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Advanced Crack Detection and Distance Estimation in Steel Plates Using Phased Array Acoustic Waves and Finite Element Analysis

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Abstract

Phased Array Ultrasonic Testing (PAUT) is a highly effective Non-Destructive Evaluation (NDE) technique extensively utilized for detecting and characterizing structural defects, such as cracks. This study presents a detailed simulation and analysis of longitudinal and shear acoustic wave propagation in a steel plate, conducted using Finite Element Analysis (FEA) with ABAQUS. Acoustic pressure data were collected and averaged across selected nodes, with a focus on significant pressure readings. The distance from the middle of the crack to the middle of the sensor line was estimated by analyzing the time interval between key pressure points and correlating this interval with the known speed of sound in steel. Advanced data processing techniques were utilized to refine the pressure-time data, preserving essential information while minimizing noise. The findings demonstrate the capability of PAUT not only in detecting but also in accurately estimating the distance from the crack to the sensor line. The comparison between predicted values and actual values of the distance from the middle of the crack to the middle of the sensor line utilizes precise dimensional measurements to ensure accuracy, with the Root Mean Square Error (RMSE) of 0.0039 and an average error of 1.85%. The extremely low RMSE indicates minimal deviation between predicted and actual values, reflecting high precision. Additionally, the average error of 1.85% shows that, on average, predictions are within 1.85% of the true values. Together, these metrics confirm that the model demonstrates exceptional accuracy and reliability, with both very small absolute and relative errors.

Keywords: Phased Array Ultrasonic Testing; Crack Detection; Acoustic Wave Propagation; Signal Processing.

1. Introduction

Phased Array Ultrasonic Testing (PAUT) has emerged as a highly advanced non-destructive evaluation (NDE) technique, acclaimed for its precision in detecting and characterizing internal structural flaws such as cracks [1]. Recent research has highlighted the advantages of PAUT over traditional ultrasonic testing methods. Zhang et al. [2] demonstrated PAUT's superior performance in inspecting complex structures, while Gholizadeh [3] reinforced its application in critical industries like oil and gas. Chimenti [4] explored PAUT’s use in aerospace for inspecting composite materials, noting its capability to detect delamination, which are challenging for conventional ultrasonic methods. Studies by Demirli et al. [5] and Silk and Bainton [6] further demonstrated PAUT's effectiveness in real-time inspections and its ability to access difficult-to-reach areas, such as welds and curved surfaces, where traditional methods struggle. The integration of advanced tools like Finite Element Analysis (FEA) has also enhanced PAUT's accuracy, as shown in simulations by Krautkramer and Krautkramer [7], which improved time delay calculations and detection of subtle defects. Additionally, signal processing techniques such as Time of Flight (ToF) have further refined PAUT's capabilities. Lamboul and Lopez [8] demonstrated that ToF improves the precision of crack distance measurements, highlighting the significance of these advancements in enhancing flaw detection and reducing noise in large-scale inspections. The growing body of research confirms PAUT’s role as a superior alternative to conventional ultrasonic testing methods, particularly in safety-critical applications where structural health monitoring is essential.

This study presents a novel approach to simulating and analyzing longitudinal and shear acoustic wave propagation in a steel plate using FEA within ABAQUS, addressing a critical need for more precise flaw detection and localization in non-destructive testing. The research focuses on the accurate detection and distance estimation of cracks, advancing the capabilities of PAUT by not only identifying the presence of structural flaws but also offering a method for precisely determining the distance from the middle of crack to the middle of sensor line. This ability with high accuracy is particularly important in industries such as aerospace, automotive, and civil engineering, where the structural integrity of materials is of paramount importance to safety and performance. The key novelty of this work lies in the estimation of the distance from the crack to the sensor line by analyzing the time interval between significant pressure points in the simulation and correlating this data with the known speed of sound in steel. This precise estimation capability adds significant value to the existing methods of PAUT, where conventional approaches are typically limited to crack detection without providing detailed localization. Additionally, advanced data processing techniques were employed to refine the pressure-time plots, ensuring critical information was preserved while minimizing noise. By enhancing both detection and localization accuracy, this study significantly contributes to improving the reliability and effectiveness of PAUT, making it a more powerful tool for structural health monitoring and maintenance. These findings highlight the potential of PAUT for non-destructive testing applications, offering not only improved safety in critical structures but also reducing inspection time and costs through more precise and efficient assessments.

2. Theory

This study leverages fundamental principles of acoustic wave propagation, finite element analysis, and phased array ultrasonic testing to investigate crack detection and distance estimation. PAUT employs an array of ultrasonic transducers to emit acoustic waves into a material, with the ability to steer and focus the beam through precise time delay adjustments applied to each transducer.

2.1 Acoustic wave propagation

The speed of longitudinal waves in a material, denoted as c_L, is a crucial parameter and can be calculated using the material's Young's modulus E and density ρ. The formula for calculating the speed of longitudinal waves is:

$$c_L = \sqrt{\frac{E}{\rho}} \tag{1}$$

2.2 Time of Flight (ToF)

ToF method is employed to estimate the distance from the sensor to the crack. ToF is defined as the time required for an acoustic wave to travel from the transducer to the crack and return back. The ToF can be expressed as [9]:

$$ToF = \frac{2d}{c_L} \tag{2}$$

where d represents the distance from the sensor to the crack and c_L is the speed of longitudinal waves. Rearranging this formula allows for the distance calculation:

$$d = \frac{ToF \times c_L}{2} \tag{3}$$

2.3 Time delay calculation

Ensuring the coherent propagation of the waves and their accurate interaction with the crack, The time delay (Δt_n) for each element was determined using the following formula:

$$\Delta t_n = \frac{n \times \mathrm{l} \times \sin(\theta)}{c_L} \tag{4}$$

where n represents the index of the element, l is the center-to-center distance between adjacent elements, θ is the desired steering angle of the acoustic beam, and c_L is the speed of longitudinal sound in steel [10].

2.4 The Root Mean Square Error (RMSE)

RMSE is a standard way to measure the difference between estimated values and actual values in statistical models. The formula for RMSE is:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{5}$$

Where n is The number of data points, y_i refers to The observed value and $\hat{y}_i$ refers to The predicted value for the i-th data point.

3. Simulation

In this simulation piezoelectric elements were not directly simulated, but their influence was represented through the acoustic pressure modeling. This study utilizes FEA in ABAQUS to simulate the propagation and reflection of longitudinal acoustic waves within a steel plate to detect the presence of a crack. The objective is to analyze the reflected signals and characterize the flaws based on their interaction with the acoustic waves generated by a phased array system.

In the simulation, a $0 \cdot 5m \times 0 \cdot 5m$ steel plate was modeled with a bulk modulus of 175×10^9 Pa and a density of 7800 kg/m^3, suitable for representing the physical properties of steel. The FEA simulation was conducted using ABAQUS to accurately model the behavior of the material under acoustic excitation. A fine structured mesh with a resolution of 0.002 and acoustic element type was employed to the plate. The phased array system, consisting of eight acoustic elements, was placed along one edge of the plate. Each element measured 3 mm in width, with a 1 mm gap separating adjacent elements, designed to generate longitudinal acoustic waves. Each element being triggered by a specific time delay relative to the previous one. The calculated time delays ensured that the resultant wave was directed at a specific angle towards a crack. The crack was introduced into the simulation using the seam crack tool in ABAQUS. Due to the crack's width being significantly smaller than its length, it was modeled as a line (Figure 1).

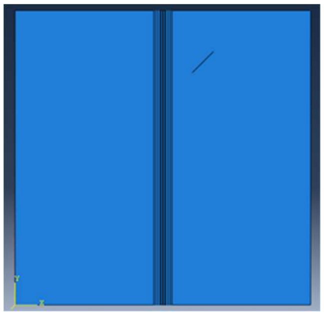

Figure 1. simulated plate, elements and the crack.

According to equation (1), The speed of longitudinal waves (c_L) within the steel was calculated. This calculated speed is essential for determining appropriate time delays for the phased array elements based on equation (4) this time delays increased linearly from element 1 to element 8. MATLAB was utilized to generate half-sinusoidal pressure signals for each element, ensuring the coherent propagation of the waves and their accurate interaction with the crack (Figure 2). Each of the elements also functioned as a pressure sensor to record the reflected waves after they interacted with the crack.

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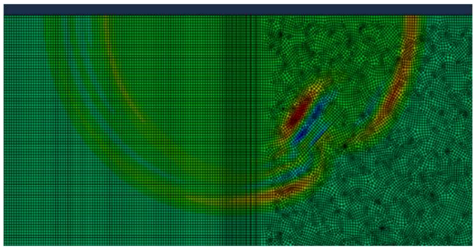

Figure 2. reflected acoustic waves after interacting with the crack.

4. Result and discussion

4.1 Acoustic pressure-time plot analysis

The process begins with getting the pressure data from each sensor element. The data from these sensors were analyzed to generate individual pressure-time plots, which were subsequently averaged to produce a comprehensive pressure-time plot (Figure 3).

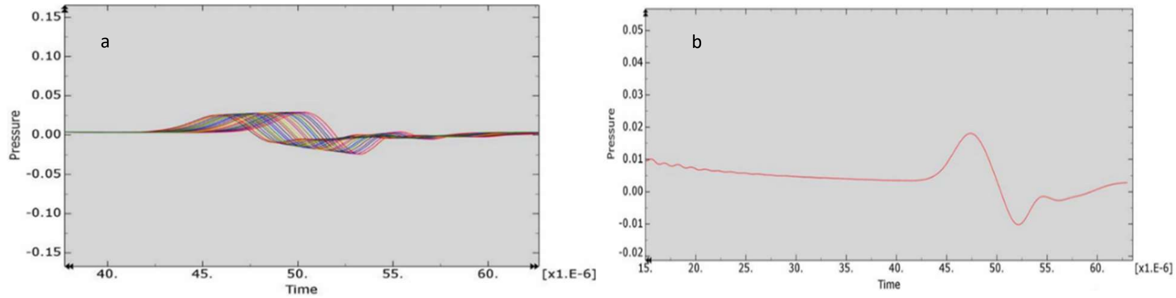

Figure 3. Individual sensors pressure-time plot (a); Averaged sensors pressure-time plot (b).

Data for time and acoustic pressure were extracted from the visualization module. In this module, an average of the acoustic pressure (POR) was calculated for selected nodes, which served as representative agents for all nodes in the model. Figure 4 shows Acoustic pressure - time plot.

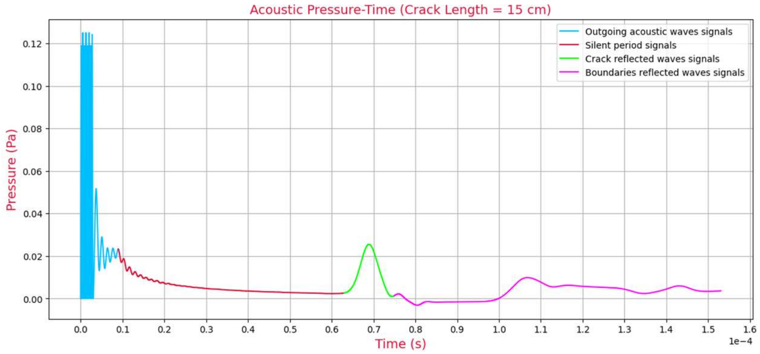

Figure 4. Acoustic pressure-time plot.

The data obtained from the pressure sensors were post-processed to produce a detailed pressure-time plot, which facilitated the analysis of acoustic wave interactions with the crack. Initially, the plot exhibited a series of peaks corresponding to the pressure pulses emitted by each element that represent the outgoing acoustic waves. Following the initial peaks, the plot exhibited a period of relative silence. This silent interval corresponds to the time required for the acoustic wave to travel from the transducer to the crack and back to the sensors. The first prominent peak following this silent period was identified as the reflection from the crack, indicating a successful interaction of the acoustic wave with the flaw. This reflection peak typically manifested as a half-sinusoidal waveform, consistent with the shape of the initial half-sinusoidal pressure signal used for excitation. After the crack reflection peak, the plot revealed additional fluctuations. These variations are primarily due to multiple reflections of the acoustic wave from the boundaries of the plate. Such reflections introduce noise into the pressure-time data.

4.2 Signal processing and distance estimation

The pressure-time plot generated from the ABAQUS simulation spans a temporal range from 0 to 8.5×10^{-5}seconds, capturing the dynamic response of acoustic waves as they interact with a crack within a steel plate. This dataset initially includes a variety of waveforms, among which the transmitted waves are irrelevant for crack analysis. To refine the dataset and enhance the accuracy of the analysis, these extraneous transmitted waveforms were systematically removed during the initial phase of signal processing. Subsequent to this initial filtering, the focus shifted to identifying the maximum pressure point, or peak, within the remaining data (Figure 5). This peak is critical as it indicates the moment of most significant interaction between the propagating acoustic wave and the crack, providing key insights into the crack's characteristics. Recognizing that data points following this peak may introduce noise or contain irrelevant reflections, these were also excluded from the dataset to prevent any distortion in the analysis. The refined dataset, now focused on the period leading up to and including the identified peak, offers a clearer representation of the wave-crack interaction. This process not only removes unnecessary information but also enhances the reliability and precision of the subsequent interpretation of the structural integrity.

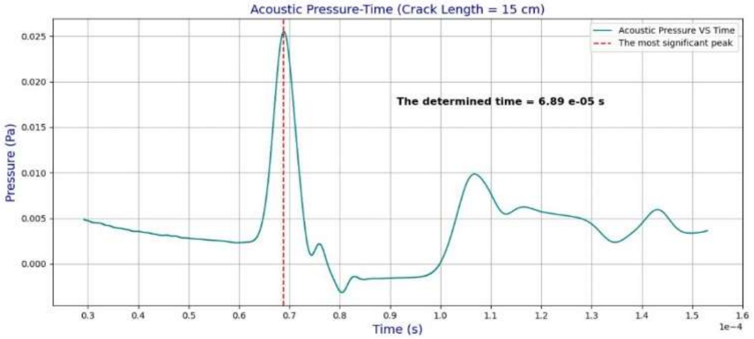

Figure 5. The maximum pressure point.

As illustrated in the Figure 6, the time corresponding to the maximum pressure generally increases with increasing the distance from the sensor line to the crack.

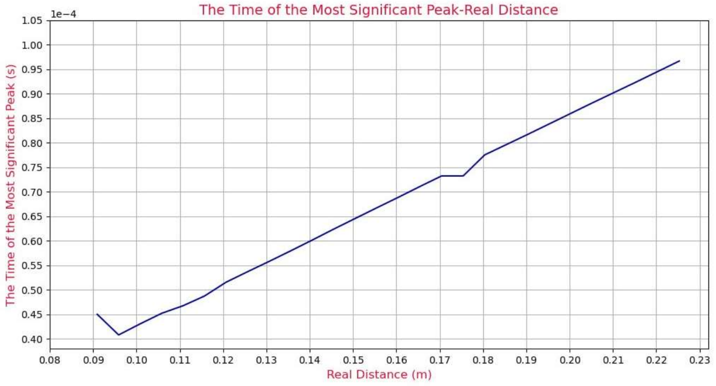

Figure 6. The time corresponding to the maximum pressure.

Estimating the distance between the center of the crack and the middle of the sensor line involves a combination of finite element analysis using ABAQUS and detailed examination of pressure-time plots. Initially, the pressure-time plot derived from the simulation is analyzed to pinpoint the maximum pressure point. This peak represents the most significant interaction between the transmitted acoustic wave and the crack, serving as a key indicator of the crack's position. Identifying this maximum pressure is essential for accurate distance estimation. Following the identification of the peak pressure, the corresponding time index is extracted from the pressure data stored in a dataframe. This time index reflects the exact moment when the acoustic wave encountered the crack, enabling the calculation of the total distance traveled by the wave. To determine the one-way distance from the sensor line to the crack, the total distance is first calculated by multiplying the time associated with the maximum pressure by the known speed of sound in steel. Since this time value represents the duration of the round trip of the wave - from the sensor to the crack and back - the calculated distance is divided by two to obtain the one-way measurement. The resulting distance is then compared with the actual distance between the center of the crack and the middle of the sensor line, as specified in the ABAQUS model. This comparison utilizes precise dimensional measurements to ensure accuracy, with an RMSE of 0.0039 and an average error of 1.85%. The extremely low RMSE indicates minimal deviation between predicted and actual values, reflecting high precision. These result confirm that the model demonstrates exceptional accuracy and reliability. The outputs from analysis are shown in the Table1.

Table 1. Real and estimated distance data and the error percentage.

Real Distance (cm)	Estimated Distance (cm)	Error percentage
0.090958937	0.106600000	17.1957
0.095901284	0.096600000	0.7286
0.100849315	0.101956965	1.0983
0.105802233	0.107049106	1.1785
0.110759382	0.110731618	-0.0251
0.115720218	0.115442221	-0.24023
0.120684286	0.122087985	1.1631
0.125651204	0.127179888	1.2166
0.130620646	0.132153376	1.1734
0.135592335	0.137245516	1.2192
0.140566033	0.142455836	1.3444
0.145541532	0.147773205	1.5334
0.150518656	0.152937816	1.6072
0.155497247	0.158086797	1.6653
0.16047717	0.163178701	1.6834
0.165458304	0.168389258	1.7714
0.170440542	0.173481161	1.7840
0.175423791	0.173481161	-1.1074
0.180407967	0.183664969	1.8053
0.185392995	0.188638456	1.7506
0.190378809	0.193611944	1.6983
0.195365348	0.198704084	1.7090
0.200352557	0.203795988	1.7187
0.205340389	0.208887892	1.728
0.210328798	0.213861379	1.6796
0.215317746	0.218834867	1.6335
0.220307194	0.22392677	1.6430
0.22529711	0.229018674	1.6518

Comparison between real distances and estimated distances is shown in Figure 7.

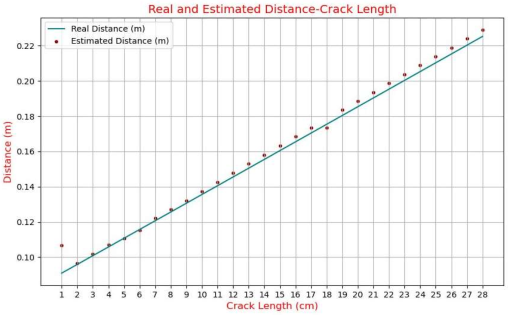

Figure 7. Comparison of real and estimated distances.

5. Conclusion

This study successfully integrates finite element analysis with acoustic wave modeling to enhance crack detection and distance estimation in steel plates. Although direct piezoelectric effects were not simulated, their influence was effectively modeled through acoustic pressure. By simulating longitudinal acoustic wave propagation in ABAQUS and analyzing pressure-time plots, the research demonstrated that the maximum pressure points correspond to reflections from cracks, providing accurate measurements. The comparison between estimated values and actual values of The distance from the middle of the crack to the middle of the sensor line, utilizes precise dimensional measurements to ensure accuracy, with an RMSE of 0.0039 and an average error of 1.85%. The extremely low RMSE indicates minimal deviation between predicted and actual values, reflecting high precision. The study underscores the efficacy of phased array techniques and careful data processing in non-destructive evaluation, highlighting their critical role in structural health monitoring and the precise characterization of material flaws.

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