Study on fundamental Lamb wave mode distortions generated using piezoelectric transducer

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Guided wave (Lamb wave) is an acoustic wave that propagates along a thin walled structure while guided by its boundaries. This wave can travel for a long distance without losing much energy. This type of wave reduces the use of sensors which are used to monitor the structure. The present study aims to develop detailed understanding of the nature of Lamb wave packet distortions when excited by piezoelectric wafer transducers directly bonded to the structure. Extensive 2D plane strain simulations are done to study the influence of the dynamics of the piezoelectric actuator wafers contributing to this phenomenon. To focus on the dynamic characteristics of piezoelectric wafer, a thermal analogy and coupled electro mechanical model are used to study the wave propagation characteristics. The results show that the dynamic characteristics of the Piezoelectric wafer are responsible for these experimentally observed distortion.

I. Nomenclature

A_0	=	Axisymmetric Mode
$CPE4E$	=	4-node Bilinear Piezoelectric Plane Strain [1]
$CPE4R$	=	4-node Plane Strain Element [1]
$CPE4RT$	=	4-node Bilinear Displacement and Temperature [1]
$CPS4R$	=	4-node Bilinear Plane Stress Element [1]
d	=	Piezoelectric Charge Constant
D	=	Dielectric Constant
E	=	Elastic Constant
FE	=	Finite Element
G	=	Shear Modulus of Elasticity
Nu	=	Poisson's Ratio
PWT	=	Piezoelectric Wafer Transducer
$PVDF$	=	Polyvinylidene fluoride
PZT	=	Lead Zirconate Titanate
S_0	=	Symmetric Mode

II. Introduction

ENGINEERING structures may degrade or become deformed over time. In many cases, this could endanger people that interact with the structures or could cause the structure to lose its original purpose. To ensure the functionality of the structures and the safety of its users, these structures can be monitored to predict their failure. With this warning, predictive maintenance can be performed or in case of a building, people can be evacuated. The practice of observing and analysing the material and geometric properties of the engineering structure over time is called structural health monitoring. Many methods have been developed to monitor many engineering structures remotely online. This study focuses on using Lamb wave-based damage detection techniques to monitor the uncertainty in the characteristics of the structure's elastic waves, which can be used as an indication of damage.

Most commonly used transducers are the PVDF and PZT wafer for the Lamb wave generation and sensing from these transducers, PZT wafers are low in weight, low cost and can be produced in different geometry and are also user

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friendly. Due to this advantageous features PZT wafers can easily be mounted on the surface of the structures and can be embedded in them. Also, PWT has been widely used for the Lamb wave generation and sensing, particularly for detection of the damage. Many of the Lamb wave-based methods use amplitude modulated sinusoidal signals as input, to generate and sense this type of the signals using PWT involve parameters like frequency, rage, amplitude, sensitivity, number of pulses, transducers size, shape window, amplitude sensitivity. From all these parameters, proper parameters are needed to be opted for the success of the Lamb wave generation and sensing in isotropic plates. Tuned wave generation with the PWT was given by Giurgiutiu [2]. All these studies guide us in identifying the frequency range for which the required Lamb wave mode is dominant.

As the wave number of the signal increases with the frequency which in turns reduces the spatial wavelength. Due to which it can be said that sensitivity of Lamb wave to damage size is dependent on its frequency content so having higher frequency is desirable. When the size of the damage is comparable to the wavelength, the sensitivity of the signal increases as the damage increases. In some damage detection techniques, they prefer to use the wavepacket shape as the indicator of the damage. So to reduce the jumbling of the signals the higher modes are avoided. The excitation of higher order Lamb waves are avoided by keeping the frequency value limited to the bandwidth of the fundamental modes S_0 and A_0. During the experiment it is observed that these fundamental modes S_0 and A_0 get distorted when the Lamb wave is excited and sensed using the PWT in there fundamental bandwidth. This phenomenon of the distortion cannot be explained using conventional dispersion characteristics of the Lamb wave. Also it is observed that there are additional wave modes close to S_0 and A_0. These additional waves can be wrongly interpreted as the damage in structure, so it is important to understand its behaviour in context of damage detection.

In this paper, the phenomenon of wavepacket distortion in PWT mounted on aluminium plates is studied. An undamaged plate attached to the transducer is used for the study during experimental generation and sensing. To understand the experimental observation, 2D FE simulations with the model of both the aluminium plate and the transducers are carried out. Simulations are done with two different models of PWT: thermal analogy model and the coupled electro mechanical model. Also, to understand the distortions of the modes, a modal analysis of the PWT is done. The results show that the presence of mode shapes occurring in the transducers may be responsible for the behaviour.

Table 1 Properties of Aluminium plate (Al-5052)

Modulus of Elasticity	70GPa
Poisson's Ratio	0.33
Density	2700 kg m^{-3}
Thermal Conductivity	237 W/mK
Specific Heat Capacity	0.91 J/gK
Coefficient of Thermal Expansion	$23.1 \times 10^{-6} K^{-1}$

Table 2 Properties of piezoelectric transducers SP-5H used for thermal analogy model

Density	7500 kg m^{-3}
Thermal Conductivity	2.5 W/mK
Specific Heat Capacity	0.45 J/gK
Coefficient of Thermal Expansion	$3.3 \times 10^{-6} K^{-1}$

Table 3 Properties of piezoelectric transducers SP-5H

Density	$7500 kg/m^3$
Electric Permittivity	
D_{11}	1.505×10^{-8}
D_{22}	1.301×10^{-8}
Elastic Constants	
E_1	6.061×10^{10}
E_2	6.061×10^{10}
Nu_{12}	0.512
Nu_{15}	0.512
G_{12}	2.350×10^{10}
G_{13}	2.350×10^{10}
Piezoelectric Constants	
d_{112}	7.41×10^{-12}
d_{211}	2.74×10^{-10}
d_{222}	5.93×10^{-10}

III. Experimental Setup

The experimental setup used for the generation and sensing of the Lamb wave is as same as shown in the **Figure 1**. An undamaged aluminium plate (AI-5052) is used as the specimen. The dimension of the plate is $700 \times 700 \times 2mm^3$ and the material properties are presented in the **Table 1**. The PWT A and PWT B which are used for the wave generation and sensing is done by the PZT SP-5H and the properties of the PWT are presented in **Table 3**. The dimension of the PWT $20 \times 20 \times 0.5mm^3$. The Hanning window of the sine wave of five cycle burst are generated using a signal generator. A digital storage oscilloscope is used to acquire the output signal. The signals that are obtained are subjected to electronic noise. This high frequency noise amplitude is smoothed in MATLAB with its built-in MATLAB function 'smoothdata' [3].

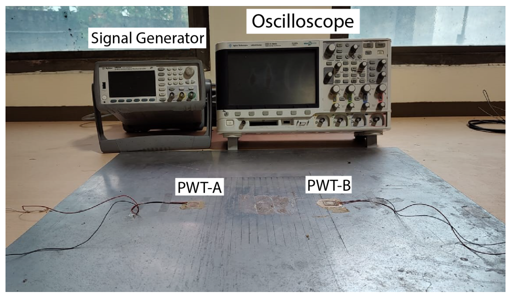


Fig. 1 Picture of Experimental Setup

IV. Experimental Study

Initially the experiment started by giving the input frequency as 120 kHz and then from there at equal intervals of 10 kHz we started observing the results till 260 kHz. For 120 kHz to 140 kHz, no distortions were observed as shown in **Figs. 2(a)** and **2(b)** but from 160 kHz a significant amount of S_0 and A_0 distortion were observed. These distortions are as shown in the **Figs. 2(c) - 2(g)**. These observation states that at certain input frequencies there are some distortion at S_0 and A_0 modes. These frequencies are strongly influenced by shape, size and type of actuator as specified in **Bijudas(2013)** [4]. Thus for better understanding of the phenomena it is essential to simulate the Lamb wave in thin aluminium plate using the PWT.

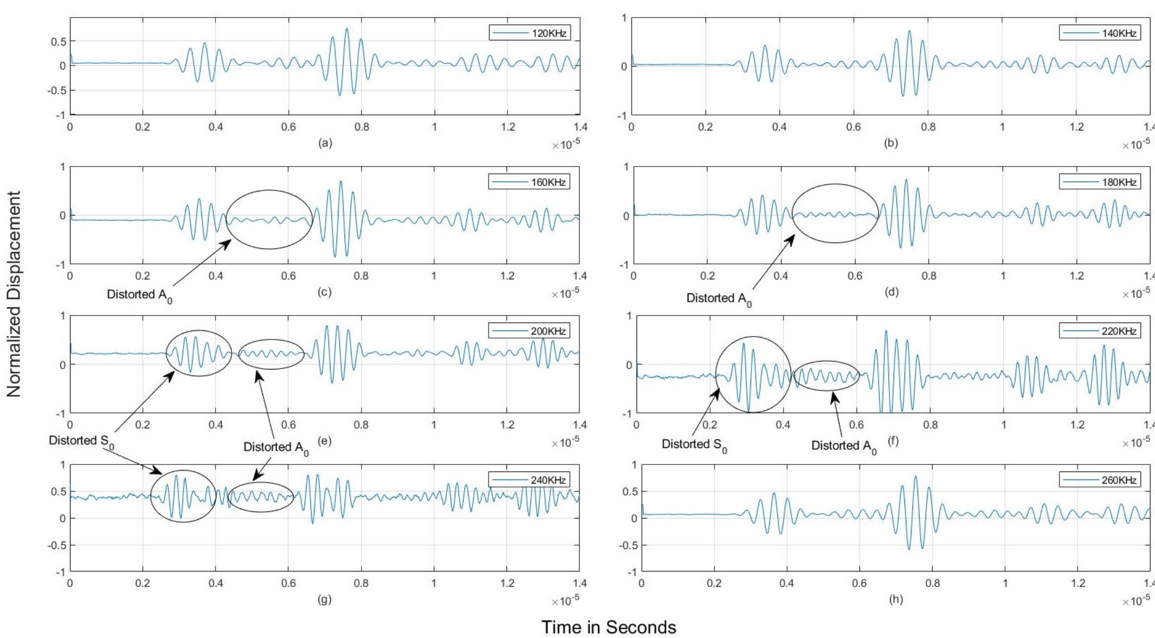


Fig. 2 Wave shape distortion in S_0 and A_0 modes at frequencies (a)120kHz, (b)140kHz, (c)160kHz, (d) 180kHz, (e) 200kHz, (f) 220kHz, (g) 240kHz and (h)260kHz

V. FE Simulation

A FE simulation is done to observe and understand the experimental behaviour of a Lamb wave passing through the aluminium plate. In this simulation, a 2D FE model of the plate thickness has been developed which is connected to a PWT. The PWT is mounted on the surface of the plate. This model is designed in ABAQUS. Two different modelling strategies namely thermal analogy model and the coupled electro-mechanical model is designed to capture the interaction of the PWT with the aluminium plate. Here the material properties of the aluminium plate and the PWT are same as used in the experimental case which are given in the **Table.1**, **Table.3** & **Table.2**. Here, modelling of a cross-section was done for an infinite plate and the PWT is also assumed to be having infinite length as shown in the **Figure 3**.

Due to high computation cost at high frequencies the 3D model FE simulation is not done here, though that might have given more closer results to the experiment. The aluminium plate is modelled using linear quadrilateral PLANE 4000 elements of type CPE4R and for the PWT modelling linear quadrilateral PLANE 29 elements of type CPE4E. Both of these are modelled in ABAQUS. For thermal analogy model, only the element type changes to CPS4R for aluminium plate and CPE4RT for PWT. The time period of the simulation is $200\mu s$ with a time step of $0.01\mu s$.

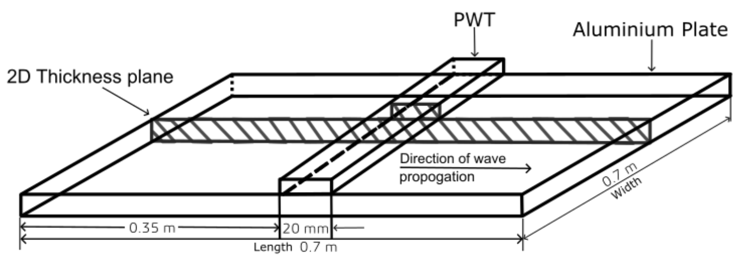


Fig. 3 Thickness plate used for 2D thermal analogy model.

VI. Thermal Analogy

The impact of the PWT dynamic participation and the impact of distributed strain actuation in the Lamb wave propagation are audited using a thermal analogy model. The actuator material used in this model has the same mechanical characteristics and properties as the piezoelectric transducers (**Table 2, Table 3**), these transducers thermally expand to simulate the actuation action. The shape of this model is same as shown in the **Figure 3**. The degrees of freedom are chosen in the x and y direction which are the temperature and the displacements. The simulation of this model can only be done by choosing the 'dynamic, temperature–displacement, explicit in the step option in ABAQUS. Here the PWT experiences the thermal expansion and contraction in response to the temperature change presented as an input signal. We have simulated the model at various input frequency from 180kHz - 260kHz. The results are shown in the **Figure 6**. Here the distance between the actuator and the sensing point is $0.17m$. The simulation seems to capture the distortion behaviour of the S_0 mode and some small amount of distortion in A_0 mode.

VII. Coupled Electro-Mechanical model

Here the coupled electro mechanical model is the plane strain model, the aluminium plate and the PWT are modelled as 2D plane as shown in **Figure 3**. Here the PWT is mounted on the surface of the aluminium plate and both are joined with the tie constraint. Here both the model has the plane strain element type but the PWT has a extra element type as piezoelectric which itself has a plane strain condition. This gives three degrees of freedom at each node which is the displacements in x and y direction and voltage. The top and the bottom surface of the PWT are modelled as the electrodes as the volt degree of freedom. Input is applied at the top surface of the PWT keeping the bottom surface as zero. The properties of the PWT are same as shown in the **Table 3**. For this 2D FE simulation we have choose the 'Dynamic Explicit' option as the step input which allows the user to give voltage as the input. The results are shown in the **Figure 5**. The simulation seems to capture the distortion behaviour of the S_0 mode and some small amount of distortion in A_0 mode.

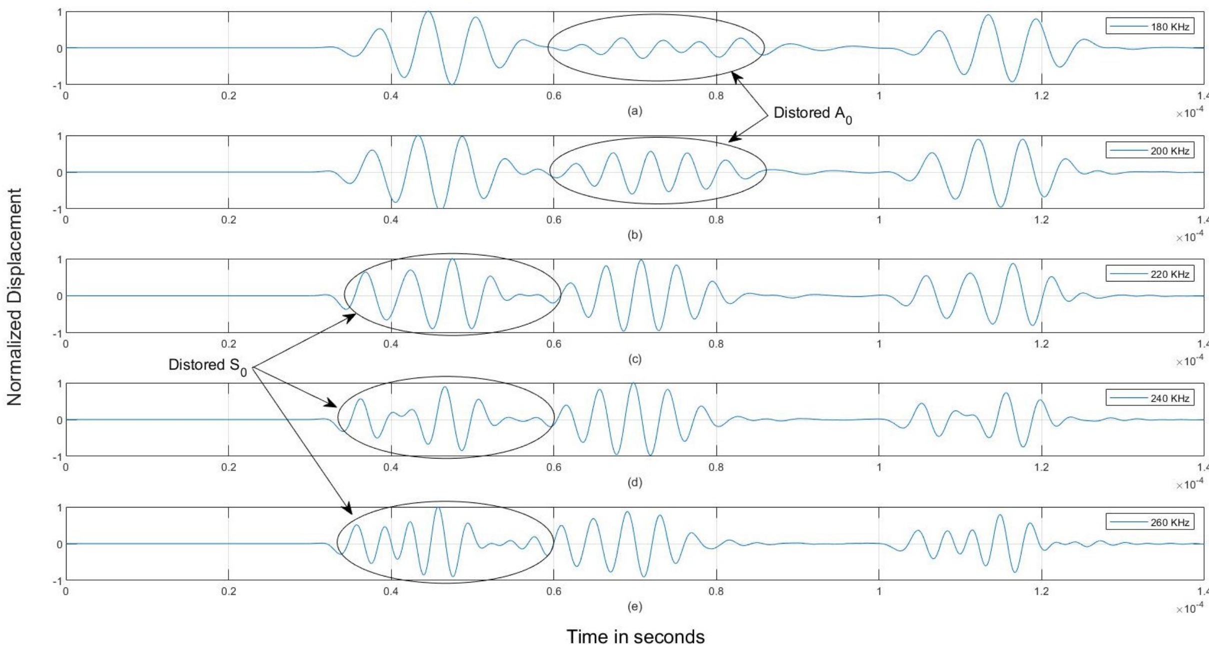


Fig. 4 Simulated Lamb wave in aluminium using the thermal analogy model at frequencies (a) 180kHz, (b) 200kHz, (c) 220kHz, (d) 240kHz and (e) 260kHz

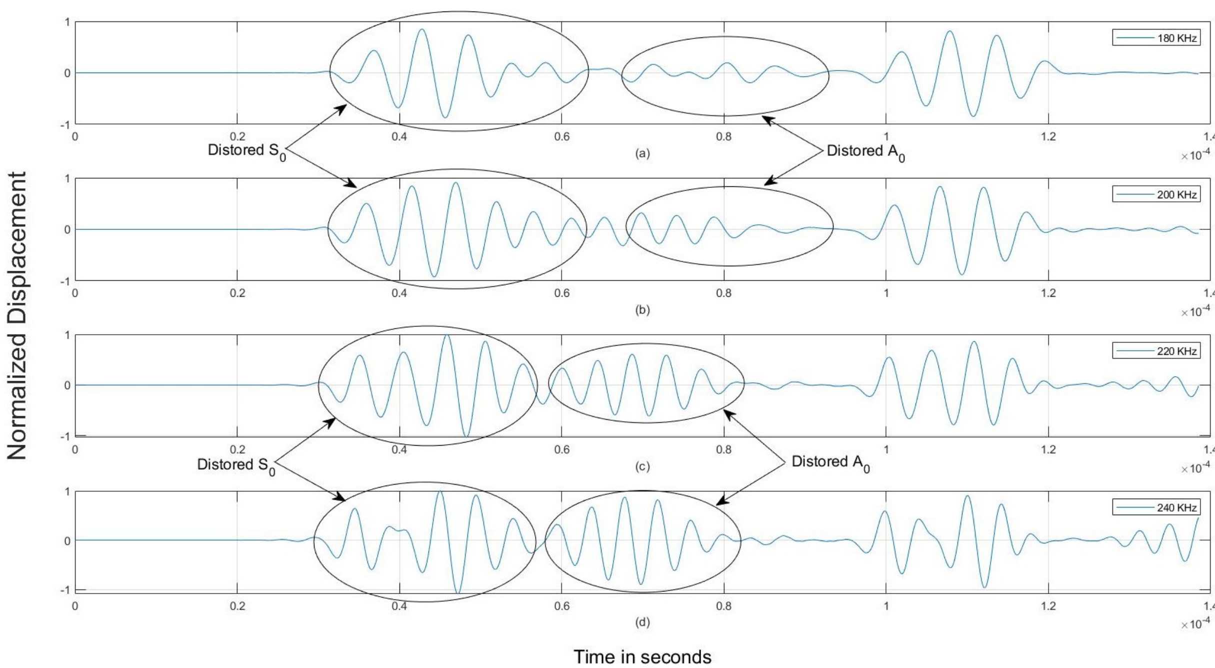
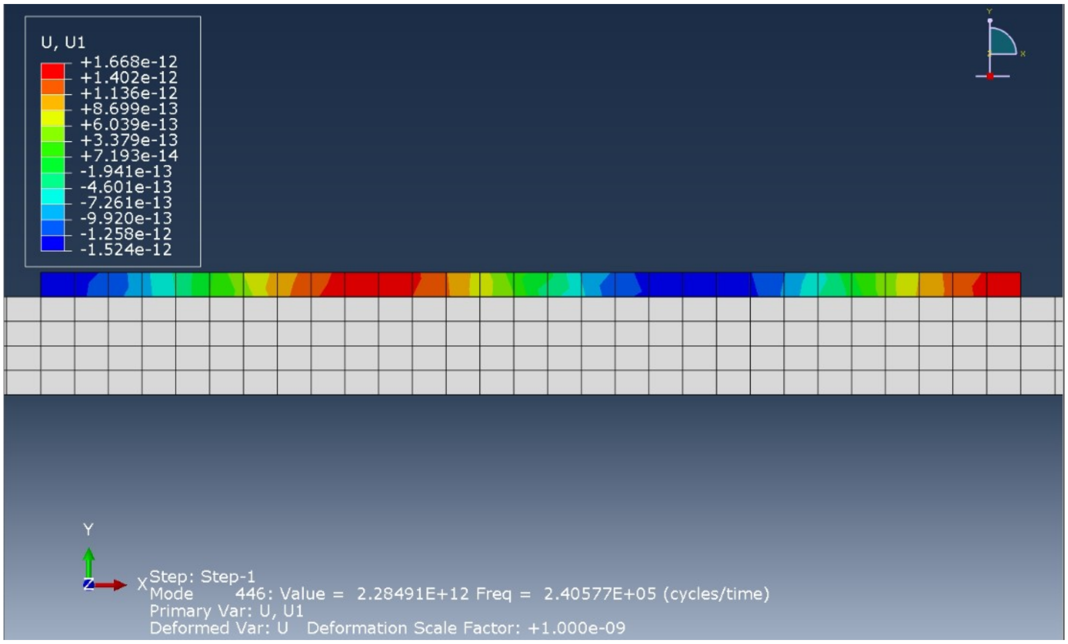


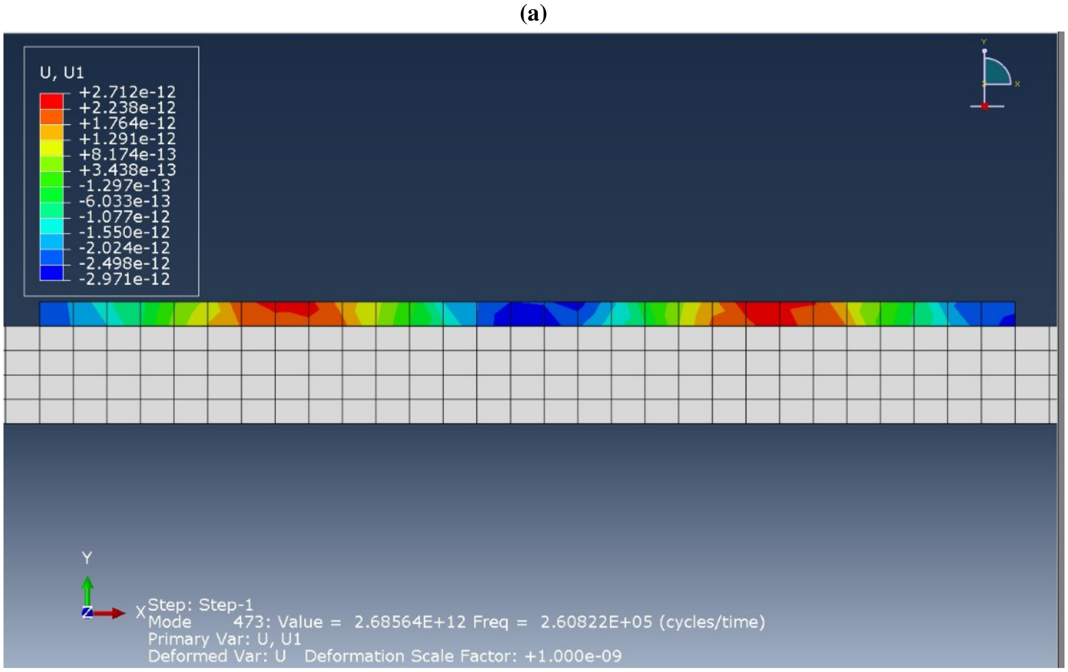
Fig. 5 Simulated Lamb wave in aluminium using the Coupled Electro-Mechanical model at frequencies (a) 180kHz, (b) 200kHz, (c) 220kHz, (d) 240kHz and (e) 260kHz

VIII. Modal Analysis

To find the reason of such behaviour of S_0 and A_0 modes, modal analysis of the PWT attached with the aluminium plate was performed. The linear perturbation option was used in static general as the Step in ABAQUS. Here the element type of the PWT as well as the plate is kept as plane strain model. The results show that at the frequency at which the distortion in wave packets were observed have higher width directional modes shapes in PWT. The results are shown in the **Figs. 6(a) & 6(b)**. From this it can be concluded that the distortions in the wave packet are generated due to the higher width directional mode shapes in PWT.



(a)



(b)

Fig. 6 Wave shape distortion in S_0 and A_0 modes at frequencies (a)240kHz and (b)260kHz

IX. Conclusion

Initially, through experimentation distortions in S_0 and A_0 modes of the Lamb wave were observed. These reponse were collected from the experimental setup as shown in **Figure 1**. It was also observed that additional new wave modes S_1, A_1..etc are appearing which are close to the S_0 and A_0 modes. The conventional dispersion characteristics of the Lamb wave were unable to explain the behaviour of this distortions. As these distortions were appearing even at the frequency ranges were S_0 and A_0 are almost non dispersive. The occured distortions are similar to the distortions observed in damaged structure. Thus, the distortions can be misleading and misinterpreted to a damage in the structure. In order to explain this behaviour, a 2D finite element simulation was performed in ABAQUS. Two different models namely the thermal analogy model and the coupled electro mechanical model are used to understand the role of the PWT in causing the distortion. It was concluded that the electro mechanical coupling effect was the reason for the distortions in **Bijudas(2013)**[4]. Finally, with the modal analysis of the PZT wafer transducer attached with the aluminium plate has been done and it can be observed that due to the higher width directional modes, these distortions are being generated.

Acknowledgments

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