Lamb Wave Based Damage Detection In Composite Laminates

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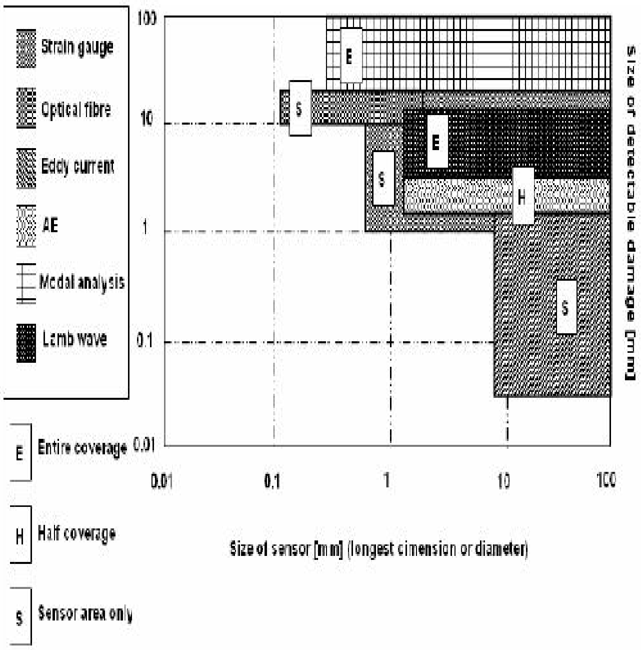
Abstract- *This study contributes to the efforts being made in the development of an online structural health monitoring system to detect the presence of the damage, its location, and severity in a composite structure using Lamb waves, which finds application, especially in dealing with aerospace structures. In this work, we try to explore the damage-recognition in multi-ply composite laminates using guided waves as they are instrumental in identifying and localizing damages. The finite element model of an eight-ply composite laminate is made with proper boundary conditions in 'ABAQUS/CAE 6.14.2'. An experimental study is done using an arbitrary function generator, amplifier, PZT sensor array, DAQ card, and an integrated oscilloscope with a tone burst input signal. As a part of this work, a newly introduced damage identification methodology is tested, which aims to deal with the limitations of the delay-sum-algorithm in the presence of variation in operating conditions like temperature. The concept of similar paths and time of flight are used in the study. A damage residue calculation is done to find out the damage location and severity by analyzing response data obtained through the Finite element model. The variation of Lamb wave characteristics with the change in the direction of propagation in anisotropic material is studied and analyzed.*

Keywords- ABAQUS; Composite laminate; Damage localization; Lamb Waves;Signal Processing;Structural health monitoring

I. INTRODUCTION

In recent years different specialized applications in civil, mechanical, and aerospace fields are widely adopted using light materials with excellent material properties. It created a need to improve material properties and reduce total weight. Thus, composite materials are developed to combine different desired properties of the elements to enhance the useful material properties. Nowadays, composites are very popular among various sectors like marine, automotive, civil. The use of composites in aerospace applications is fast, replacing the traditional material due to their high strength and stiffness to weight ratio.Moreover, composites have higher corrosion stability. The aerospace market is one of the most important to the composites industry. However, the anisotropy in physical and mechanical properties resulted due to fiber reinforcements, and the presence of laminates is also high. The damage and failure of metallic structures are well understood, but damage in composite materials happens in more ways than in metals [1]. Thus, to make sure of the reliability of the composite structures under various operating conditions is a challenge.

The usage of NDT methods to analyzelarge structures is a time-consuming and costly option. Also, NDT methods followed today are not capable of achieving in-situ damage identification. Thus, conventional NDT techniques are improved to make online damage identification, which is now better known as structural health monitoring (SHM). The basic idea is to get the response of the part to a known input, process the response, and then analyze it to extract the features introduced due to the presence of damage. Then identify the relation between those features and damage attributes through a physical setup or by using data-driven statistics. A sound SHM system can predict the remaining life span of the structure. Therefore, efforts are being made to create a reliable SHM system that can detect the presence of damage, its position, and level of severity in composite structures.



Comparison of damage detection methods; minimum size of identifiable damage vs. size of the transducer[3]

II. LITERATURE SURVEY

Fundamentals and theory

This section reviews the fundamentals of propagation of Lamb wavesfor use in structural health monitoring.

Propagation of waves in the free space is simple because gases can't support shear forces. Therefore, sound waves propagate as a longitudinal wave. The wave consists of compressions and rarefactions, so wave motion depends upon the bulk modulus of the gas (*B*). The velocity of such waves can be calculated by,

$$c = \sqrt{\frac{B}{p}} \tag{2.1}$$

Similar kind of relation for longitudinal waves in solids exists, with Young's modulus E instead of B,

$$c = \sqrt{\frac{E}{p}} \tag{2.2}$$

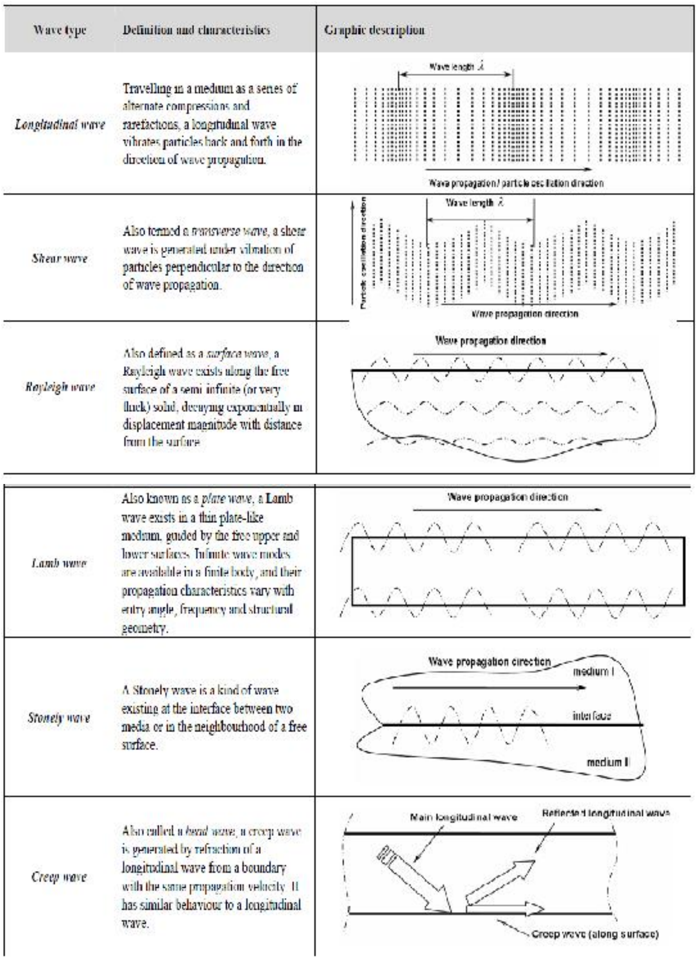
But this is correct for axial propagation in thin rod only. As solids allow shear forces, flexural waves can also exist. In this situation, one of Lamé constants μ (shear coefficient of rigidity) becomes significant, and velocity of a flexural wave can be given by,

$$c_t = \sqrt{\frac{\mu}{p}} \tag{2.3}$$

Transverse rigidity makes the solid stiff and causes an increment in the velocity of longitudinal waves,

$$c_l = \sqrt{\frac{\lambda + 2\mu}{p}} \tag{2.4}$$

As $\lambda + 2\mu = E + 2\lambda\gamma$. Where λ and μ are the Lamé constants (λ = Ev/((1−2v)(1+v)) and μ = E/(2(1+v)) and γ is Poisson’s ratio. Some crucial points can be noted here- an unbounded medium supports the propagation of two different non-interacting sound waves, in the presence of a surface, these waves will result in interference- caused because of including boundary conditions [7]. Secondly, wave velocities are not dependent on the frequency of the wave (*nondispersive)*. Thirdly, as the structure considered is not finite, the velocities don’t depend on the geometry but only on material properties. Lastly, the material constants shown here are valid for an isotropic medium, and so velocities are independent of the propagation direction. In general situations, one or more of these statements may be not true. The case is more complicated in a bounded medium. Depending on the geometry of the structure, several types of wave motion are possible.



Wave type	Definition and characteristics	Graphic description
Longitudinal wave	Travelling in a medium as a series of alternate compressions and rarefactions, a longitudinal wave vibrates particles back and forth in the direction of wave propagation.	
Shear wave	Also termed a *transverse wave*, a shear wave is generated under vibration of particles perpendicular to the direction of wave propagation.	
Rayleigh wave	Also defined as a *surface wave*, a Rayleigh wave exists along the free surface of a semi infinite (or very thick) solid, decaying exponentially in displacement magnitude with distance from the surface	
Lamb wave	Also known as a *plate wave*, a Lamb wave exists in a thin plate-like medium, guided by the free upper and lower surfaces. Infinite wave modes are available in a finite body, and their propagation characteristics vary with entry angle, frequency and structural geometry.	
Stonely wave	A Stonely wave is a kind of wave existing at the interface between two media or in the neighbourhood of a free surface.	
Creep wave	Also called a *head wave*, a creep wave is generated by refraction of a longitudinal wave from a boundary with the same propagation velocity. It has similar behaviour to a longitudinal wave.	

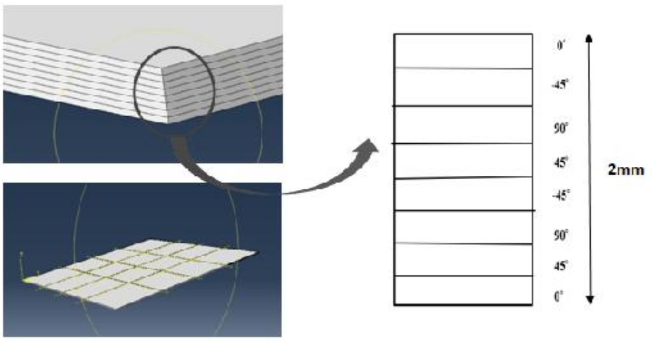
Figure1:*Types of wave motion possible*[7]

III. MATERIAL AND METHODOLOGY

The material used for the present study is composed of glass fiber, multi-ply, and multi-axial non-crimp fabric (NCF), with a reinforcement architecture. The fabric reinforcement has an area density of 1.90 kg/m^2 and a ply thickness of 1mm. The composite layup consists of two such fabrics [0/-45/90/+45/-45/90/45/0], which is a non-symmetric layup. The properties of the glass fiber lamina used in the simulation are given in Table [3.1]

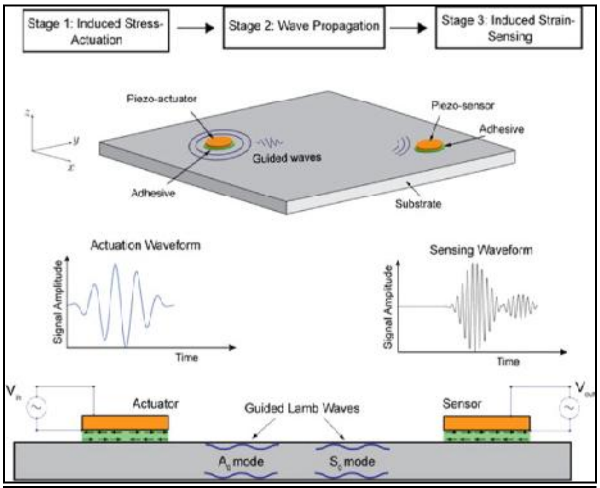
Mechanical properties of composite plate used in the study

Parameter	**Engineering Constants**	**Unit**	**Value**
longitudinal modulus	E1	GPa	38.8
transverse modulus	E2, E3	GPa	10.9
in-plane shear modulus	G12, G13	GPa	4.6
out-of-plane shear modulus	G23	GPa	5.3
poisson's ratio	v23		0.25
through-thickness Poisson's ratio	v12 , v13	-	0.26
longitudinal tensile strength	σ_{1t}	MPa	599
longitudinal compressive strength	σ_{1c}	MPa	442
transverse tensile strength	σ_{2t}	MPa	53
transverse compressive strength	σ_{2c}	MPa	137
shear strength	T	MPa	51.4
Density	P	kg/m³	1.87



Piezoelectric transducers

A piezoelectric lead zirconatetitanate (PZT) wafer/element activates and receives lamb waves through in-plane strain coupling [2]. It offers a higher frequency range with low power consumption, low acoustic impedance, and low cost. Moreover, they can be integrated into host structures very easily. Further, a sensor array for multi-point measurement can be achieved using many PZT sensors. They are very robust but may exhibit nonlinear behavior under large strains or when operating under high temperatures. The weak driving force, brittleness, and presence of multiple wave modes also narrows down its application. For avoiding the brittle nature of PZT ceramic and to get a better surface-conformability, glass powder and piezoceramicfiberisincluded in an epoxy resin forming poled film sheets.



Research Gaps

After reviewing the literature, the following research gaps are observed-

- Most of the numerical simulation-based study didn't account for the anisotropy and multiple plies of the composite. Various assumptions, like 2-D space or direction independent velocity, or free-free boundary conditions, restrict the previous studies.
- In the last few years, efforts have been made to incorporate a lamb wave-based structural health monitoring system on real-life applications. But it requires more improvement, to adapt it for large and complex structures like aircraft structures, piping systems, etc.
- Even though some baseline free methods exist for damage identification, the operational and environmental conditions affect their reliability. Thus, an improved method free from these factors is required.
- Most of the researchers based their studies on isotropic or quasi-isotropic materials. Very few works are found on the application of Lamb waves in anisotropic materials having no symmetrical configuration.

Research goal and objectives of the study

The research goal of this study is to understand, model, and identify the lamb wave fields in laminated composite plates excited by surface stresses.

Objectives of this study are-

1. To develop a 3D FEM model of a thin multi-ply composite plate with proper boundary conditions and perform numerical simulations of Lamb wave propagation
2. To confirm the efficiency of similar path methodology to detect the presence and extent of damage, based on the simulated response data and experimental data.
3. To perform Lamb wave-based damage localization, to point out the location of arbitrary structural damage effectively using the delay-sum algorithm

IV. SIMULATION AND EXPERIMENTAL STUDY

Modelling of Composite Plate

Propagation of Lamb waves is simulated in a multi-axial cross-ply laminate using a numerical model. The simulations are done using the FEM in ABAQUS/Explicit. Eight-node linear brick elements (C3D8R) with reduced integration and hourglass control are used to model the 3D composite laminate (540mm*540mm*2mm), a square plate consisting of 8 layers, as shown in fig [1]. The stacking sequence of the laminate is multi-ply multi-axial, [0/-45/90/+45/-45/90/45/0], which is a non-symmetric layup. The properties of the glass fiber composite used in the simulation study are given in Table [1]

Material property inputs used in the simulated model

E_{11}	E_{22}	E_{33}	v_{12}	v_{13}	v_{23}	G_{12}	G_{13}	G_{23}	ρ
(Gpa)	(Gpa)	(Gpa)	-	-	-	(Gpa)	(Gpa)	(Gpa)	(Kg/m^3)
1.09E+10	3.88E+10	3.88E+10	0.26	0.25	0.25	4.6E+09	5.3E+09	5.3E+09	1870

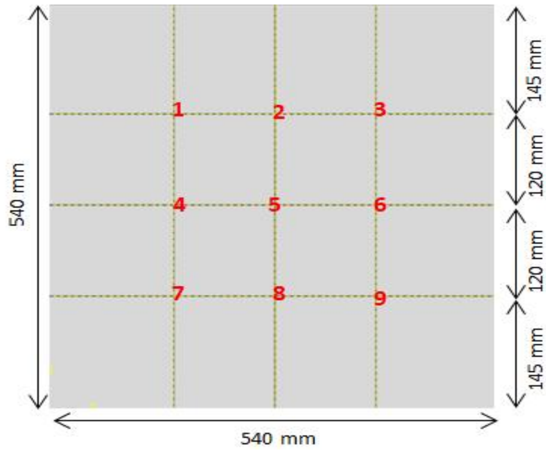


Figure1: *Healthy plate with dimensions modeled in ABAQUS*

The plate is modeled with appropriate boundary conditions, as shown in fig [2].

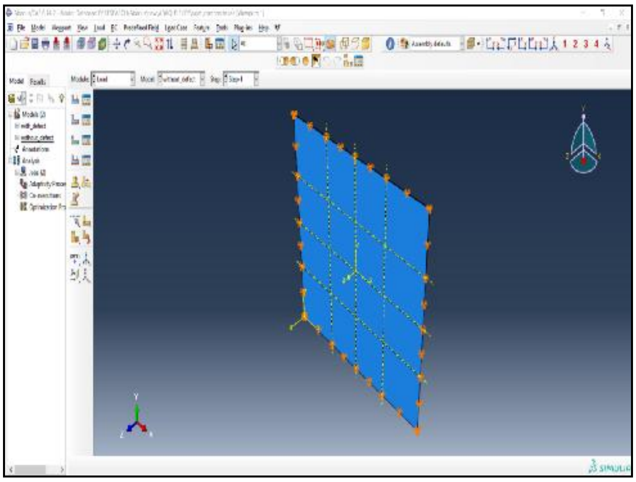


Figure2: *Screenshot of ABAQUS window*

Experimental Setup

The experimental setup for the present study is shown in fig.[5] consists of HMF2525 arbitrary function generator for signal generation, a LE150/100-EBW high power amplifier for the amplification, circular PZT-5H transducer discs, and PCI-5105 NI-Card for data acquisition.

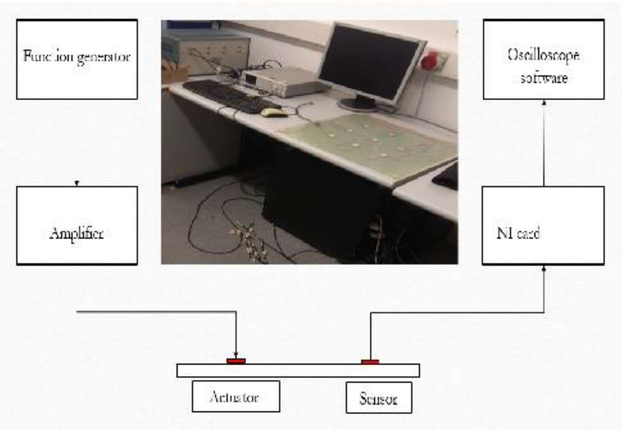


Figure5: *Schematic & experimental setup used in the study*

The glass fiber composite plate consists of eight unidirectional non-crimp fabric (NCF) layers with layup[0/-45/90/+45/-45/90/45/0]. The dimension of the plate is 540mm*540mm*2mm. The sensor network has nine circular piezoelectric transducers (PZT-5H) having 25mm dia and 1mm thickness. Transducers are attached on the surface in the center using epoxy resin with glass powder, as shown in fig.[6]. Eachtransducer is placed on the same plane with the separation of 120mm in both X and Y direction. The inspection area covered by the transducers has a dimension of 240mm*240mm.

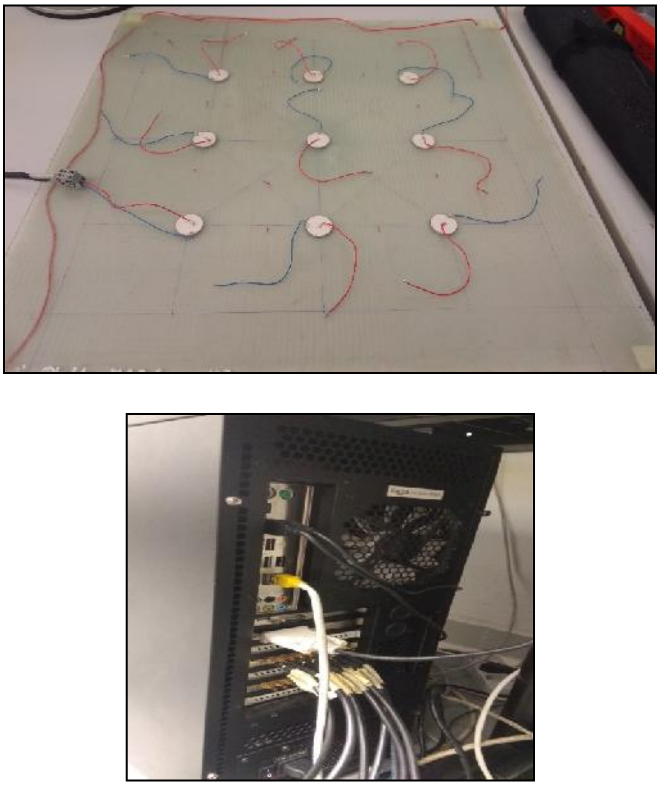


Figure6: *Plate with PZT sensors mounted on it and cables connected to NI-card*

V. RESULT

Different observations and results are obtained from the simulation study done in ABAQUS CAE. Some of them are very basic but important to mention as they make the background for further results.

Actuation Efficiency

All the numerical analysis depends upon the actuation of the correct wave in the 495nalyse495 plate because if the actuation signal itself is flawed, then further analysis using it will also be wrong. Thus, the input load or actuation signal obtained from simulation data is compared with the original input for actuation. Fig.[1] presents this comparison. A slight mismatch between the two waveforms can be seen from the figure, which is expected because discrete data is provided as the input signal; thus, it extrapolates or interpolates to cause this variation. Also, some pre-triggered values appear as a delay, but it is so small that it can be neglected without any loss of quality.

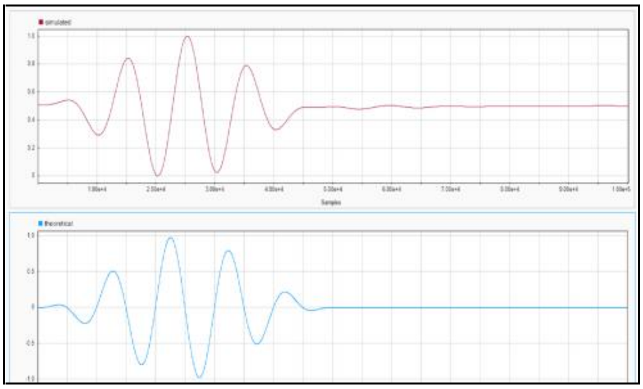


Figure 1: *Comparison of the theoretical and simulated actuation signal*

Multiple Wave Modes

As discussed in previous chapters, Lamb waves have three fundamental wave modes, namely symmetric wave mode (S_0), antisymmetric wave mode (A_0), and shear wave mode (SH_0) depending on the particle displacement. In ABAQUS, there is an option to 495nalyse the wave propagation in different directions separately. Fig.[2] shows the displacements amplitudes in specific directions.

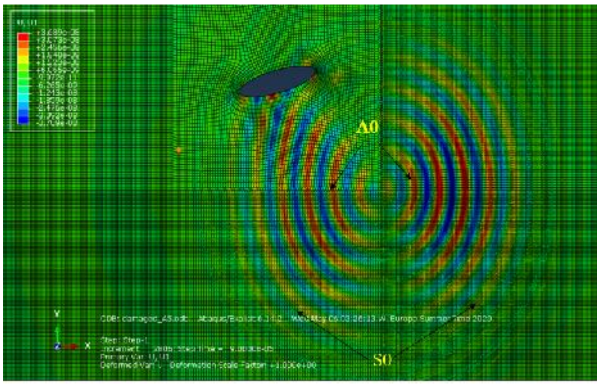


Figure 2: *(a) In-plane Displacement in the direction of propagation of the wave (U1)*

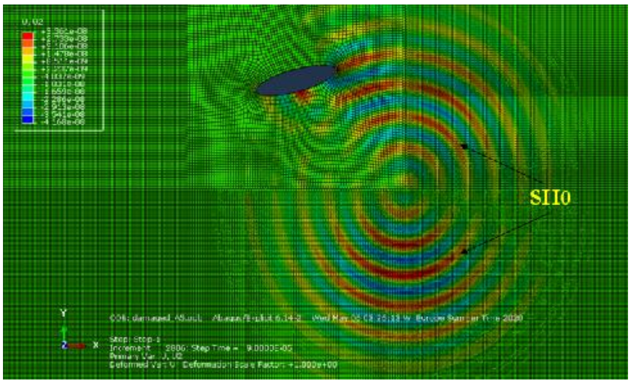


Figure2 : *(b) In-plane Displacement in the direction perpendicular to that of propagation of the wave (U2)*

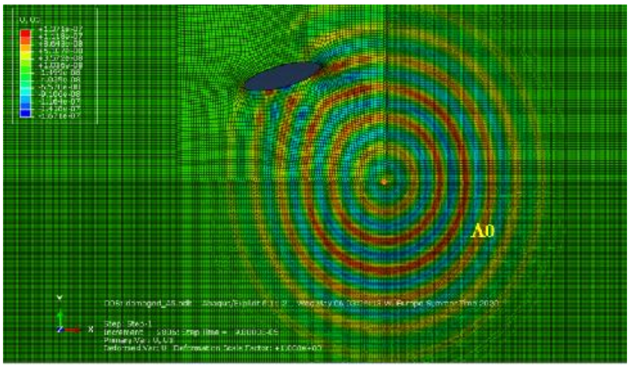


Figure 2:*I Out-of-plane Displacement (U3)*

Figure 2(a) shows the in-plane displacements. We can observe that both symmetric and antisymmetric modes are present. The amplitude of antisymmetric mode is more than that of symmetric mode. It is also seen that symmetric mode travels faster than the antisymmetric mode (velocity of S_0 is higher than A_0).

Figure 2(b) shows the shear wave mode propagation in the plane. The shear mode can also either be antisymmetric or symmetric to the middle plane. But exact mode cannot be identified by this figure.

Figure 2I shows the out-of-plane displacements or antisymmetric mode. The magnitude of amplitudes is higher for this case. The elliptical wave-front is also observed due to anisotropy in the plate. Antisymmetric mode (U3) displacements are used for the analysis in this study due to their strong amplitudes. But faster attenuation of amplitude can also be observed from the figure.

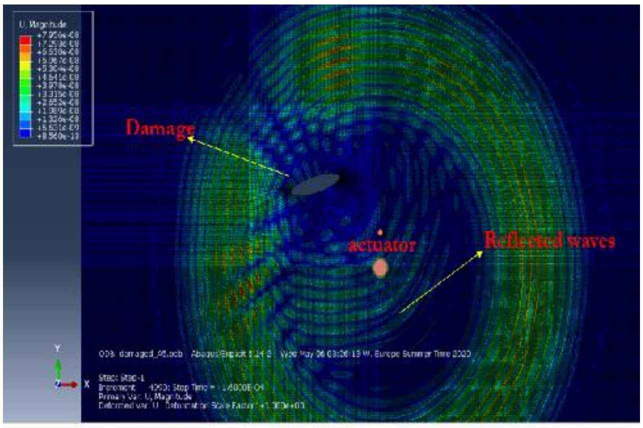


Figure 3: *Magnitude of displacement showing Actuated wave & damage scattered wave*

Fig. [3] shows the magnitude of displacement (i.e., U1+U2+U3). Waves actuated by the actuator and waves scattered from the damage can be seen clearly in the figure.

VI. CONCLUSION

The recent methodology for detecting damage with the help of the Lamb wave is tested and illustrated in this study. The study started with discussing the fundamentals of Lamb wave like phase and group velocity, dispersion curves, attenuation, different modes of propagation, and general characteristics equation. Then different parameters that influence the damage detection method are briefly discussed, like different transducer options, how to properly select the wave shape, number of cycles, frequency of the actuation signal, and the sensor network. Then, detail of numerical simulation study using ABAQUS/CAE is given with various experiments done during the study. Then the experimental setup used for the present study is introduced with an idea of the amount of manual work required to be done in collecting data and then processing it. Based on the various studies conducted, the primary conclusion drawn are mentioned below-

1) The dispersion curve is drawn from the response data obtained via numerical simulations in ABAQUS. The non-similarity between the two in magnitude is observed, indicating the limitation of the code

written. It works best for isotropic and transversely isotropic materials, but not for anisotropic materials.

2) Anisotropic material is used for the study, found out the directional dependence and its importance in damage localization study.
3) A 3-D FEM model is made in ABAQUS/CAE to simulate the lamb wave propagation in the multi-ply composite laminate. A convergence study is done to determine the best element size and time step for obtaining optimized results quickly. Different wave modes are identified and analyzed using simulations.
4) The efficiency of damage detection methodology is tested through various simulations performed and found out that it is robust and can be applied to compensate for variation in operating load and environment.
5) By using a modified Delay-sum-algorithm study is successful in obtaining the location of through-hole damage with reasonable accuracy. (<2% error)
6) Experimental work didn't turn out to be successful due to unforeseen circumstances, despite the various efforts made. Thus, only results based on simulation data are presented in the present study.

VII. ACKNOWLEDGMENT

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REFERENCES

[1] V. Giurgiutiu, "Lamb wave generation with piezoelectric wafer active sensors for structural health monitoring," *Smart Struct. Mater. 2003 Smart Struct. Integr. Syst.*, vol. 5056, no. March, p. 111, 2003, doi: 10.1117/12.483492.

[2] Z. Su, L. Ye, and Y. Lu, *Guided Lamb waves for identification of damage in composite structures: A review*, vol. 295, no. 3–5. 2006.

[3] S. S. Kessler, "In-Situ Damage Detection of Composites Structures using Lamb Wave Methods In-Situ Damage Detection of Composites Structures using Lamb Wave Methods Seth S . Kessler a , S . Mark Spearing a and Mauro J . Atalla b Massachusetts Institute of Technology EWSHM," no. June 2014, 2002.

[4] K. I. Ogurtsov, "Stress waves in an elastic plate," *J. Appl. Math. Mech.*, vol. 24, no. 3, pp. 640–652, 1960, doi: 10.1016/0021-8928(60)90171-4.

[5] D. N. Alleyne and P. Cawley, "The Interaction of Lamb Waves with Defects," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 39, no. 3, pp. 381–397, 1992, doi: 10.1109/58.143172.

[6] D. E. Chirnenti, "Guided waves in plates and their use in materials characterization," *Appl. Mech. Rev.*, vol. 50, no. 5, pp. 247–284, 1997, doi: 10.1115/1.3101707.

[7] J. L. Rose, *Ultrasonic guided waves in solid media*, vol. 9781107048. 2014.