Effect of Notch on Arrival Time of Lamb Wave in Plates of Different Thicknesses: A Simulation Study

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Abstract

Lamb wave is the kind of ultrasonic wave guided between two parallel surfaces. It is a special wave which acts like a standing wave in X direction and travelling wave in Y direction and is highly dispersive in nature. Due to these reasons, it has good capacity to scan a whole structure. This is why Lamb wave is used widely in structural health monitoring. In this work, we have studied on lamb wave propagation in isotropic aluminium plate using finite element simulation. It first consists of the convergence and validation of results on propagation of lamb wave in normal isotropic homogenous plate with varying plate thickness. Then we study the effect of presence of notch on time of arrival of lamb wave, that is, how much time it would take from start where it is excited to reach the end of the plate having the notch.

Keywords: Lamb wave, Isotropic plates, Notch.

1. INTRODUCTION

Guided waves are the type of waves which remain confined in structure and propagate through long distance with minimum energy/amplitude loss. These waves are extremely important for structural health monitoring systems due to their properties like they travel through long distance, remain confined in structure and they can also travel through curved walls. Lamb waves are the waves which is guided between two surfaces, upper and lower surface and during the propagation, show two types of mode shapes symmetric mode shapes designated as S_0, S_1, S_2…… S_n and antisymmetric mode shapes designated as A_0, A_1, A_2…… A_n. All of these mode shapes are present at different frequency-thickness product, but due to highly dispersive nature of lamb wave we are able to see zero order mode shape (S_0, A_0) mainly.

The zero-order mode shapes deserve special attention among all mode shapes because it is only mode shape which present at all frequency spectrum range from zero to high frequencies. At low frequency it is known as extensional mode which outline elastic stiffness and nature of motion that govern the propagation velocity. The zero-order symmetric mode shape at lowest frequency is called as extensional mode. As the frequency increases, the phase velocity drops and group velocity approaches towards a minimum and at this frequency each velocity converges towards the Rayleigh wave velocity.

The existence of lamb wave was first examined by Lamb [1], by using some Rayleigh wave equations developed by Rayleigh [2]. The lamb wave was mostly used in detection or quantification of damage. Toyamaa *et al* [3] saw that there was decrease in velocity of S_0 mode shape as transverse crack density increases. Then Yang *et al* [4] observed that the propagation of lamb wave was not much affected when stringer material and height kept same, but there were series of effects created on lamb wave when material and height were varied. Janarthan *et al* [5] used A_0 lamb wave mode shape for detecting the damage in stiffened composite panels and antisymmetric mode shape successfully detected the damage present in carbon-epoxy composites. Damages are present in different forms like cracks of different shape and size which is buried in the plate. Wan *et al* [6] used nonlinear lamb wave to detect the presence of micro crack in the plate. Elgamal *et al* [7] studied the arrival time of lamb wave with a different plate thickness like if we increased the plate thickness with increase in frequency of excitation then how much time the wave takes to reach from one point to another. Senyurk [8] extended this work and used lamb wave for detecting cuts and impact damages which generally occurred at the aircraft wing slat and also found out S_0 mode shape was more suitable for detecting impact damage than the A_0 mode shape. When the lamb wave comes in contact with a notch or crack, we can see the conversion of mode. Alkasam *et al* [9] studied the conversion of mode of lamb wave after interacting with a damage in thin plate. Zheng *et al* [10] extended the work on lamb wave by combining the lamb wave technique with electro – mechanical impedance for detecting the damage so that we can also get the characteristics property of damage. For finding the displacement of lamb wave there are number of theories which have been used. Orta *et al* [11] seen that higher order theory gave accurate results.

In the paper, Elgamal *et al* [7] studied the arrival time of waves in a standard isotropic plate with varying thicknesses of that plate. We extended the work by creating a notch, and its size is comparable to the thickness of the plate, see how much effect is created by a notch on the arrival time of wave. We have used a Finite Element Software Abaqus CAE to run the simulation. First, we validated the Elgamal *et al* [7] and then created a notch to study the wave arrival time further; the detailed procedure is given in the next section.

2. PROBLEM DEFINITION

In this work, a two-dimensional finite element simulation of Lamb wave propagation through isotropic Aluminium plates is carried out in Abaqus CAE. The dimension of the plate is considered to be 300 mm × (1.98, 2.64, 3.3) mm, as shown in Figure 1, with the latter dimension representing the thickness of the plate.

Figure 1. Geometry of Aluminium Plate

The material properties of the aluminium plate considered are as given in Table-1.

Table 1. Material Properties of Aluminium Plate (Elgamal et al [7])

Material	**Elastic Modulus, E (GPa)**	**Shear Modulus, G (GPa)**	**Poisson's Ration, υ**	**Density, ρ kg/m^3**
Al 2024-T3	73.1	27	0.33	2780

The excitation is carried out by lamb wave at 150 kHz excitation frequency using 5.5 bursts of sinusoidal wave in the time domain in which time is in second, as shown in Figure 2. The excitation pulse is given at the x=0 mm (where x is the distance measured length-wise) on the middle node in *the y direction*. At least one node has fixed boundary conditions to create

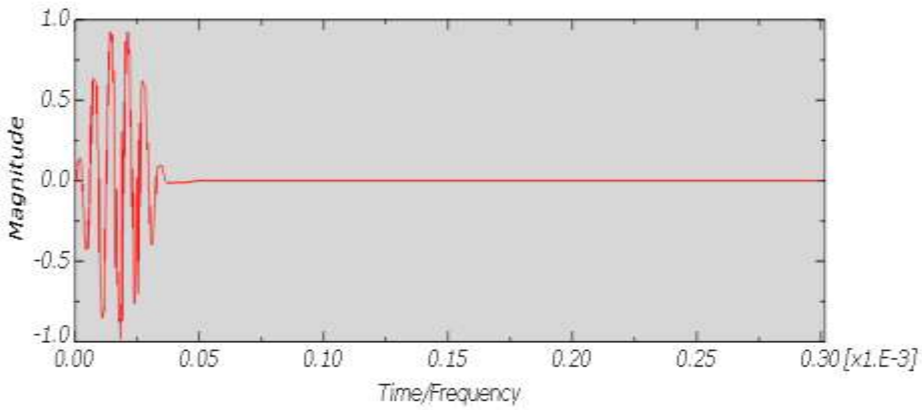

Figure 2. 150 kHz Actuator Signal in time domain

3. Results and Discussions

The results obtained from the stated finite element simulations are presented and discussed in the following sub-sections. It includes the convergence study regarding the effect of mesh density and validation of the time of arrival of wave in the isotropic plate. After that, the impact on the wave's arrival time with varying notch sizes in the isotropic plate is analysed.

3.1 Convergence and Validation Study

The simulation starts in a standard isotropic plate with a CPS4R element, a 4-node bilinear plane stress element, and a Quad-dominated (1×1) mm element shape size with a free type technique. As we decreased the element size, our result converged towards the solution. The time step is selected as 0.001 sec for completing the simulation in Finite Element Software because at this time step, we got a good agreement with Elgamal *et al* [7].

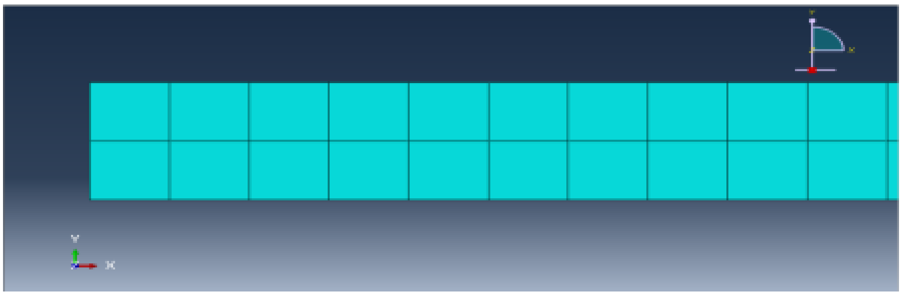

Figure 3. 600 Elements Quad- Dominated Mesh Element

Next the convergence study of the arrival time of lamb wave at receiver end follows, as in Figure 4.

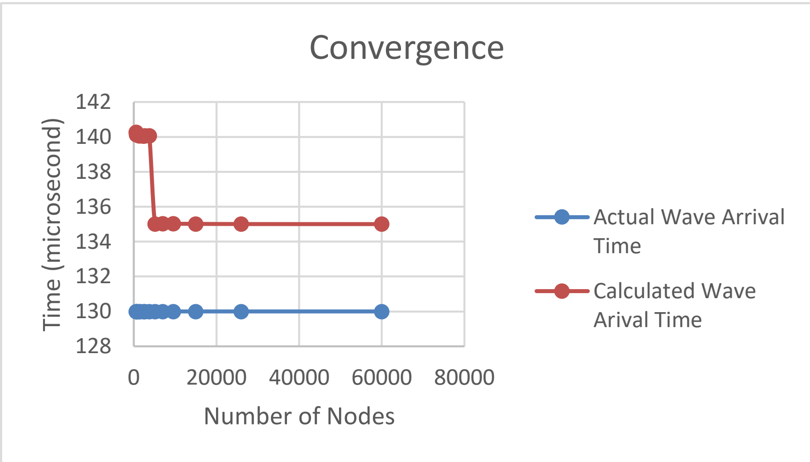

Figure 4. Graphical Representation of Convergence

The Table-2 shows the convergence study of the isotropic normal plate

Table 2. Convergence Study

Quad Element Size (mm)	Number of Elements	Actual Result (micro second) (Elgamal *et al* [7])	Simulated Result (micro second)	Error in Percentage
1×1	600	130	140.27	7.9
0.9×0.9	666	130	140.13	7.79230
0.8×0.8	750	130	140.18	7.83076
0.7×0.7	1287	130	140.06	7.73846
0.6×0.6	1500	130	140.07	7.74615
0.5×0.5	2400	130	140.04	7.7230
0.45×0.45	2668	130	140.06	7.7384

0.4×0.4	3750	130	140.07	7.746
0.35×0.35	5142	130	135.016	3.85846
0.3×0.3	7000	130	135.033	3.8715
0.25×0.25	9600	130	135.024	3.8646
0.2×0.2	15000	130	135.018	3.86
0.15×0.15	26000	130	135.006	3.85076
0.1×0.1	60000	130	135.004	3.8492

Now, based on this convergence study, the element size of 0.1 × 0.1 mm, is the best suited for meshing and is used for further simulations. Figure 5 shows the arrival of the wave at the end of the plate without notch.

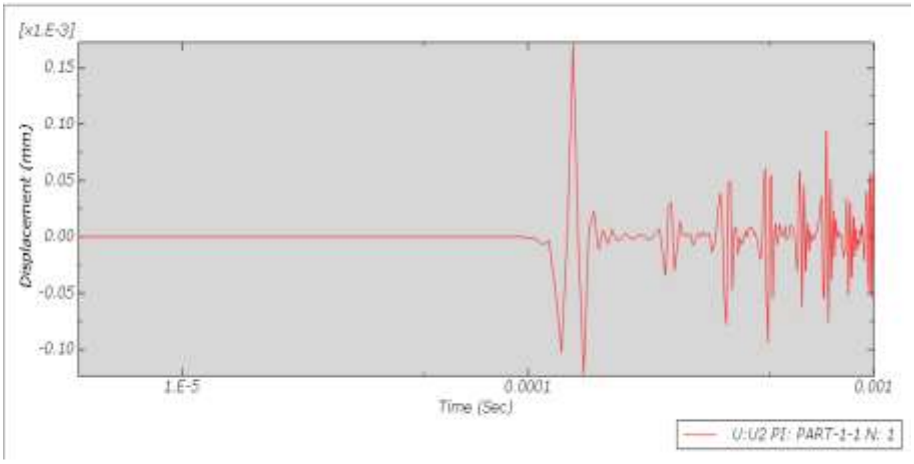

Figure 5. Wave Captured for 1.98 mm plate at Receiver end

After selecting the mesh size and done with all the algorithms, now we are moving towards the validation part here; the time of arrival of lamb wave for different plate thicknesses has been validated, as presented in Table 3.

Table 3. Validation of Base Paper (Elgamal *et al* [7])

Thickness of plate (mm)	**Actual Result (micro second) (Elgamal *et al* [7])**	**Simulated Result (micro second)**	**Error in percentage**
1.98	130	135.004	3.8492
2.64	125	125.013	0.0104
3.3	120	120.009	0.0075

3.2 Effect of Notch

Now we have created a notch having varying dimensions and are trying to see how much time it will take to reach from start point to endpoint. A circular notch is created at the centre of the plate with a starting radius of the notch is 0.3 mm, and its size increases with an increment of 0.1 mm till it is comparable to the thickness of the plate. Such a typical plate with a notch is shown in Figure 6.

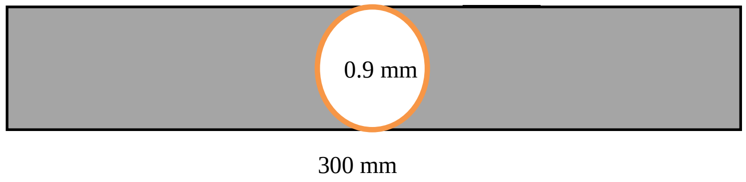

Figure 6. Isotropic Aluminium plate with notch

The wave arrival time for Plate thickness of 1.98 mm, with varying notch dimensions, are presented in Table 4.

Table 4. Simulated Result for Plate thickness 1.98 mm, with varying notch dimensions

Radius of Circular Notch (mm)	**Actual Result (microsecond)**	**Simulated Result (microsecond)**	**Error in percentage**
0.3	135.004	135.003	0.001
0.4	135.004	135.001	0.002
0.5	135.004	135.007	0.002
0.6	135.004	140.002	0.002
0.7	135.004	140.002	3.702
0.8	135.004	140.002	3.702
0.89	135.004	140	3.700
0.9	135.004	140	3.700

As we see from Table 4, if the size of the notch is comparable to the plate thickness, then it affects the wave arrival time of the lamb wave. Figure 7 shows the wave received at the plate end; wave arrival time is the first maximum displacement obtained at the plate end. Here as we see, if the circular notch dimension is about 0.9 mm, then the wave takes 140 micro-second, just a little more than a normal plate, which shows a circular notch creates a significant increment in wave arrival time.

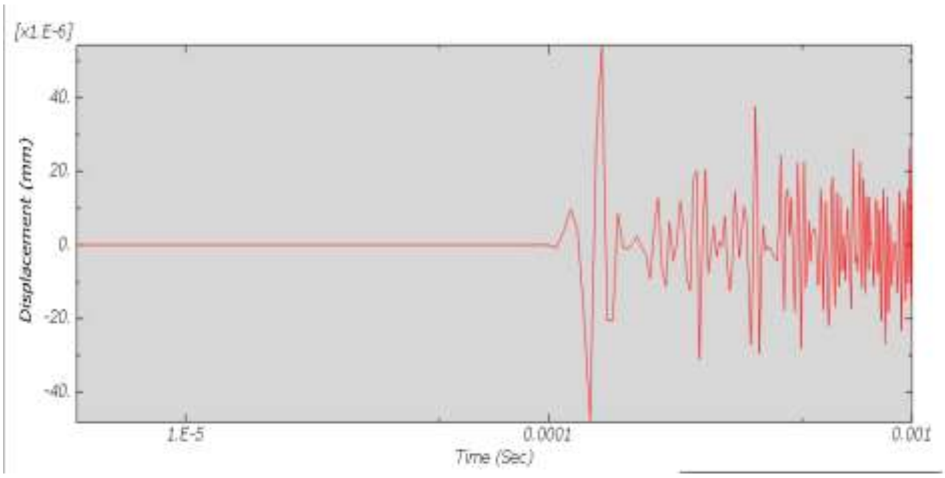

Figure 7. Wave Captured for 1.98 mm plate with notch at Receiver end

Figure 8 shows the wave arrival time for a 2.64 mm plate with a circular notch of the radius of 1.30 mm, so as discussed, for a 1.98 mm plate, it will produce little effect on the wave arrival time. This means if the notch dimension is approximately equal to the plate thickness, then it creates a significant effect on arrival time.

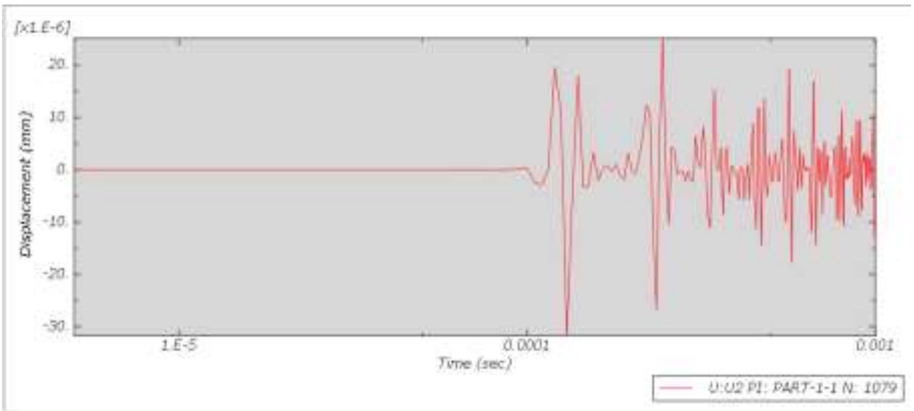

Figure 8. Wave Captured for 2.64 mm plate with notch at Receiver end

Figure 9 shows the arrival time for a 3.3 mm plate with a circular notch of radius 1.30 mm. The result shows more or less the same expected scenario as discussed in Figures 7 and 8. The wave takes more time to reach the receiver end, thereby indicating a significant effect on arrival time for thicker plates.

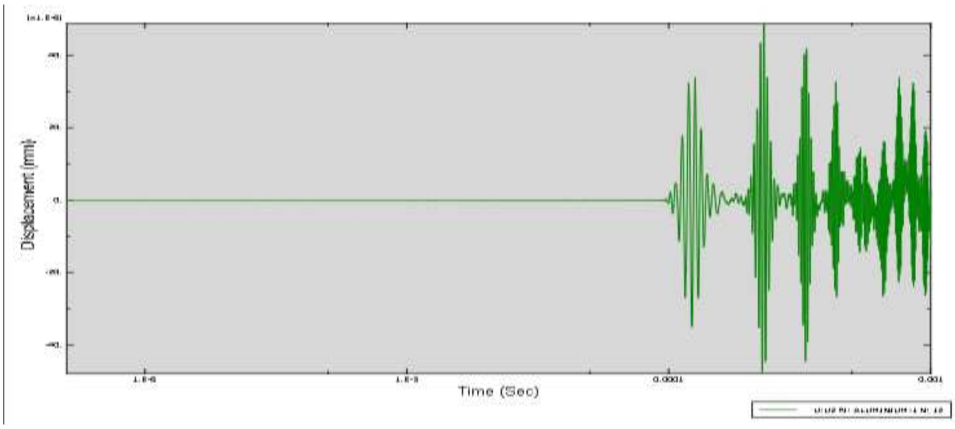

Figure 9. Wave Captured for 3.3 mm plate with notch at Receiver end

Table 5. Comparing the arrival time of wave propagating through normal plate and plate with notch

Thickness of plate (mm)	Radius of notch (mm)	Result of normal plate (micro second)	Result of Plate with Notch (micro second)
1.98	0.9	135.004	140
2.64	1.30	125.013	130.002
3.3	1.60	120.009	126.004

4. CONCLUSION

The results of wave propagation in a simple homogenous isotropic plate show the wave arrival time decreases as the thickness of the plate increases. For the notch section, if the notch size is not comparable with plate thickness, it will not affect wave arrival time. However, if the notch size is comparable with the plate thickness, it shows some effect on the wave arrival time of the lamb wave. So, we can conclude that whether it is a standard plate or a Plate with a notch, the wave arrival time decreases as plate thickness increases. One can also extend the work by increasing the number of notches, and varying the material property of the plate.

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