Application of Wavelet Transform as a Signal Processing Method for Defect Detection using Lamb Waves: Experimental Verification

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A Lamb wave-based crack detection method for aluminum plates health monitoring is developed in this paper. Piezoelectric disks are employed to actuate and capture the Lamb wave signals. The position of crack is assumed to be aligned with the sensor and actuator. Extraction of high quality experimental results of lamb wave propagation in a plate-like structure is considerably complicated due to phenomena such as multimode excitation, wave dispersion, material attenuation, and boundary reflection. The main goal of this study is to utilize a customized wavelet transform technique to purify the captured Lamb wave signals. Significant features of these signals were then extracted from the wave energy distribution. Experimental results show that the developed method has a promising capability in identification of crack positions.

Keywords: Lamb Waves, Wavelet Transform, Damage Identification

1 Introduction

Many NDE techniques have been researched for detecting damage in plate-like structures; however Lamb wave based methods have recently shown to be a reliable way to locate damage in this kind of structures. These methods have been implemented with a variety of approaches, including the use of separate actuators and sensors to monitor transmitted and/or reflected waves and multipurpose patches which actuate and sense simultaneously; each of which having their own advantages and disadvantages in detecting certain types of damages in various structures.

The techniques which utilize Lamb wave propagation involve the fundamental concept that a propagating wave will be reflected and/or partly transmitted when it encounters a defect or boundary. Mentioning the wave packet arrival times and velocities at particular locations, the presence of a defect and its location can be inferred [1]. Several aspects regarding these techniques were researched and addressed in literature. Some researches are focused on the interaction of Lamb waves with damage and discontinuities [2]. The Lamb modes excitation and reception has been attracted lots of attention, too. For example, for integrated health monitoring systems, a few studies propose to work with a comb transducer for the emission to select and isolate a Lamb mode in an elastic isotropic plate [3].

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Similarly, Grondel et al. [4] have used thin piezo-ceramic transducers to generate and receive a selected Lamb mode in composite structures. These thin transducers can be bounded or integrated in the structure [5] to ensure a permanent and a real time health monitoring.

Generally, discontinuities cause reflections and mode conversions. As signals obtained from a Lamb wave based inspection are complicated due to defect scattering or mode conversion, appropriate signal processing techniques is needed to extract defect sensitive features. For example, Gao et al. have adopted the 2-dimensional Fourier transform to analyze dispersion curves in thin copper plates [6]. On the other hand, the Hilbert-Huang Transform (HHT) [7] has also been explored for detecting anomalies in beams and plates [8]. Quek et al. showed that HHT technique is able to produce a high resolution energy-frequency-time distribution for a non-stationary surface wave signal, from which the group velocity and phase velocity dispersion curves can be measured to much higher accuracy than achieved by conventional Fourier-based methods. Lemistre et al. employed the wavelet transform for processing of Lamb wave signals to obtain the frequency-time spectrum for locating damage in composite plates. They used the multi-resolution property of wavelets to isolate various propagating lamb modes to locate damage [9]. Another example is the time-frequency analysis performed on laser generated lamb waves to detect concealed corrosion of aluminium components in aircraft using a continuous wavelet transform. The generated Lamb mode was compared with calculated dispersion curves and detection was determined based on the attenuation of that mode [10].

This paper aims to develop a wavelet transform based method to detect the location of cracks in a plate. As the time of flight analysis is usually used to determine the location of damage, the arrival time of a specific Lamb mode should be extracted accurately. For this purpose, a wavelet based signal processing method is introduced here and verified experimentally. An aluminium plate with 120 mm long simulated crack is used as a test bed. Experiment results showed that the estimated location matched the real position of the simulated crack closely.

2 Experimental setup

The Experimental Setup used for tests consists of a rectangular isotropic aluminium plate, 11 piezoelectric disks including 2 actuators and 9 sensors, with properties as presented in table (1), a 50/750 TREK high-voltage amplifier, a NI 6070E DAQ and a TDS2012C Tektronix oscilloscope. The complete setup is shown in Fig. (1). The plate is 1m×2m in size and 3 mm in thickness with free edges and containing a through thickness crack, 120 mm in length.

Table 1 Geometric properties of piezoelectric disks

	Diameter (mm)	Thickness (mm)
actuators	17	3
sensors	8	1

As shown in Figure 2), the two actuators, denoted by A1 and A2, were placed in the middle of plate, sensors, which are denoted by S1 through S9, arranged around them and crack was placed on the line connecting actuator A1 to sensor S1 and 72 cm far from actuator.

Figure 1 The experimental setup

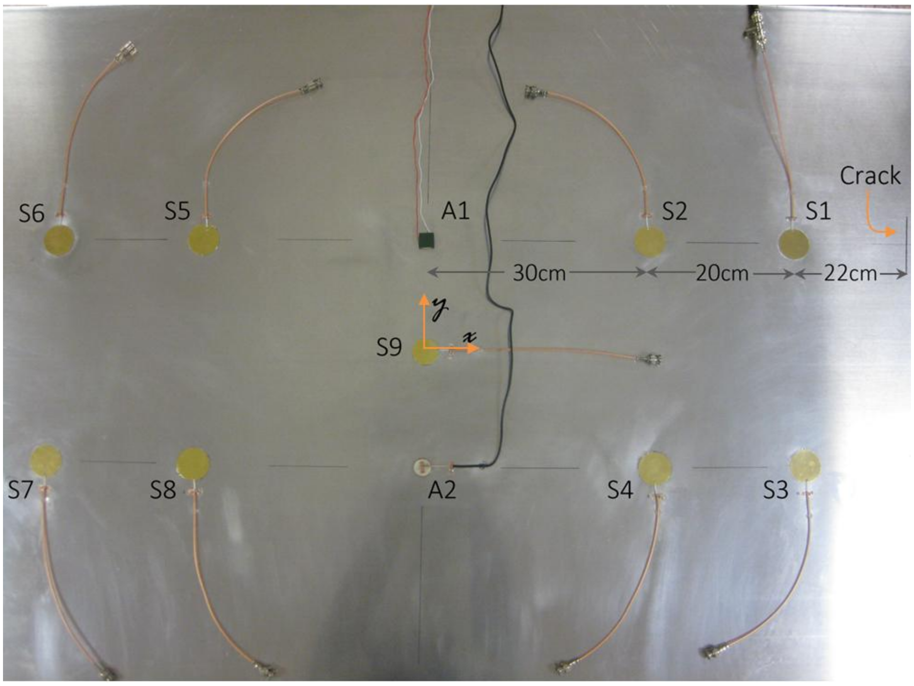

Figure 2 Sensors and actuators arrangement on the plate

Based on dispersion investigation, the excitation frequency must be selected precisely in order to avoid multiple mode excitations. Based on the resonance frequency of available actuators, the excitation frequency is set to 100 kHz. For a 3mm thick aluminum plate, based on numerical solution of fundamental equation of Lamb waves, which results are shown in Fig. (3), the group velocities of A_0 and S_0 modes are 2421 and 5413 m/s, respectively.

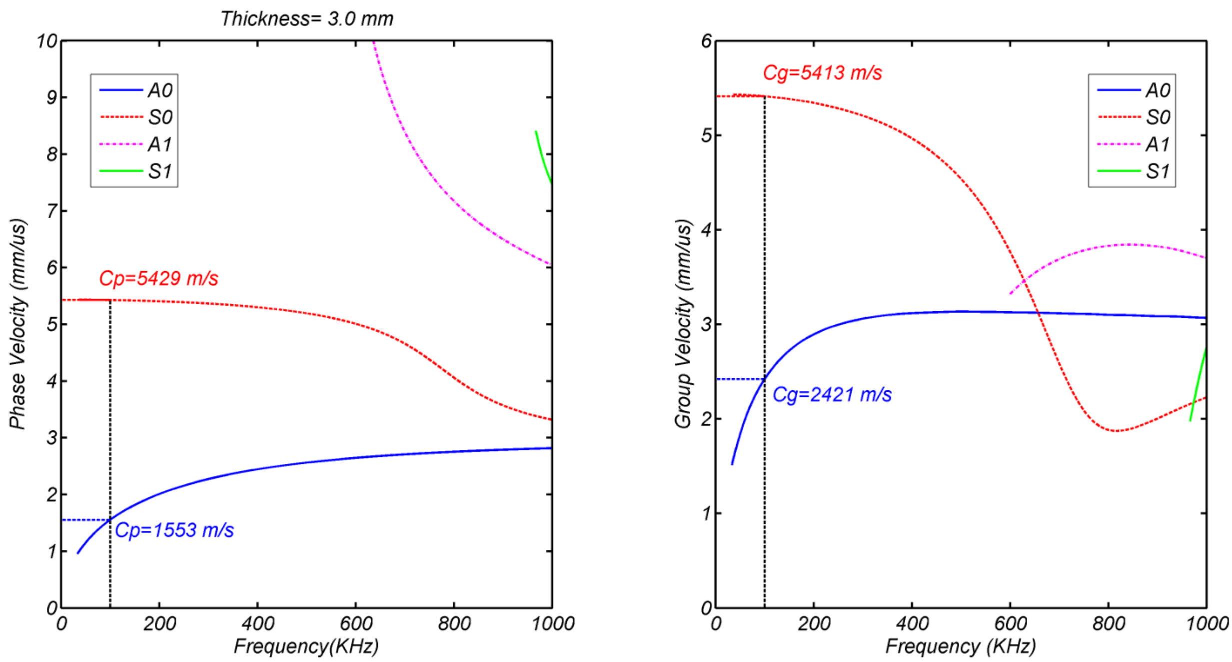

Figure 3 phase and group velocity dispersion curves for guided waves in a 3 mm thick aluminum plate with 100 kHz excitation frequency

The narrowband actuating signal, called tone burst, is constructed based on the following equation:

$$A(t) = \frac{1}{2} \times \sin(2\pi f t - \pi N) \times (1 + \cos(\frac{2\pi f}{N} t - \pi)) \tag{1}$$

Where f is the actuation frequency in Hz and N is the number of cycles in tone-burst signal. Here a 5 cycle, 100 kHz tone-burst is used. Regarding the 100 kHz excitation, a 1MHz sampling frequency was chosen for data acquisition device.

3 Signal Processing

A suitable signal processing method should be chosen and applied to wave signals in order to make it easy and also reliable to extract the important required features from signal. There are several reasons which make it difficult and further impossible to use the captured signals conveniently, for example PZT actuators normally generate both symmetrical and anti-symmetrical wave modes simultaneously; meanwhile, mode reflection and/or conversion that occur at boundaries and structural discontinuities may result in complicated multimode signals. Furthermore, other diverse factors like material attenuation, natural structural vibration and ambient noise, also affect the signals and make it more difficult to extract the significant features, because it is so challenging to ascertain whether changes in signal characteristics are related to damage, ambient noise or boundary conditions.

Advanced signal processing algorithms such as the two-dimensional Fourier transform (2D FT) and wavelet transform (WT), in which the time, space and frequency domains are combined, are used widely for signal processing in this extent. In this work, the wavelet transform was used to process the captured lamb wave signals. While methods like 2D FT either require a large amount of data from multiple sensors for spatial Fourier transform or have a fixed resolution in both time and frequency, by using wavelet one can transform wave signals from the time domain into the time–frequency domain.

Theoretically, the continuous wavelet transform (CWT) is defined as [12]

$$W_{\psi}(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\psi^{*}\left(\frac{t-b}{a}\right)dt \tag{2}$$

Where a, b, ψ and ψ^{*} are the scale parameter, time shift, basic wavelet and complex conjugate of ψ, respectively. If the scale parameter *a* and time shift *b* are binary-based, the basic wavelet can be discretized as [12]

$$\psi_{m,n}(t) = 2^{m/2}\psi(2^{m}t - n) \tag{3}$$

The CWT is then simplified to the discrete wavelet transform (DWT) subsequently and the signal can be reconstructed from the wavelet analysis formula as [12]

$$x_{m}(t) = \sum_{-\infty}^{+\infty} a_{k}\psi_{m,n}(t) \tag{4}$$

Where n, m and a_k are the dyadic time-scale integers and wavelet amplitudes. The DWT decomposes and reconstructs the signal at separate levels of frequencies with multi-resolution analysis, whereas the CWT operates at every scale and continuous time shift over the full domain of the signal, and this feature of DWT is just to reduce the redundant coefficients of equal magnitude [9].

The concept of scale in the WT is used as a substitute for frequency, which is proportional to its reciprocal. In the time-scale domain, each scale resembles a certain region of frequencies in the time–frequency domain. Based on this fact, the scattered signal by a defect can then be isolated in a specific frequency range. Afterwards, by extracting the difference in the time of flight (ToF) between incident and damage-induced wave components, the location of damage can be found by the reconstructed signal at the level corresponding to the excitation frequency using the DWT or in the wave energy distribution via the CWT [9]. In the present work, both DWT and CWT were performed successively to extract the characteristics of the acquired Lamb wave signals.

4 Experiment Results of Velocity Measurement

A typical time domain signal, captured from S1 while actuating A1, before and after of introducing the crack is displayed in Fig. (4).

As shown, an initial wave packet is occurred near 100µs, which is exactly the time the actuation signal is excited and this packet is seen in all the sensors. Afterwards, as the group velocity of S_0 mode is larger than A_0, as mentioned before, the first peak associated to a Lamb mode is S_0 mode. Occurrence of the first wave packet is mostly due to hardware noises and should be neglected during analysis.

The difference in signals obviously depicts the presence of a reflecting source. So it’s required to measure the ToF of different wave packets subsequently calculate the velocity of wave packets and then map the location of crack.

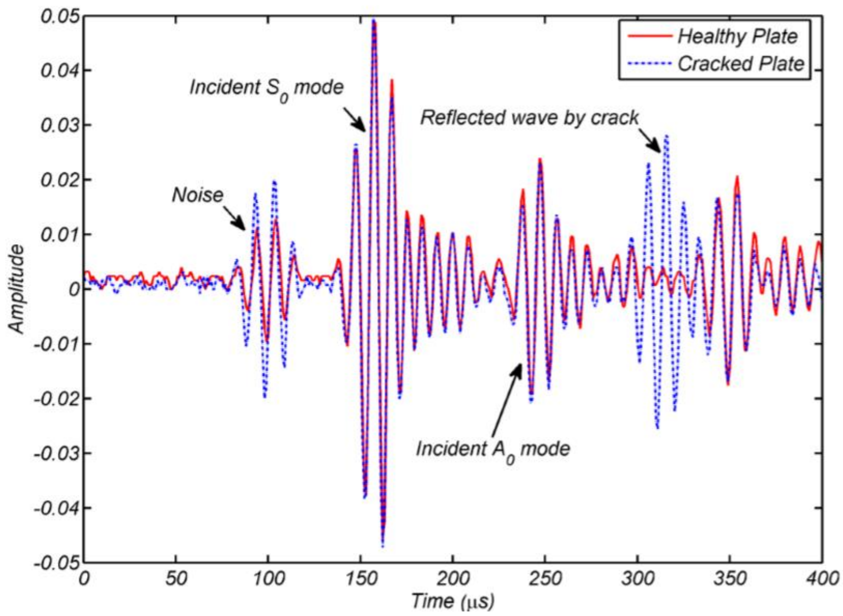

Figure 4 Captured signals for A1-S1 actuating-sensing pair

The first key concept is to decide how to measure the ToF of wave packet. To accomplish this, the previously introduced signal processing method was used. But it was also compared with other common methods, which results' are presented here. FFT of signal corresponding to cracked plate in Fig. (4) is shown in Fig. (5). As can be seen here, frequency content of signal is noisy around 100 kHz and one cannot obtain any useful data.

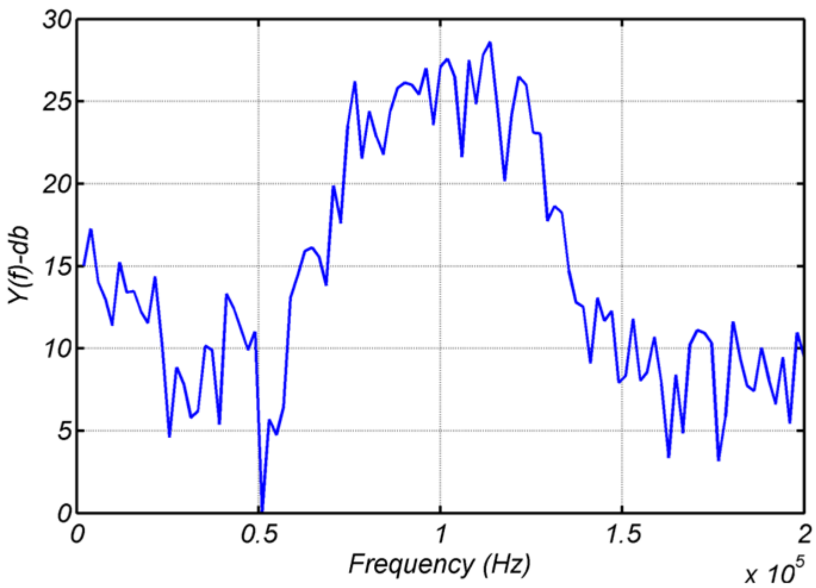

Figure 5 Fast Fourier Transform of Lamb wave signal

Furthermore, Hilbert transform of signal is also computed, which result for a little portion of signal (peak of incident S_0 mode) is depicted in Fig. (6). For this signal, the transform has just put a noisy spline on the original signal and one cannot obtain correct incident time of wave.
As mentioned before, in order to measure the exact ToF of wave packet, wavelet transform is used here. Hence the signals were decomposed into multiple frequency ranges by the DWT, and the relevant level including the excitation frequency of 100 kHz was chosen, filtering the noises from other frequency bands. Afterwards, wavelet coefficients were calculated in the

time-scale domain via the CWT from the purified signals. Thereafter the energy distribution based on wavelet coefficients was extracted using scalogram. By using this method the signal and its energy distribution are concentrated in a narrower band of the frequency, so as to eliminate extra parts and improve the identification of ToFs.

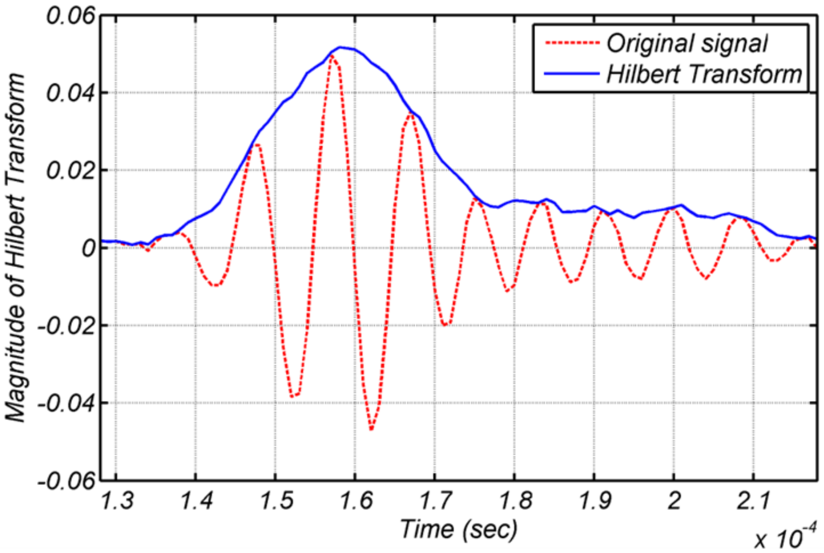

Figure 6 Hilbert Transform of Lamb wave signal

In this work, the signals were decomposed into three levels corresponding to different frequency ranges using a db8 wavelet. As shown in Fig. (7), the main parts of the source signal are focused in detailed parts of level 2 (d_2) and level 3 (d_3), equivalent to 62.5–125 kHz and 31.25–62.5 kHz, respectively. So the denoised signal was reconstructed using detailed part level 2 which contains the excitation frequency. Other ranges of frequency are due to ambient noises and also dynamic response of structure.

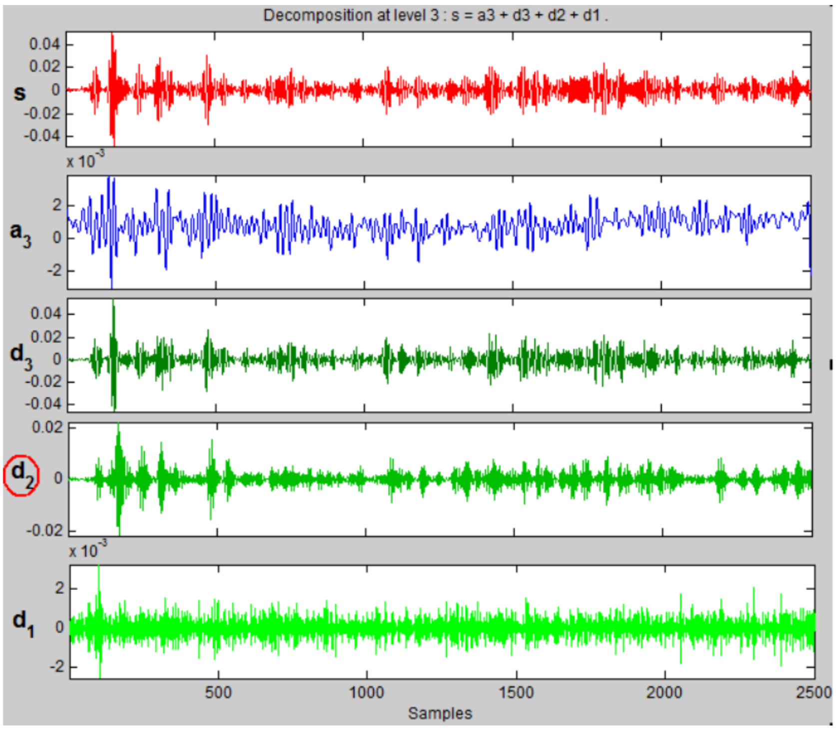

Figure 7 DWT decomposition of signal of A1-S1 actuating-sensing pair

The next step is to calculate the energy distribution of reconstructed signal using CWT, as shown in Fig. (8) for the typical signal which was already discussed. Consequently, energy coefficients of signal in 100 kHz (excitation frequency) can be extracted as depicted in Fig. (9). At this stage, the ToF of different wave packets can be easily found by finding the arrival time of their related energy peaks.

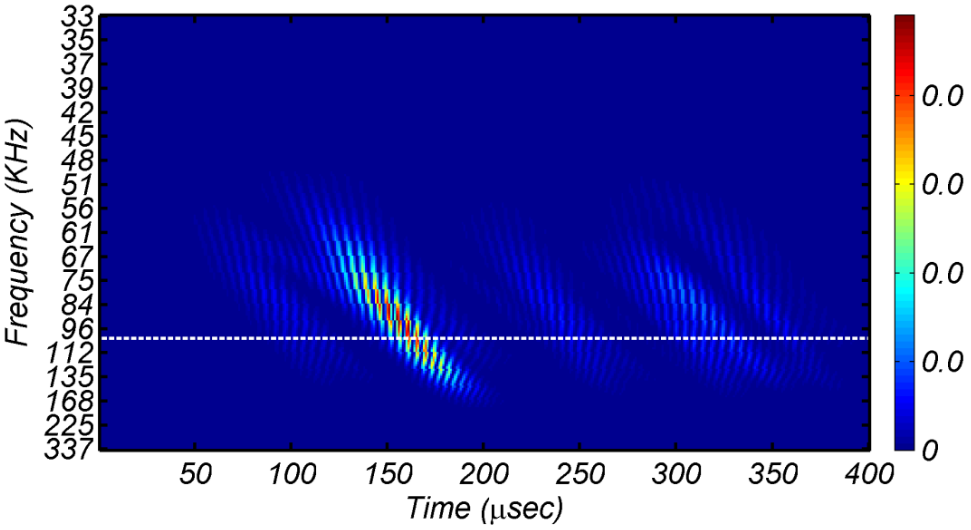

Figure 8 Scalogram, percentage of energy for each wavelet coefficient of signal

Results of extracting ToFs for incident S_0, incident A_0 and crack reflected wave packets for A1-S1 and A1-S2 actuating-sensing pairs are presented in table (2). It must be noted here that due to the fact that the exact zero time of signals cannot be determined, experimental group velocity of wave should be computed using the difference of arrival time for two different sensor-actuator pairs.

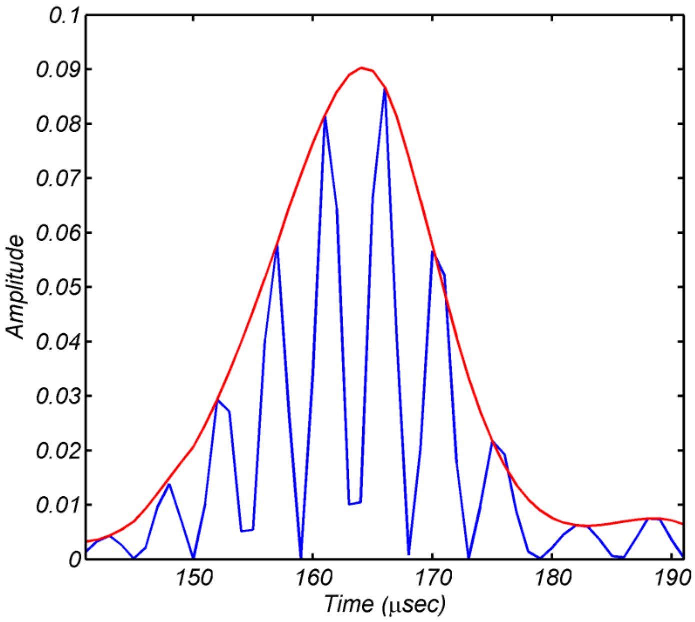

Figure 9 Percentage of energy for wavelet coefficients at 100 kHz frequency

After all related TOFs are extracted from the sensors' signals, the crack can be located. It can be noted that based on the above ToFs, averaged group velocities of S_0 and A_0 modes measured by these 2 actuating–sensing pairs were 5556 and 2520 m/s, respectively, which was slightly different from the values obtained from dispersion curves for Al plate.

Table 2 Time of Flight of wave packets (μs)

	S_0	A_0	crack reflected
A1-S1	214	265	279
A1-S2	178	247	315

Using the above ToFs, the average x coordinate of location of crack, would be 70.44 cm, which shows a 2.17% error which is mostly acceptable.

4 Numerical verification of velocity measurement results

In order to make sure that assumptions about wave modes are correct and experimental group velocity is measured correctly, a numerical analysis of a similar problem is performed using a FEM software, which characteristics are shown in Fig. (10). A 6061-T6 aluminum alloy is assumed for the plate.

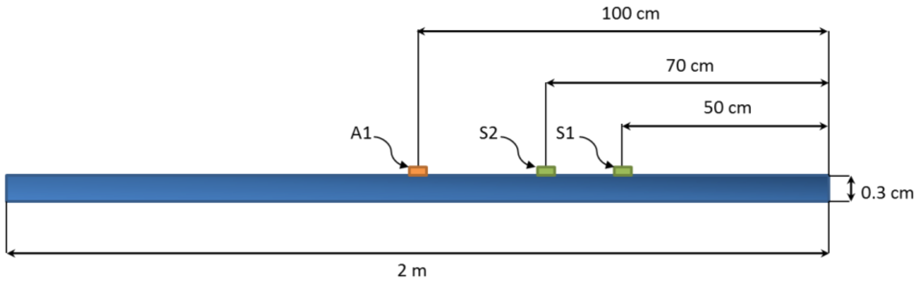

Figure 10 Geometry of simulated problem in software

Incident signals of both sensors are depicted in Fig. (11). As can be seen here, there is not any more the initial peak which was observed in experimental signals and this fact approves the assumption that this peak is a noise. In order to measure the ToFs, a similar approach same as experimental signals was performed, with a little difference that here is no need to denoising part.

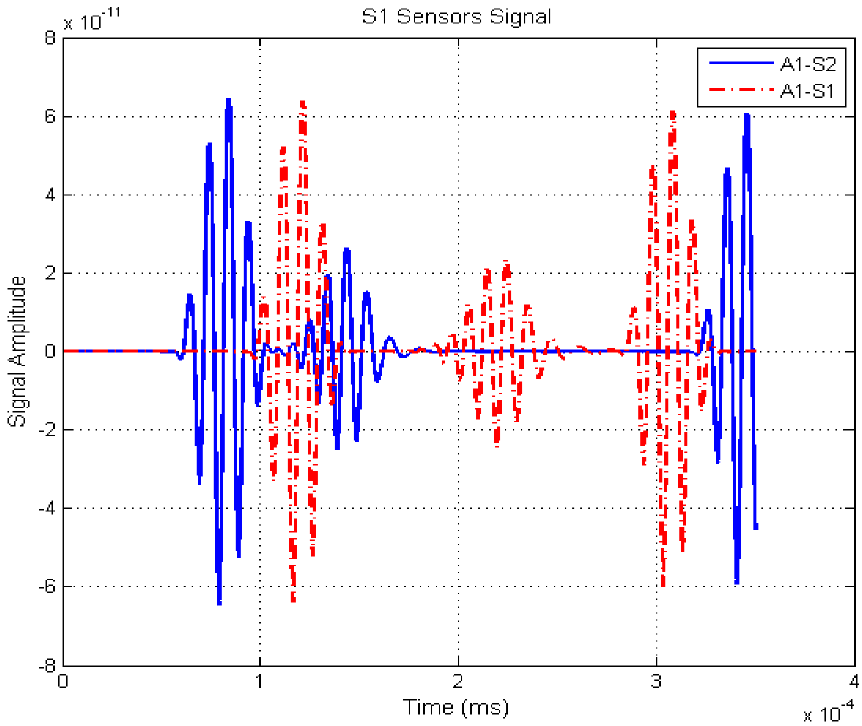

Figure 11 Recorded signals by sensors S1 and S2 in simulations

Based on the results of simulation, group velocity of first wave packet is 5353 m/s which depicts a 1.1 % error. The last important point is the verification of assumption made about first peak to be the Sis the verification of assumption made about first peak to be the Sis the verification of assumption made about first peak to be the S_0 mode which is clearly verified as shown in Fig. (12).

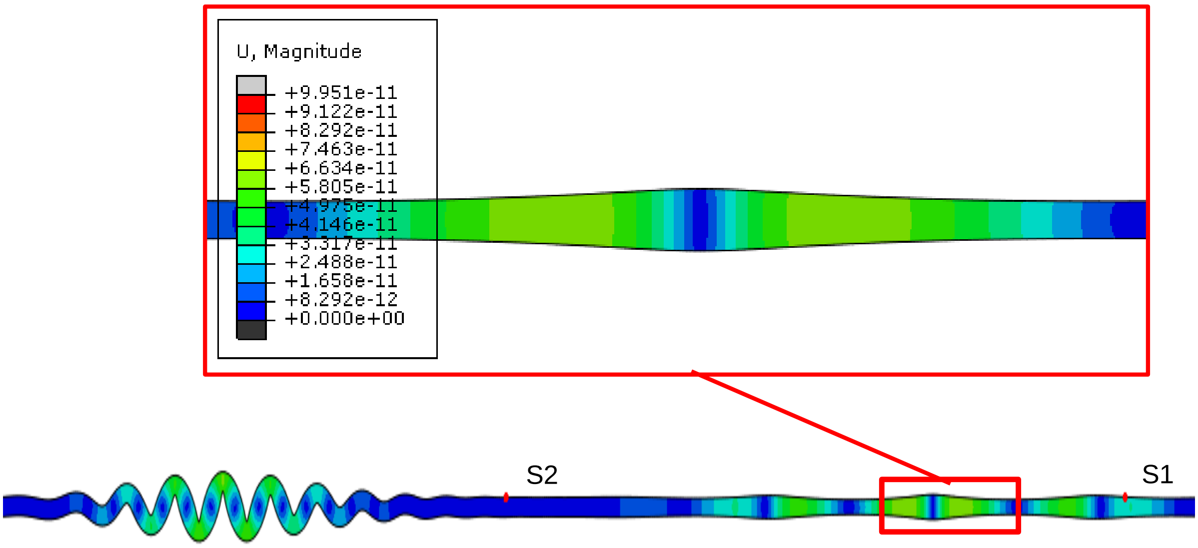

Figure 12 The displacement of particles while the wave moves from left to right

6 Experiment Results of Measuring Reflection Coefficient

Another notable result obtained during this research is the study of defect size variation on the main goal which is the identification of crack location. Six different lengths of a 2 mm wide crack as a defect were simulated on the plate, which are listed in table (3).

Table 3 Defect sizes used in the experiments

Defect Name	Defect Length
D0	2 mm
D1	3 mm
D2	5 mm
D3	4 cm
D4	8 cm
D5	12 cm

The changes in signal due to variation of defect size are shown in Fig. (13). Regarding the fact that the wavelength for S_0 mode of guided wave in frequency of 100 kHz is about 5 cm, it is reasonable that no significant changes can be seen in Figs. (13-a) to (13-d) which are corresponding to defect sizes from 2 mm to 4 cm. However by computing the integral of area below the curve and subtracting the healthy state from all defected states, changes occurred due to variation of defect size can be easily recognized (Fig. 14 and Fig. 15).

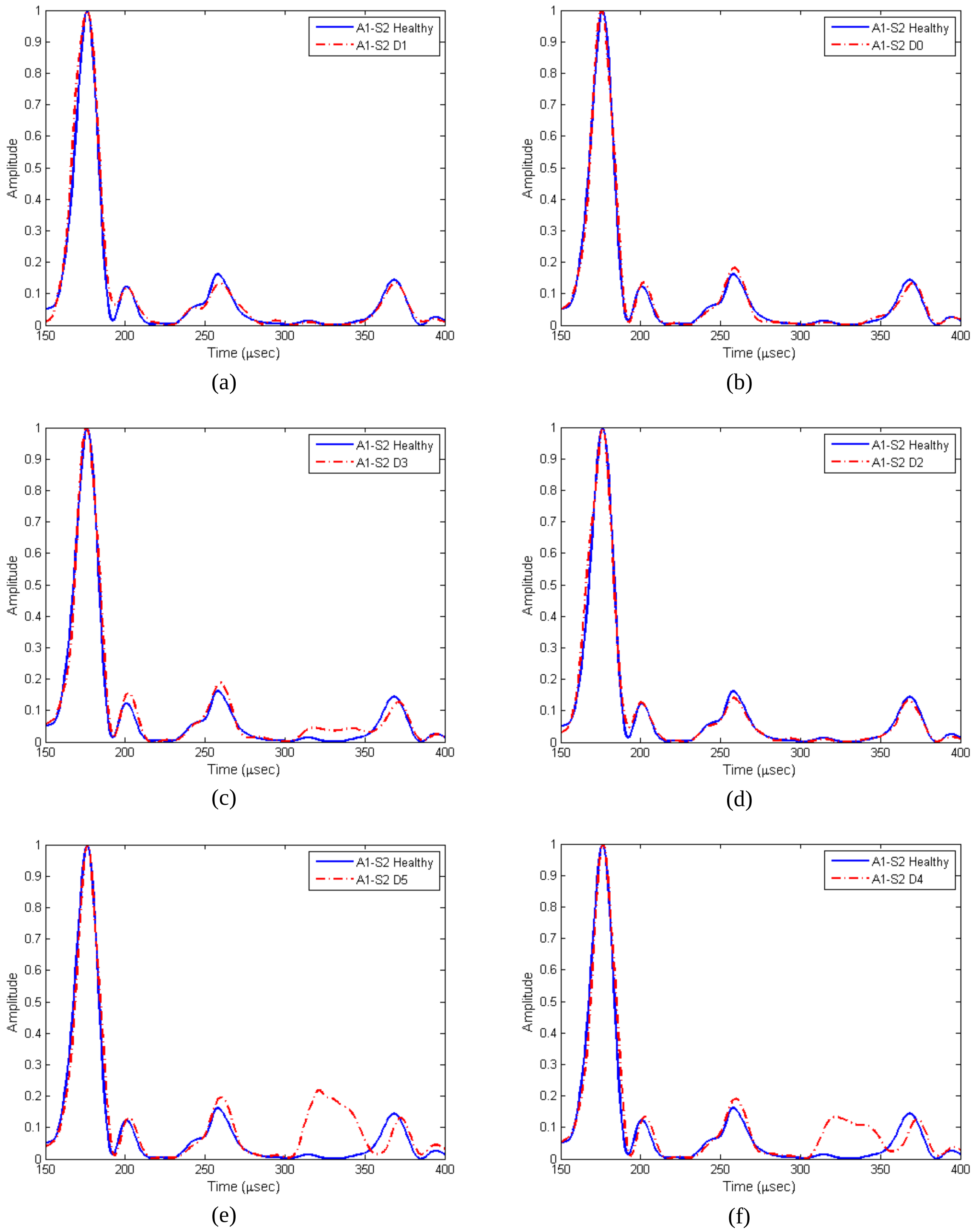

Figure 13 Changes occurred in sensor S2 due to variation of defect size

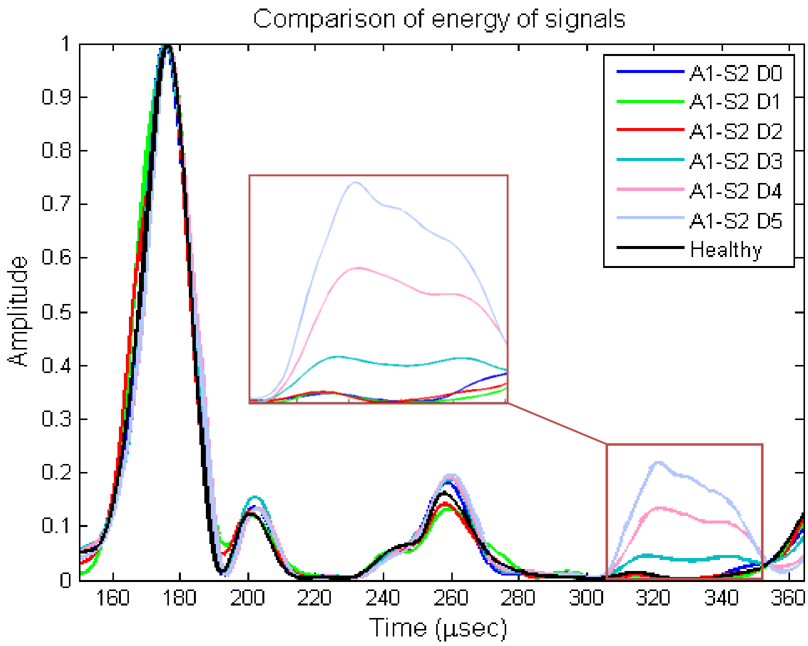

Figure 14 Comparison of changes occurred in signal due to change in defect size

As can be seen here, defects D0 to D2 has made no reflections and consequently cannot be detected using this excitation frequency. The other important point is that as the defect size increases, the reflection increases notably which can be used further to estimate the defect size.

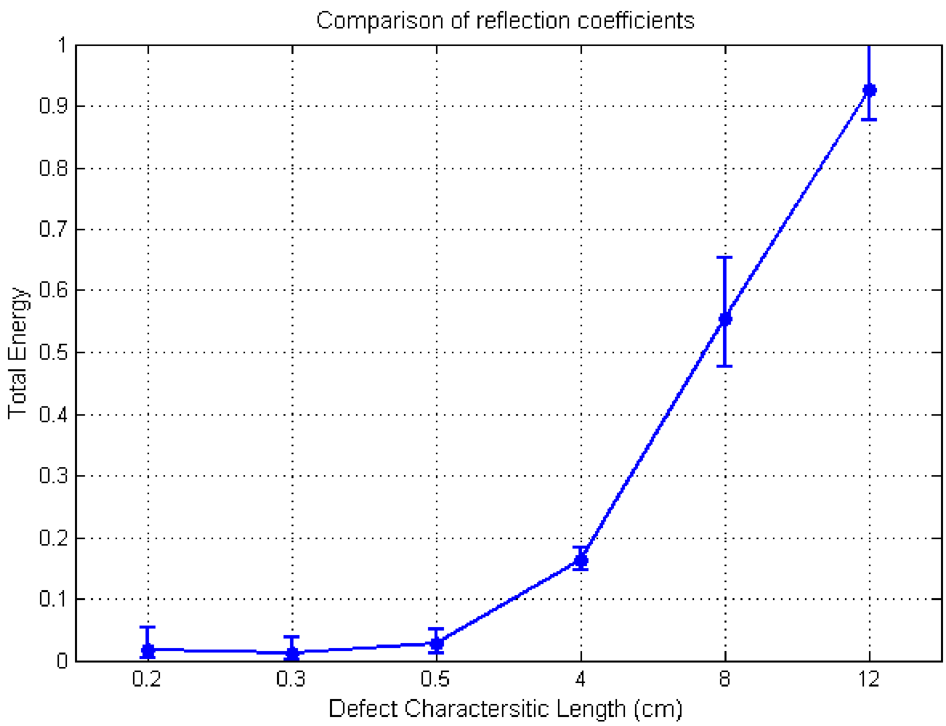

Figure 15 Reflection coefficients computed for sensor S2

6 Conclusions

A 2 m × 1 m aluminum plate with a crack was investigated experimentally in this study. A few piezoelectric disks as actuators and sensors were used to actuate and capture the Lamb wave signals. The raw captured signals were first denoised using a DWT and then the energy distribution of the purified signal was calculated using CWT. The group velocity of Lamb wave S_0 and A_0 modes and also the location of crack were consequently determined by applying the ToFs extracted from energy distribution of signals with a satisfactory accuracy.

The crack was assumed to be in line with actuators and sensors, and tests were performed on a single type of crack with six different sizes. Using acquired signals, the effect of variation of defect size on the results of experiments was also investigated. The assumptions which were used for processing the acquired experimental signals have been verified using numerical simulations.

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Nomenclature

f	Actuation frequency in Hz
N	Number of cycles in tone-burst signal
$A(t)$	Amplitude of tone-burst signal
a	Scale parameter
b	Time shift
ψ	Basic wavelet
ψ^*	Complex conjugate of ψ
$\psi_{m,n}(t)$	Discretized basic wavelet
$x_m(t)$	Reconstructed signal from the wavelet analysis

چکیده

در این پژوهش با بکارگیری امواج ورقی روشی برای پایش سلامت یک صفحه آلومینیومی ارائه شده است. از دیسک‌های پیزوالکتریک برای تحریک و دریافت سیگنال های امواج ورقی استفاده شده است. در بستر آزمایشگاهی طراحی شده ترک های تعبیه شده با عملگرها و حسگر های پیزوالکتریک در یک راستا می‌باشند. استخراج نتایج آزمایشگاهی با کیفیت بالا از انتشار امواج ورقی در یک سازه صفحه ای شکل با چالش‌هایی همچون تحریک چند مودی، دیسپرژن امواج، میرایی ماده و بازتاب های مرز سازه مواجه است. هدف اصلی این مقاله استفاده از تبدیل موجک بهینه سازی شده برای جداسازی امواج ورقی دریافت شده می‌باشد. در ادامه نیز مشخصه ای از توزیع انرژی سیگنال به منظور تعیین محل عیب استخراج شده است و نتایج تجربی توانایی بالقوه این روش در شناسایی عیوب را نشان می‌دهد.