $A_{0}$ Lamb wave mode with delamination was studied (Karthikeyan P, Ramadas C et al.) by numerical FE model, and delamination sizing can carried out by taking lines scan across the defects. In the present work air-coupled wave propagation problem in through transmission normal and oblique incidence methods is first studied numerically for finding through thickness resonance and variation of signal amplitude and validated using experiments. Secondly imaging of delamination with single sided L-scan approach using fundamental $A_{0}$ mode is studied experimentally.

NUMERICAL MODEL OF AIR-COUPLED OBLIQUE INCIDENCE METHOD

Oblique Incidence L-scan has been employed in the inspection and imaging of composite has been demonstrated experimentally [3, 4]. Finite element modeling was used to simulate ultrasonic wave propagation in plate and air. The modeling provided a prediction of the two-dimensional distribution of sound wave energy for every point in time that it is solved over. Output from the model can be a pressure history A-scan plot or contour plots of the distribution of the
propagating stress wave. This technique enables an exact replica of an experiment to be produced and the results can be visualized in a way that is not possible experimentally. The 2D plain strain model used for numerical simulations is shown in Fig 1. This was the basic model, and the only changes between models were made in thickness of the plates. For oblique incidence model, excitation angle depends on $A_0$ mode angle for a particular thickness of plate. Selection of the element size and time step size were selected as per Courant criterion. For the numerical model the input ultrasonic excitation (load) was applied on the on air wedge as a pressure load having a shape of a 7-cycle 200 KHz sine pulse with Hanning Windowed. The size of the element selected was 0.1mm in both air and plate material. The total element number for this model is 16lakhs. The time step used was 10 nano seconds. Time integration was carried out using explicit central difference integration scheme. In FE model, no damping was incorporated. Attenuation was not considered in numerical modeling. The maximum amplitude of the output pressure was obtained from location directly opposite side each plate model. Simulations are repeated for various thicknesses of plates. Similar simulation is also carried out on composite plates.

The results from numerical model are then compared with experimental data recorded. The trend of numerical estimations of increase in voltage in oblique incidence with respect to normal incidence is similar in agreement with experimental data recorded as shown in fig.2. Also as thickness of the plate increases, it deviates from numerical study. This may be due to attenuation not being taken into account in the model.

SINGLE-SIDE L-SCAN IMAGING

In the Single-side L-scan imaging transmitter and receiver are on the same side of the structure to be inspected. Transmitting and receiving transducers being oriented at the appropriate phase matching angle for the generation and detection of the $A_0$ mode; they are placed close together and raster scanned over the surface of the plate to produce an image called as L-scan [6]. Figure 3 showa and example of single side L-scan imaging.

PRACTICAL ISSUES WITH SINGLE-SIDE L-SCAN IMAGING

Single-side inspections have geometric restrictions on the transducers if not taken care may result in merging of nearby defects causing overlap as shown in figure 3(b) also avoid
interference with direct air signal. The interference of direct air signal and Lamb wave signal from the plate is illustrated in figure 4 are due the effects introduced by the finite size of the real transducers, separation between the two transducers, frequency of transducer, and liftoff. Currently commercially available lower frequency air-coupled transducers are large in diameter, which does allow the transducer to bring it closer. The low frequency of transducer has longer pulse length duration in received signal which invariably interferes with the direct air path. Lift off of the transducers increases the chances of direct surface reflection from plate to interference with the guided wave signal through the composite plate. These geometric restrictions on the can overcome by choosing following parameters given in table 1 and scanning carried out using these points are shown in Fig. 5.

Table 1: Practical recommendations for carrying out single-sided L-scan for thin composite laminates of less than 5mm thickness

- Selection of transducer having minimum diameter 15mm
- Minimum transducer separation distance
- Higher frequency transducer 400KHz or 500KHz
- Minimum lift off less than 5mm

**SIZING OF DELAMINATION IN SINGLE-SIDED L-SCAN IMAGING**

The delamination sizes in singled sided L-scan image are stretched in the scanning direction due to finite transducer
Fig. 5: Schematic of transducer configuration with air-coupled ultrasound (a) through transmission (b) L-scan with small diameter 500 KHz transducers (c) C-scan (b) single side L-scan with delaminations well separated.

Fig. 6: Imaging with air-coupled ultrasound composite plate (0/90/90/0) with 50mm delamination width (a) Normal incidence through transmission C-scan (b) single side L-scan image having larger size

separation distance. The sizing of imaged delamination is more cumbersome than in through-transmission. An accurate determination of the delamination needs some mathematical reduction.

Actual size of delamination in the above figures can be expressed as follows.

\[ S = P + D - d_a; \]  

Where \( d_a = \frac{1}{2}(d_1 + d_2) \)

where, \( S \) = Size of delamination in L-scan, \( P \) = probe separation distance, \( D \) = Actual size of delamination, \( d_a \) = average diameter of probes and \( d_1 \) and \( d_2 \) are probe (transmitter and receiver) diameters. Hence the size of the delamination by L-scan in Figure 7(b) is 85 mm instead of actual size of 50 mm. Actual size can be found by substituting the values transducer diameters \( d_1=13 \) mm \( d_2=9 \) mm below

\[ 85 = 44 + D - \left(\frac{13+9}{2}\right) \]

\[ D = 85 - 44 + \left(\frac{13 + 9}{2}\right) = 52 \text{mm} \]
SUMMARY AND CONCLUSION
For understanding the variation in amplitude of received A-scan signal, normal incidence and oblique incidence L-scan finite element simulations were carried out. It was shown numerically that oblique incidence gives higher amplitude in plate having smaller thickness. Near through thickness resonance of the plate the amplitude of the received signal increases in normal incidence thickness. This was validated experimentally. It was observed that delamination size in single sided L-scan is strongly affected by the many factors. A simple expression was derived to size the delaminations. Using the proposed correction equation identification of delamination size is possible. The predicted delamination sizes were found to be in good agreement with the actual delamination sizes. Thus experimental results show that the air-coupled single sided L-scan is reliable for characterizing delaminations and holds considerable promise in diagnosing delaminations in thin composite materials. These results encourage the development of single sided air-coupled inspection approach for in-service inspection thin composite structures.

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