Experimental Investigation of Crack Detection and Quantification Using PWAS Array

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ABSTRACT

Crack detection and size estimation are two key functionalities of a structural health monitoring algorithm. An experiment of crack detection in an aerospace grade aluminum sheet metal alloys was designed using an array of piezoelectric wafer active sensors (PWAS). Gaussian-distribution based damage mapping algorithm was used for analyzing the guided wave signals. Since multiple modes of Lamb waves often complicate the guided wave scattering, this can pose a significant challenge for an algorithm’s functionality. Mode rejection using appropriate tuning of the PWAS was used to selectively excite a single Lamb wave mode. In this case, symmetric Lamb waves were excited in the structure. A pitch-catch experimental mode was utilized. The crack was detected, localized, and the crack size was estimated.

STATE OF THE ART

The damage detection, localization and quantification are the most important features to assess the structural health of aerospace, mechanical and civil structures. SHM utilizes Lamb waves to determine these structural damage features. Lamb waves are suitable for fast structural damage detection since they propagate a long distance without any significant energy loss [1], [2]. The analyses of Lamb wave interaction could potentially detect, localize and estimate the size of various kinds of damage in structures [3]–[5]. Attempts have been made for quantifying structural defects using Lamb wave scatter field.
A network of sensors was used for defect visualization in pitch-catch experimental mode [6]. Wavenumber analysis was used for damage mapping in various materials [7] [8]. A transverse crack in a metallic beam was quantified by a signal processing algorithm in the time-frequency domain based on the wavelet transform technique [9]. This technique suppressed the diverse broadband interferences and effectively extract useful damage information. However, damage quantification in one-dimensional structure was considered.

The interaction of Lamb waves with rivet hole crack was studied both theoretically and experimentally [10], [11]. The studies showed that the crack in the hole significantly changes the scatter wave field. Fatigue crack and defects in adhesive bonding were identified by analyzing the scatter Lamb wave [12], [13]. Crack length estimation in stiffened aluminum plate was performed using local scatter analysis [14]. However, imaging method was not used. Array of PZT sensor network and wavenumber analysis were used for crack identification and crack imaging [2]. Wavefield imaging based on Lamb wave and guided wave imaging for pipe structure were studied [15], [16].

This paper presents a pitch-catch experimental investigation to detect, localize and quantify the crack size by using a Gaussian distribution-based Lamb wave imaging technique. Multiple networks of PWAS transducers were used to capture the scatter Lamb waves from a manufactured crack in an aerospace aluminum alloy.

![Figure 1. SHM Experimental setup for crack detection and quantification](image)

**EXPERIMENTAL SETUP**

An SHM experiment was designed and conducted on an aerospace grade aluminum sheet metal alloy. The dimension was 610 mm x 610 mm (2 ft by 2 ft) with 1.6 mm thickness. This aluminum specimen was instrumented with an active network of eight PWAS transducers as illustrated in Figure 1. A simulated crack which is a
very narrow slit was manufactured by using a 0.25 mm thin dental cutting disk, hereafter referred to as “crack”. The crack length was about 10 mm and oriented horizontally. The center of the horizontal crack was located at (305, 300) mm (origin was at the left bottom corner). The network of PWAS transducers circumscribed the crack at the center. The diameter of the circular network was about 300 mm. All the PWAS transducers were identical dimension (diameter = 7 mm and thickness = 0.2 mm).

A 3-count tone burst excitation signal at a center frequency of 450 kHz was used to perform the pitch-catch experiment. This frequency was chosen based on the tuning curve of PWAS and the dispersion curve of the aluminum. At this frequency-thickness product, the symmetric Lamb wave (S0) was dominant in this plate specimen. The same PWAS transducer was used as a transmitter and a receiver of Lamb wave signals. An oscilloscope was used to record the Lamb wave signals. The specimen edges were covered with damping clay to minimize the edge-reflected wave signals.

**EXPERIMENTAL RESULTS: WAVEFORM AND SIGNAL PROCESSING**

The waveforms of the pitch-catch experiment are illustrated in Figure 2. The transmitter PWAS (#T3) was transmitting the Lamb waves while the rest of the seven PWAS transducers were receiving the signals. In this configuration, the Lamb waves hit the crack perpendicularly and the scatter waves from the crack is expected to be maximum.

![Figure 2](image_url)

Figure 2. Pitch-catch signals recorded by all the sensors (R1 to R8) while the transmitter was PWAS#T3: (a) pristine signals; (b) measured signals
In the beginning, a set of baselines were recorded when there was no crack in the circular network. Then another set of measurement was performed when there was a crack. The experimental waveform results of the two sets are illustrated in Figure 3a,b. In each of the signals, the first wave packets are \( S_0 \) Lamb wave. These \( S_0 \) wave packets are stronger than \( A_0 \) wave packet at 450 kHz frequency, as expected.

![Figure 3. Scatter \( S_0 \) wave signals obtained by the subtraction process in the time domain signals](image)

The scattered wave signals (scattered \( S_0 \)) were determined by the subtraction of baselines from the signals measured with 10-mm crack. The scattered signals from various combination of transmitter and receivers were used for imaging methods to quantify the crack size. It can be noticed that some angular locations have very weak scatter waves such as \(#R1, #R5\). This means these locations are insensitive to the crack. It also reveals the non-axisymmetric Lamb wave scatter from this crack source.

**EXPERIMENTAL RESULTS: CRACK DETECTION AND LOCALIZATION**

Lamb wave-based imaging method was used for crack detection and localization. Before discussing the experimental results, the principle of the imaging method is briefly discussed. The detail of this principle can be found in ref. [5]. The imaging method involves the Gaussian distribution function and scattering signals. In this method, the scattering wave signals are calculated using pitch-catch and/or pulse-echo experimental mode/s. The interested structural area is divided into pixels. The time-of-flight (TOF) of every pixel was determined using the equation of ellipse/circle. The pitch-catch experimental mode involved elliptical orbit and the generic TOF can be determined by using the Eq. (1)

\[
t_{ij} = \frac{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{v_g} + \frac{\sqrt{(x_i - x_R)^2 + (y_i - y_R)^2}}{v_g}
\]  

(1)
where \( t_{ij} \) is TOF of scattered signal, \( x_T, y_T, x_R, y_R, x_i, y_j \) are the coordinates of transmitter sensor, receiver sensor, and pixel, respectively, \( v_g \) is the group velocities of Lamb wave mode of the wave propagation path \( T_i \) to \( R_j \). When the pixels lay on the damage orbit of a particular sensing path then, \( t_{ij} = t_d \). The total number of sensing paths is \( N = N_T!/(2!(N_T-2)!) \) (where, \( N_T \) is total number of transmitters). The flow chart of this method is illustrated in Figure 4.

![Flow chart of the method](image)

Figure 4. Imaging algorithm using our method based on Gaussian function [5]
The crack detection and localization imaging results using summation algorithm is illustrated in Figure 5. The pixel with highest field value (brightest pixel) indicates the crack location. The brightest location (predicted crack location) was determined as (306, 300) mm, whereas the actual crack center located at (305, 300) mm. There are also some other relatively brighter points (“phantom”) at the intersections of two crossing imaging paths which may mislead the results. However, they can be eliminated using a threshold (not shown here). The network with one transmitter may not be sufficient to estimate the crack size, hence multiple networks were used as discussed next.

![Figure 5. Crack detection and localization result using one network with one PWAS transmitter (PWAS#T3)](image)

**EXPERIMENTAL RESULTS: CRACK QUANTIFICATION**

For estimating the crack size, two networks with two PWAS transmitters were used. In this case, PWAS #T2 and PWAS #T3 were the transmitters whereas the rest of them were the receivers. The imaging results with summation algorithm are illustrated in Figure 6. The crack tips can be identified by using the sensing paths of two transmitters. The pixels with maximum index values were identified as the two crack tips. A threshold setting of 0.8 was used to narrow down the brightest pixels. A zoomed in view is illustrated on an inset figure which clearly shows two brightest pixels which are about 9-mm apart. Hence, the predicted crack size was about 9-mm whereas the actual crack size was 10-mm. Also, it can be noted that the crack is oriented horizontally as observed from the imaging result.
Figure 6. Crack quantification result using two networks with two PWAS transmitters (PWAS#T2 and PWAS#T3)

CONCLUSION

The experimental investigation showed that the Lamb wave-based imaging with Gaussian distribution functions can successfully detect, localize and quantify the crack size. One network with one PWAS transmitter and associated receivers maybe able to detect and localize the crack, however, multiple networks are needed to accurately predict the crack size. In this experimental investigation it was found that two networks with two PWAS transducers estimated the crack size within reasonable accuracy. The network should be chosen such that the scatter wave signals from the crack are relatively stronger.

FUTURE WORK

Pulse-echo experimental modes can be used besides the pitch-catch mode. The imaging methods can be further improved by incorporating a sensor configuration study. Multiplication imaging algorithm of Gaussian distribution can be used.

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REFERENCES


