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Study of Multistage Damage Detection Method Based on Lamb Waves and Thermal Effect

Amina Saouab[1,*], Hajar Chouiyakh[1], Mustapha Faqir[1], Kenza Bouchaala[1], Fathi Ghanameh[1], Elhachmi Essadiqi[1]

[1] Université International de Rabat, Aerospace Engineering School, LERMA lab, Rocade Rabat-Salé, 11100 Sala al Jadida, Morocco

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ABSTRACT

Non-destructive testing has been implemented in many industries to ensure structural safety and reliability by detecting defects. In this study, Lamb waves are used for early damage detection and characterization. The aim of this research work is to develop a methodology for damage characterization (detection, localization, severity, and life estimation). Different problems associate with Lamb waves propagation as their dispersive behavior, and the effect of varying temperature on the amplitude and arrival time of the wave. Current study focuses on investigating the multistage damage detection method based on Lamb waves. It uses a network of transducers to improve damage detection and localization. It is aimed to validate the present technique by ellipse method to improve damage localization of the previously detected damages. To model the first stage of the technique, numerical simulations were performed on an 800x800x1.293 mm aluminum plate, using FE software ABAQUS explicit. Obtained signals from the simulation can detect s the presence of damage by comparing the baseline signal with damaged signals. The corresponding delays have been validated and compared with those of literature to improve the estimation of damage position.

1. Introduction

Maintenance executives are looking for cost effective, reliable, and monitoring inspection solutions to ensure safety and reliability of structures. Generally, in structures like bridges, ships, and planes are subjected to various internal and external factors, either mechanical or environmental. This may cause their systems to malfunction, early failure or collapse [1]. To overcome this, an implementation of real time inspection system is necessary. It consists of embedding sensors and actuators in the structure to get an information about the health of the monitored structures [2]. Structural health monitoring (SHM) aims to control permanently the integrity of metallic and composite structures. It is a key part of any maintenance strategy (preventive and systematic). Because of its automatic aspect, inspection time is saved particularly for avoiding assembly/disassembly works. In fact, a wealth of techniques has been developed to assess damage

* *Corresponding author.*
E-mail address: amina.saouab@uir.ac.ma

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through the well-known four stages like a) damage detection, b) localization, c) type size, and d) life prediction [3, 4]. SHM encompasses all non-destructive and analysis techniques (NDT), such as: visual testing, penetrant testing, X rays, magnetic particle testing, eddy current testing and ultrasonic testing (UT). These NDT methods have different sensitivity levels for damage detection in structures. However, ultrasonic testing (UT) has the advantage for detecting damage using high frequency sound waves, and it is sensitive to surface and sub-surface damages for isotropic and composite materials [5, 6].

UT method uses the sound waves and can propagate in four principal modes depending on the particles motion, i.e., longitudinal waves, shear waves, surface or Rayleigh waves and Lamb waves. The guided Lamb waves were discovered by Horace Lamb in 1917 and can propagate through the thickness of thin plates [7]. The technique is widely known as one of the most encouraging tools for quantitative identification of damage in metallic and composite structures, as the waves propagate in thin plates having two parallel and free boundaries [8].

Recent advances in Lamb waves based SHM technology have shown great potential in the feasibility of detecting and locating the position of damage in structural components. Researchers recently focused on different model updating techniques for damage identification [9], yet there remain many challenging tasks due to the complexity induced by their highly dispersive characters. When a dispersive wave propagates in an elastic medium with different velocities, its speed depends on the frequency as well as the thickness of the medium that propagates through. There is also the false positives due to temperature by changing environmental conditions which affect the velocity of Lamb wave [10], thus, the time of arrival and amplitude of the wave will be changed [11]. There are some methods that suggest isolating damage sensitive features from temperature changing [12].

The common techniques for Lamb waves-based damage detection are the pulse echo and pitch catch. The pulse echo technique uses one transducer as a transmitter to excite the structure and as a receiver of the output information, while the pitch catch technique uses two transducers, one as a transmitter and the other as a receiver [13].

To detect cracks in complex structures, and to improve the accuracy of damage characterization, sensors networking is an interesting solution that has caught up the attention of researchers recently. For instance, a multistage damage detection to detect and locate damages in an aluminum plate was reported in [3]. Both numerical and experimental studies were verified for damage detection using a network of piezoelectric (PZT) transducers, and quantitatively estimated the damage location using tangent circle and least squares method. In another work, a new method was developed that uses the reflected boundaries as a tool to detect damages, and considered as and obtained effective results using a single transmitter-receiver pair [14]. Another technique based on the use of actuators/sensors arrays combined with artificial neural networks and probability ellipse method was presented in [15]. A combined damage detection and localization strategy was developed in this paper [16], damage detection was performed with supervised learning. The path damage indices for each transducer pair was calculated in [17], based on the environmental and operational conditions, the path damage indices was compared to the threshold to reduces the conditions that can act as false scenarios of damage [18, 19]. The challenging part of these techniques are the wave modelling and result interpretation, in which this study aims to investigate the multistage damage detection method applied on an aluminum plate.

2. Outer tangent circle

Consider five transducers P_0, P_1, P_2, P_3 and P_4 mounted on an isotropic plate and form a square cell of side d. The plate contains a damage located in (x, y) position as shown in Figure 1.

As the transducer P_0 is exciting the plate, the four other sensors will capture the signal emitted by the central actuator as well as the one scattered by damage. The outer tangent circle method is based on calculating the delays caused by the presence of damage. For example, the delay observed in sensor 4 noted by Δt_{04} is calculated by the difference between the two paths: the first path of a duration t_{04}, that of the wave propagating from actuator 0 to sensor 4 directly, and the second path of a duration $(t_{0d} + t_{d4})$. Where t_{d4} is the time of travel from the actuator P_0 to the damage and t_{d4} the time of flight from damage to P_4.

In terms of distances, the time delay caused by damage presence can be expressed as:

$$\Delta t_{04} = (t_{0d} + t_{d4}) - t_{04} = \left(\frac{d_1}{v} + \frac{d_2}{v}\right) - \frac{d_0}{v} \tag{1}$$

where v is the group velocity. The distances d0, d1, and d2 can be calculated using the geometric relations in Figure 1 by:

$$d_0 = \frac{\sqrt{2}}{2} d \,;\, d_1 = \sqrt{(x-0)^2 + (y-0)^2} \,;\, d_2 = \sqrt{(x_4 - x)^2 + (y_4 - y)^2} \tag{2}$$

Hence equation 1 becomes:

$$\sqrt{(x-x_0)^2 + (y-y_0)^2} + \sqrt{(x_4 - x)^2 + (y_4 - y)^2} = v.\Delta t_{04} + \frac{\sqrt{2}}{2}\mathrm{d} \tag{3}$$

This equation is that of an ellipse with two focal points P_0 and P_4. Hence, we can obtain three other ellipses of focal points P_0-P_1: P_0-P_2 and P_0-P_3. For sake of clarity, the equations of the three ellipses can be written as:

$$\sqrt{(x-x_0)^2 + (y-y_0)^2} + \sqrt{(x_4 - x)^2 + (y_4 - y)^2} = v.\Delta t_{04} + \frac{\sqrt{2}}{2} \tag{4-a}$$

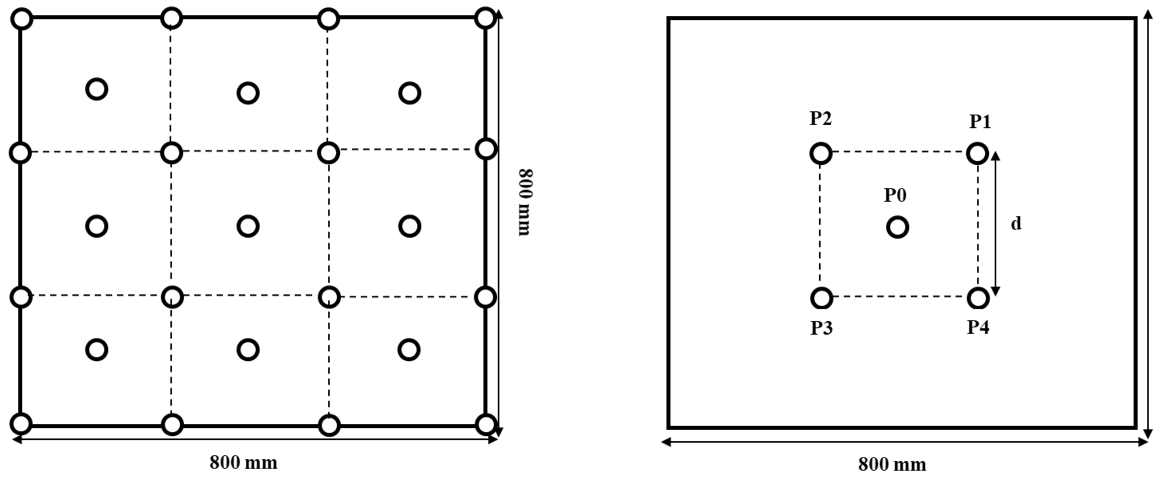
$$\sqrt{(x-x_0)^2 + (y-y_0)^2} + \sqrt{(x_4 - x)^2 + (y_4 - y)^2} = v.\Delta t_{04} + \frac{\sqrt{2}}{2} \tag{4-b}$$

$$\sqrt{(x-x_0)^2 + (y-y_0)^2} + \sqrt{(x_4 - x)^2 + (y_4 - y)^2} = v.\Delta t_{04} + \frac{\sqrt{2}}{2} \tag{4-c}$$

The main objective of this paper is to validate numerically the outer tangent circle method for different crack positions. Further we intend to investigate the predictability of cack severity by using the same approach.

3. Multistage Detection Method

Consider a plate with a set of PZT transducers arranged as cells and for each cell a centred transducer P0 is put. As depicted in Figure 1, the multistage detection method [3], uses three stages to improve the detectability and assessment of the damage in structures, also it uses different analysing techniques for each stage. For the first stage, the centred PZT transducer P0 is used as an actuator/excite the Lamb wave in a radially outward direction to locate and isolate the damaged sub-cell. The four corner transducers will receive the direct signal from P0, and the signal scattered by damage. In the second stage, a detection strategy is focused on analysing and studying the isolated cell with size d=240mm. A pulse echo technique is used for each corner transducer (P1, P2, P3, P4), where it uses transducers as transmitters and receivers of signals at the same time for example exciting at first P1 and sensed by P2, P3 and P4.



(a) Network of sensors arranged as cells (b) The isolated sub-cell

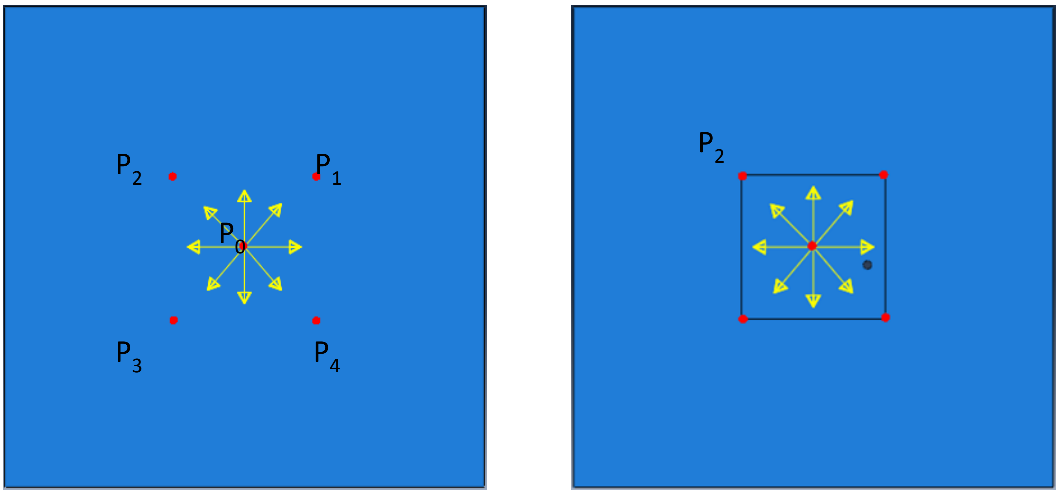
Fig. 1. Aluminum plate used to investigate multistage damage detection

The numerical simulations were performed on an 800x800x1.293mm square aluminum plate using FE software ABAQUS explicit. The material properties of aluminum plate are given in Table 1 below:

Table 1
Material properties of the aluminum plate

Mass Density	Young's Modulus	Poisson's Ratio
2700 kg/m3	71GPa	0.3

The PZT transducers lead zirconate titanate are used to both excite and sense the Lamb wave signals in a radially outward directions, they had a diameter of 5.4mm as shown in Figure 2. The load used in the PZT are modelled as concentrated force to avoid the added interactions from each other, to create a load as shown in figure we used spherical coordinate system type to have the signals of the wave in all directions



(a) (b)

Fig. 2. (a) The healthy case and (b) Damaged case of aluminum plate modelled by Abaqus CAE

The excitation signal used for the actuators was modelled as shown in Figure 3, by an in-plane force with 5.5 cycle sinusoidal tone burst modified by Hanning window at a central frequency of 383 kHz calculated by: $\frac{1}{2}(1-\cos\left(\frac{2\pi t}{T}\right))$. The section of the plate is created with 3D shell elements and assigned homogeneous section to create instance part for the full assembly. The time step dynamic explicit is used in this study to perform many small times increments at the total time efficiently, which is the period of Lamb wave propagation 150 μs, with a time increment of 0.02 μs.

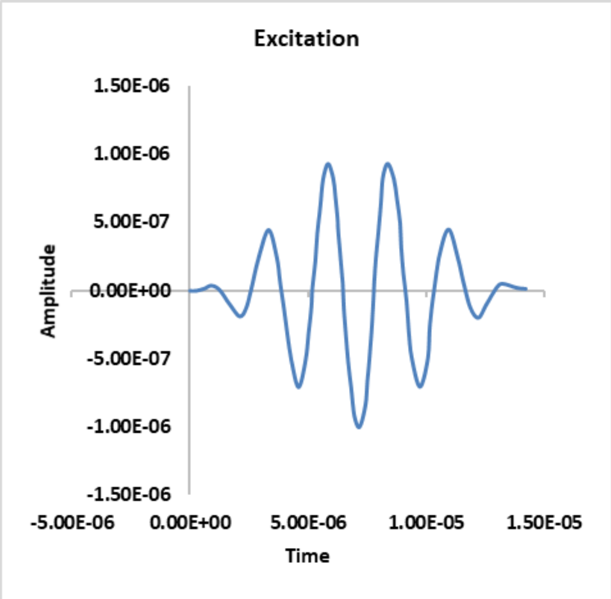


Fig. 3. Excitation signal modelled by Hanning window 5.5 tone burst to excite P0

To better characterize the interactions of Lamb waves with any discontinuities, the plate was meshed with 3D shell element S4R by an element size of 0.5mm in all simulation models used in this work (see Figure 5).

5. Results and Discussion

As a result, from the numerical simulations to detect the changes in the structure. A healthy case of the structure was investigated to form a baseline signal of the study. The output signal shown in Figure 4, the signal of Lamb wave propagation arrived at sensors P_1, P_2, P_3 and P_4 is the same for all sensors due to the distance from the actuator and all sensors is the same. While for the second case, damage is introduced by adding a circular damage with a diameter of 7mm, located at (90, -30) from the centre of the plate.

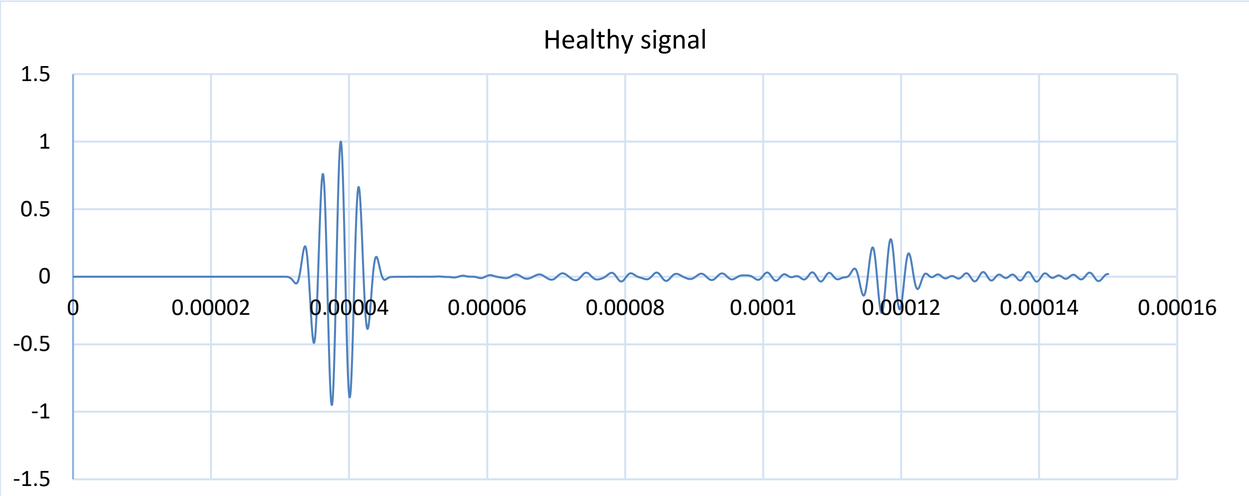
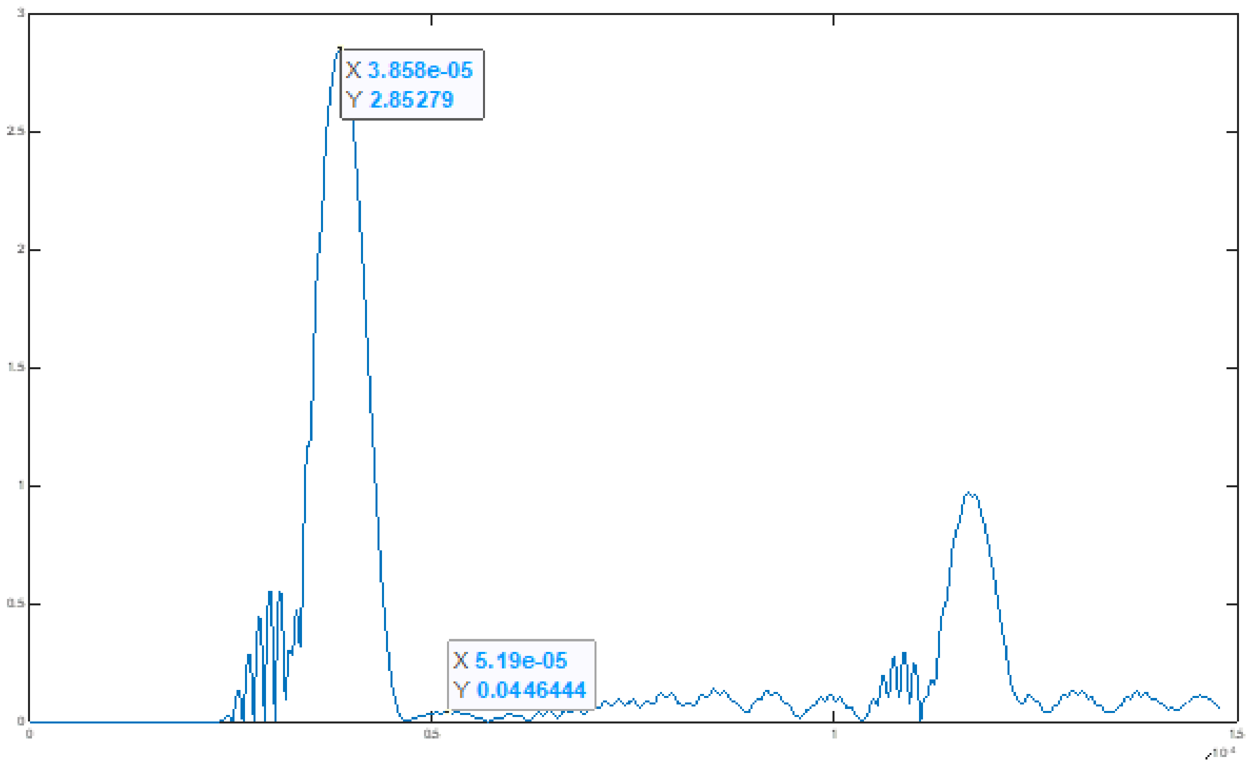
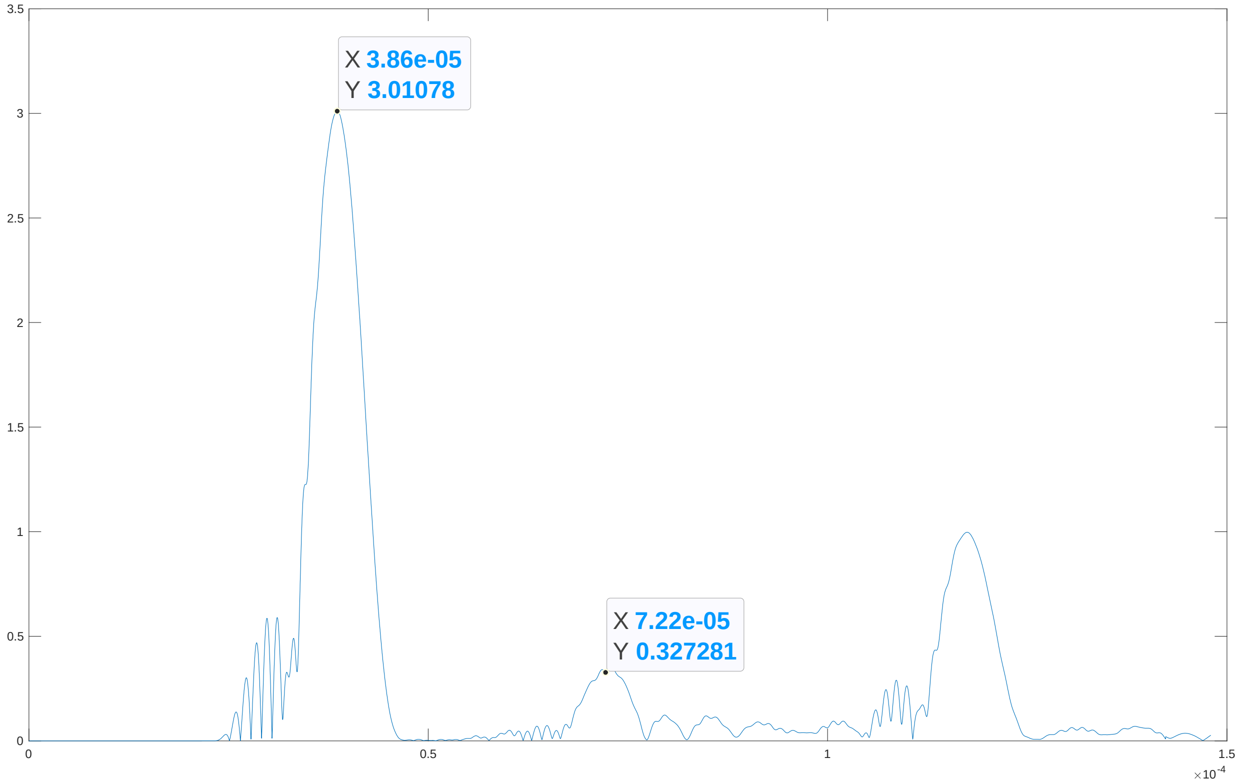


Fig. 4. The output signal of the healthy aluminum plate

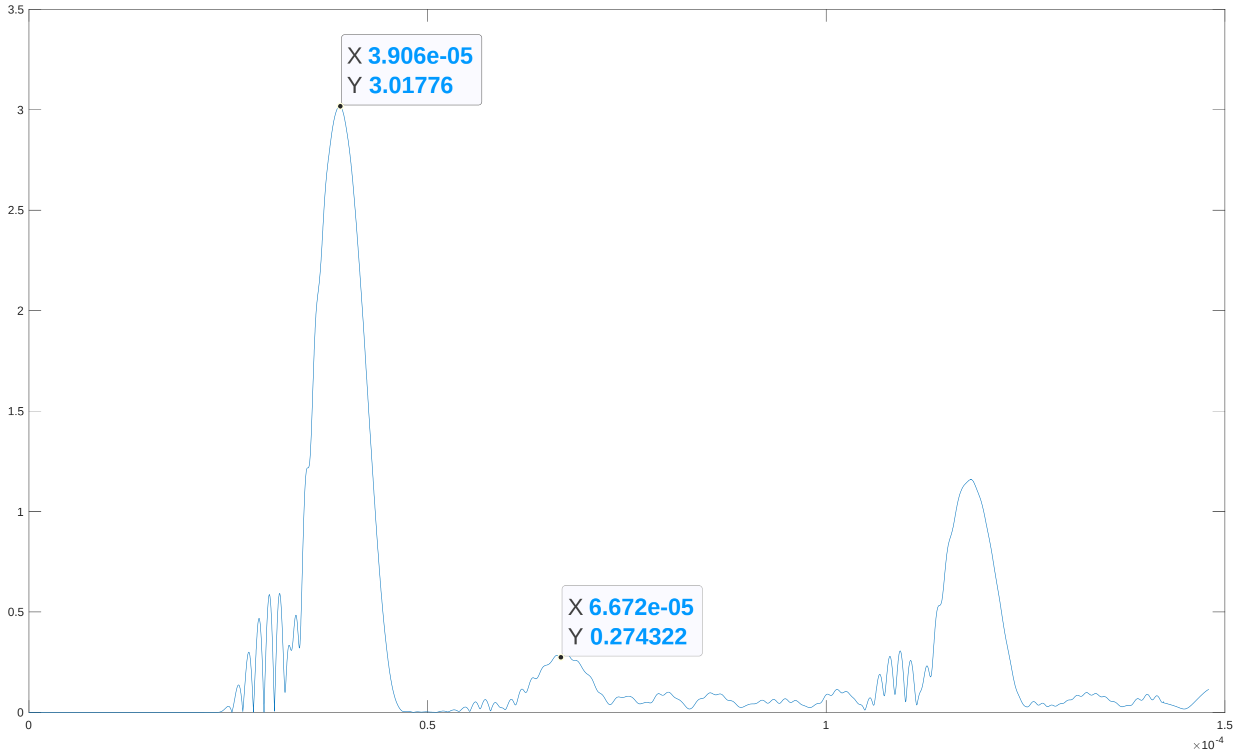
From the numerical simulations of the first stage, we got four different output signals for the sensors (P1, P2, P3, P4) were obtained and transferred to continuous wavelet transform using MATLAB to observe the differences in the signals visible Figure 5. Based on literature [3], The output signal of P2, for damaged case is more likely to show the presence of the damage since it is the one that receive the reflections from damage first. For the path where damage is located P0-P4 it shows that the reflection from damage is very small and close to the first peak of the wave arrival.



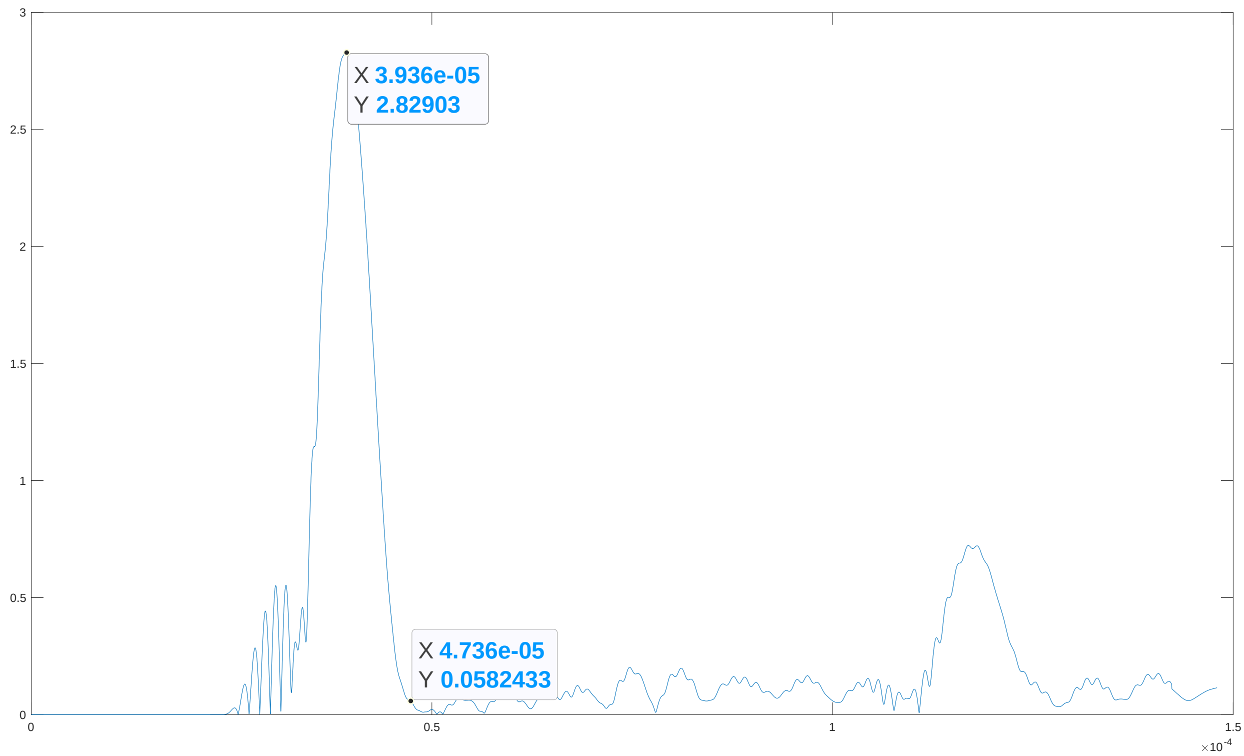
(a) CWT of the output signal P_1



(b) CWT of the output signal P_2



(c) CWT of the output signal P_3



(d) CWT of the output signal P_4

Fig. 5. The output signals of sensors P_1, P_2, P_3 and P_4 for damaged aluminum plate

To verify the disturbances caused by damage, there are some parameters that can change and work as an indicator of damage presence. Based on the output signals of the sensors, a delay time can be calculated and compared. The reflections shown in the damaged signals are not the same, the difference between them and their time of arrival is stated in table 2. The difference between the first and second peaks gives the delay time of each sensor.

Table 1
Delay time for PZT transducers P_1, P_2, P_3, P_4, with P_0 excitation

	First Peak (s)	Second Peak (s)	Time Delay (µs)
P_1	3.858E-05	5.19E-05	13.32
P_2	3.86E-05	7.22E-05	33.6
P_3	3.906E-05	6.672E-05	27.66
P_4	3.936E-05	4.736E-05	08.00

In this study, different damage positions were used to verify the ability of this method in improving damage detection and localisation. Same for all damage positions the delay time was extracted table 3 and compared using ellipse method.

Table 2
Delay time for different cases of damage position

	Damage position (90, -30) (µs)	Damage position (90, 30) (µs)	Damage position (-90, 30) (µs)	Damage position (-90, -30) (µs)
P_1	13.32	07.20	28.9	31.76
P_2	33.6	27.56	06.30	13.26
P_3	27.66	32.69	15.4	04.06
P_4	08.00	12.59	31.9	26.64

To estimate the location of damage, the outer tangent circle method was investigated in this work. An ellipse is drawn using a focal point P_0 in MATLAB each ellipse was solved by Eq. (4) where,

$(x_0, y_0) = (0,\ 0)$

$(x_1, y_1) = (120,\ 120)$

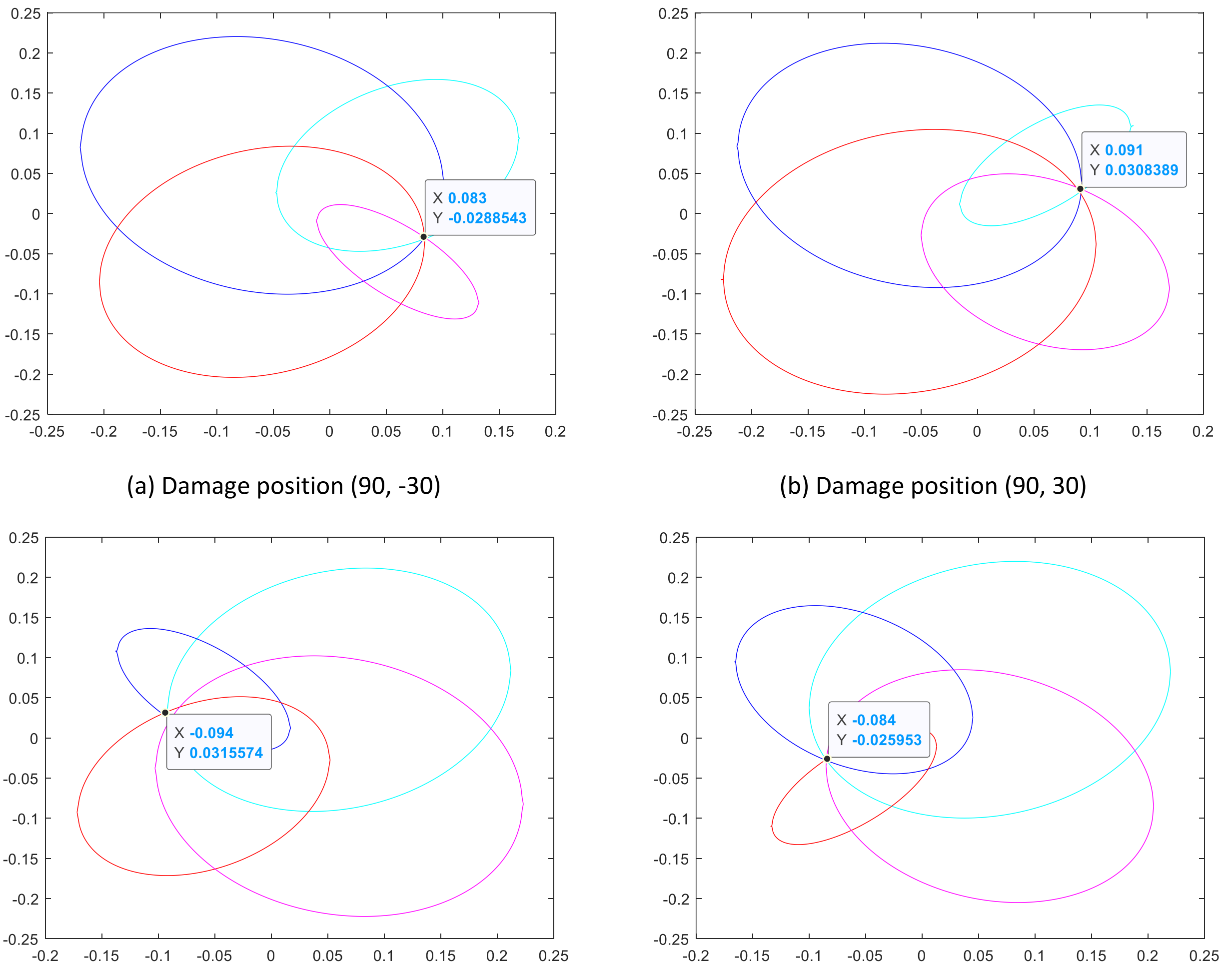
$(x_2, y_2) = (-120,\ 120)$

$(x_3, y_3) = (-120,\ -120)$

$(x_4, y_4) = (120,\ -120)$

$d = 240mm$

The delays of the signals received at sensors P_1, P_2, P_3 and P_4 are calculated in reference to baseline signal. For example, the delay at sensor P1: Δt_{01} is the difference between the time of arrival at P_1 of both healthy and damaged plates. These delays help to draw ellipses for the four cases (four different crack positions) as shown in **Error! Reference source not found.**. The intersection between the four ellipses for the first case (a) shows that the approximate location of damage is at (86, -28) mm from the origin of the square compared to the actual position of damage which is at (90, -30) mm, second case (b) the estimated position is (91, 30) mm where the actual position is (90, 30) mm, the third case (c) shows the estimated position (-94, 31) mm where the actual position is (-90, 30mm), and for the last case the estimated position is (-84, -25) mm. So, the ellipse method can give a close estimation of damage position.



(a) Damage position (90, -30)

(b) Damage position (90, 30)

(c) Damage position (-90, 30)

(d) Damage position (-90, -30)

Fig. 6. Damage localization using ellipses

To investigate the ability of ellipse method in estimating damage size, different damage sizes were used for this matter, d=7, 9, 11, 13mm. keeping the same position of damage for all cases (90, -30). By calculating delay time of each case as shown in

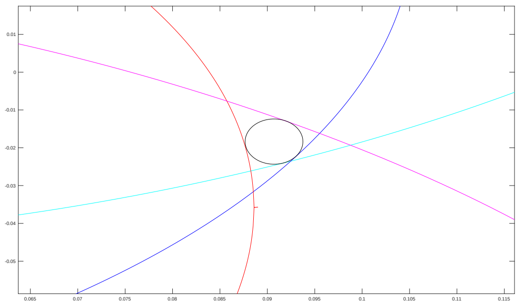
Table 3

Delay time of the ellipses were drawn using MATLAB.

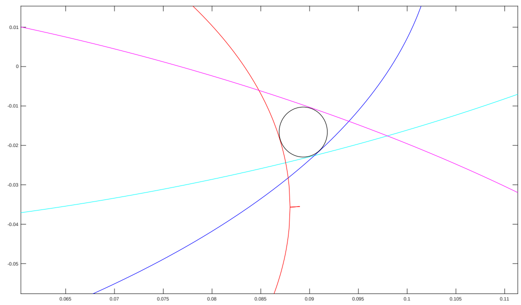
Table 3
Delay time of the four sensors, for different sizes of damage

Size (mm)	P1 (μs)	P2 (μs)	P3 (μs)	P4 (μs)
7	13.32	33.60	27.66	08.00
9	12.80	32.90	27.70	06.40
11	13.00	32.00	26.70	07.38
13	13.10	32.13	26.50	08.58

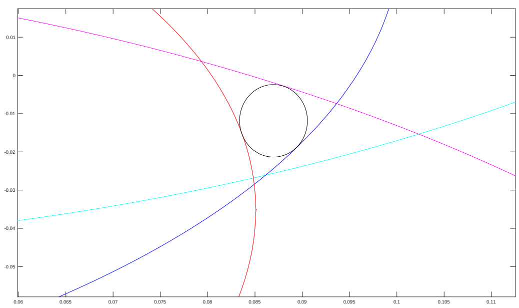
As a result, the ellipse method can show that there is a difference in damage size depend on the four ellipses for each case which is clear in Figure 7. The intersection between the ellipses is different from one case to another. A circle was drawn to measure the area where the ellipses were intersected. It is observed that as long the size of damage increases from 7 to 13mm the area of circle changes and goes bigger, it means that the ellipse method can have different parameters to be investigated for damage size estimation.



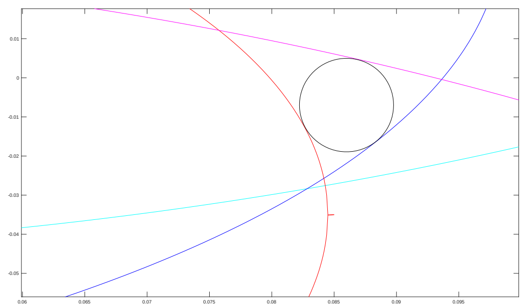
(a) Intersection of 7mm case



(b) Intersection of 9mm case



(c) Intersection of 11mm case



(d) Intersection of 13mm case

Fig. 7. The intersection of ellipses for different damage sizes

5. Conclusions

The multistage damage detection method based on Lamb waves introduced in this study can detect the presence of damage in plates and locate the approximate position of damage. The PZT transducers arrangement used in this work, each square transducer cell is used to identify the damage locally. The data collected in the first stage can be the same used in all stages without any additional tools or techniques. The advantage of this method is that it can save both computational time and evaluation cost during the process, the method is relatively straightforward to implement for damage detection in shape of circles. The ellipse method can be very accurate in locating damages by collecting more data from different excitations. Different sizes of the damage and the effect of temperature variation will be investigated for further work.

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