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A NOVEL ELLIPSE LOCALIZATION METHOD IN COMPOSITE PLATE USING LAMB WAVE

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ABSTRACT

This work focuses on damage localization of composite materials using Lamb wave. The work extends the widely known ellipse method. It combines the ellipse method and the probabilistic inspection of defects (RAPID) method to achieve an accurate damage identification. The Bayesian method is used to fuse the two algorithms, and estimate the damage location from the posterior distribution. Finite element simulation is used to demonstrate the performance of the proposed method. The delamination is simulated within three sets of quasi-isotropy composite plates. Numerical results obtained with different damage locations in composite plates validated the performance of the proposed algorithm. Results highlighted the accuracy and robustness of the new algorithm.

Keywords: ellipse localization, Lamb wave, Finite Element Method, Bayesian

1. INTRODUCTION

As one of the important guided ultrasonic waves, Lamb wave has been proven to be a promising candidate in the application of future Non-destructive evaluation (NDE)[1]. Lamb wave-based technique has outstanding advantages of strong penetration and minimal attenuation over a long distance, and can be used to detect various types of damage (delamination, debonding, hole, crack, etc.)[2].

For damage localization, piezoelectric transducers are usually surface attached on the structure to form a transducer network. When Lamb waves excited by an actuator pass through the damage area, part of waves will scatter around the edge of the damage and be received by all the remaining sensors. The scattered waves can be obtained by comparing the recorded signal from healthy and damaged states. The scattered waves contain the information of damage feature such as: Time-of –Flight, wave energy etc. As one of the widely used damage sensitive features, the Time-of-flight (ToF) refers to the time taken by the concerned wave packet to pass from the actuator to the damage to the sensor. Ihn et al. [3] diagnosis the damage location as the intersection of elliptical probability loci on all the transducer paths using ToFs. Although many authors have used this elliptical strategy for damage localization [4], an accurate identification of damage location continues to remain challenges. One of the problems is that once the damage happens on the direct wave path, the scattered waves reflected by the damage are coincide with the transmission wave, thus it is difficult to calculate the ToFs for the scattered waves. Under such a situation, other features such as correlation, amplitude may be more appropriate than ToF for damage localization due to the fact that these features contain the damaged information on the straight path. Zhao et al. [5] innovatively introduced a reconstruction algorithm for probabilistic inspection of defects (RAPID) into a damage imaging method to improve the damage localization performance. This probabilistic imaging method has been extended to complex situations[6]. Although RAPID method is sensitive to the damage on the wave paths of transducers, the method is difficult for damage located far away from the wave path. The aim of this work is to combine the ellipse method and RAPID algorithm to achieve a more reliable and accurate damage identification using Bayesian method.

2. Methodology development

2.1 Damage localization using ToF

For quasi-isotropic plate-like structures, the geometric relationship for damage localization is schematically shown in Figure 1. Here, a i^{th} single actuator-sensor pair is presented with the coordinates (x_{ia}, y_{ia}) for the actuator and (x_{is}, y_{is}) for the sensor. And the coordinates of the center location of damage is (x_d, y_d). Theoretically the calculated ToF in the i^{th} actuator-sensor path T_i is defined as

$$T_i = \frac{\sqrt{(x_d-x_{ia})^2+(y_d-y_{ia})^2}+\sqrt{(x_{is}-x_d)^2+(y_{is}-y_d)^2}}{V_g}, \qquad (1)$$

where V_g is the group velocity of the Lamb wave at a given excitation frequency. As shown in Figure 1, assuming the velocity V_g is constant and T_i is given by scattered signal. The method assumes that the locus of the possible damage location

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is an ellipse with the actuator and sensor as the foci. The accurate damage location can be obtained by combine all the possible location derived from all sensor path.

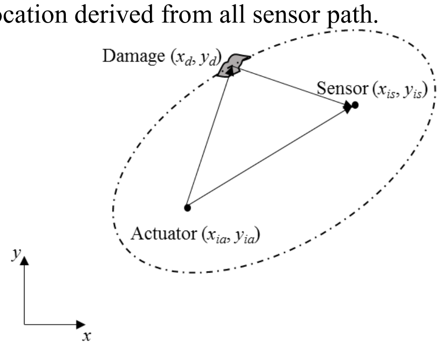

Figure 1. Ellipse method for damage localization.

The ToF-based ellipse method is difficult to extract the ToF feature in the specific scenario that the damage locates in the wave path. On the other hand, the ellipse approach has requirement of sensor number, it may yield to unreliable results with sparse sensor cases

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2.2. Damage localization using reconstruction algorithm for probabilistic inspection of defects

The reconstruction algorithm for probabilistic inspection of defects (RAPID) method is based on a physical intuition that a damage would cause the most significant signal change in the direct wave path, and the influence of damage decreases with the distance between the direct wave path and the damage location increases. The correlation is used as the feature to locate the damage. The correlation coefficient ρ is given by [5]

$$\rho = \frac{\sum_{k=1}^{K}(X_k-\mu_x)(Y_k-\mu_y)}{\sqrt{\sum_{k=1}^{K}(X_k-\mu_x)^2}\sqrt{\sum_{k=1}^{K}(Y_k-\mu_y)^2}}, \tag{2}$$

where the data set X, Y are baseline data and detected data, respectively. μ is the mean of the respective data set and K is the length of the data set. The damage probability distribution given by the transducer network can thus be expressed as

$$P(\mathrm{x},\mathrm{y}) = \frac{1}{N_p}\sum_{i=1}^{N_p} P_i(x,y) = \frac{1}{N_p}\sum_{i=1}^{N_p}(1-\rho_i)\frac{\beta-R_i(x,y)}{\beta-1} \tag{3}$$

where $P_i(x, y)$ is the damage probability distribution of i^{th} (i =1, 2, …, N_p) transducer pair. 1-ρ_i is the value of signal difference. $(\beta - R_i(x,y))/(\beta-1)$ is the spatial distribution function of i^{th} path, with its contour in the shape of an ellipse, as shown in Figure 2.

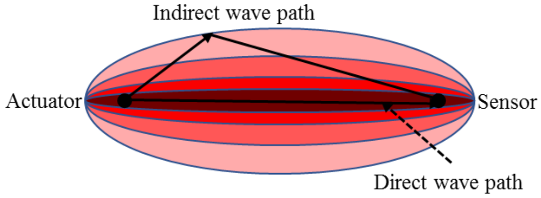


Figure 2. Illustration of the elliptical distribution function of the RAPID algorithm.

Generally, if a damage occurs, a set of transducer pair signals will be affected. However, the transducer paths which are far away from the damage area are insensitive to the damage.

2.3 Bayesian approach for damage localization

One outstanding advantage of the Bayesian approach here is that the probability distribution of the RAPID method can be easily incorporated into the ToF-based ellipse analysis as prior information to reduce uncertainty[7]. The present study employs Bayesian method for damage localization based on the mentioned above two methods.

Assume that the measurement uncertainty is described by ε, and ε follows a normal distribution with zero mean and variance σ^2. The probabilistic description of the measured ToF for the i^{th} actuator-sensor path T_m^i can be expressed as

$$T_m^i = T_c^i(x_d, y_d) + \varepsilon \tag{4}$$

where $T_c^i(x_d, y_d)$ is the theoretical calculated ToF using equation (1), with damage location parameters x_d, y_d. And these unknown parameters of damage location can me simplified as a vector $\boldsymbol{\theta}$ = [x_d, y_d, σ]. The likelihood function $p(D|\boldsymbol{\theta})$ is a probability distribution of the measured ToF data D = [T_m^1, T_m^2, …, $T_m^{N_p}$]. N_p is the total number of transducer paths. In this case, the likelihood function can be written as

$$p(\boldsymbol{D}|\boldsymbol{\theta}) = \prod_{i=1}^{N_p}\frac{1}{\sqrt{2\pi}\sigma}\exp\left\{-\frac{(T_m^i - T_c^i(x_d,y_d))^2}{2\sigma^2}\right\}. \tag{5}$$

Here, the prior distribution given as the relating the probability distribution of RAPID shown in equation (3) and non-information prior distribution of σ, can be defined as

$$p(\boldsymbol{\theta}) = \frac{1}{\sigma}\frac{1}{N_p}\sum_{i=1}^{N_p}(1-\rho_i)\frac{\beta-R_i(x_d,y_d)}{\beta-1}. \tag{6}$$

It is worth mentioning that such prior distribution can theoretically make uncertainty of damage localization reduce, because the RAPID prior reduces the scope of algorithmic search. Combining the prior information provided by RAPID method and the likelihood function obtained by ToF method, the parameters of damage location can be obtained by Bayesian approach.

3. Validation of the proposed Bayesian method for damage localization

3.1. Finite element model

The finite element model (FEM) is employed to investigate the performance of the proposed method. Three-dimensional FEM simulations are performed using ABAQUS software. As shown in Figure 3, a 450 mm×450 mm×1.28 mm and $[45°/-45°/0°/90°]_s$ composite laminate with four PZT transducers are constructed. Two numerical simulations are performed, one with delamination damage and one without the damage. The circular delamination with a 40mm diameter is modeled at the center of the composite plate. The delamination is modeled by a volume split in which the FE nodes across the delamination surfaces are separated by a small distance. Solid elements with square dimensions 0.4 × 0.4 mm^2 are used. The excitation signal used in this study is a 160kHz narrow-band 5-cycle sinusoidal tone burst modulated by a Hanning-window.

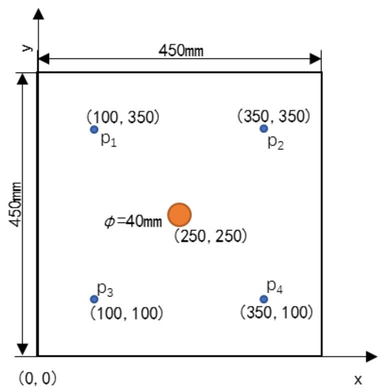


Figure 3. Layout of the composite plate with four PZT transducers in the numerical study.

3.2 Signal processing and features extraction

The signals are extracted for all wave paths of healthy and damaged plates. In order to extract ToF information, the signal from the damaged plates are subtracted from that of the healthy plates. Thereafter a Hilbert transform is applied to the scattered signal in order to extract the envelope. In order to extract the correlation feature, the time window of the first wave package is used. The Figure 4 shows the first wave package of healthy and damaged signals of p1-p4 path for demonstration purpose.

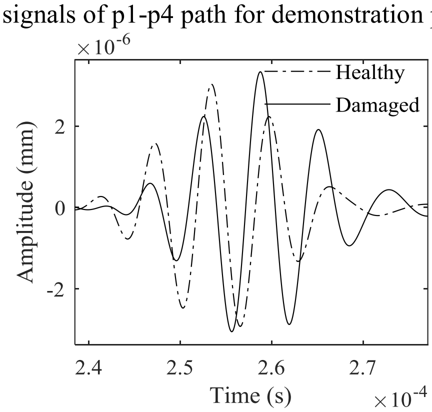
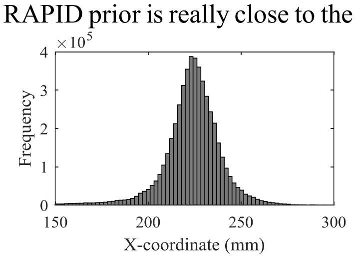


Figure 4. Healthy and damaged time windowed signal of first wave packet for p1-p4 path

3.3 Damage localization results

In this study, the group velocity of A_0 mode at the frequency of 0.16 MHz is experimentally calculated as 1520 m/s. The MCMC procedure is performed to identify the damage location. For each parameter, a total of 5 000 000 samples are obtained. Figure 5 illustrates the histograms formed by the samples for each parameter. Figure 6 illustrates the joint PDF of damage location. It can be observed that the localization result of Bayesian estimation with RAPID prior is really close to the actual damage.



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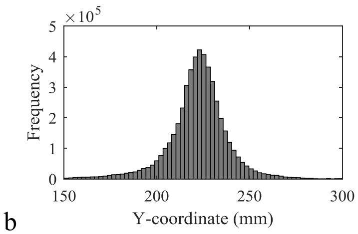

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Figure 5. Histograms of MCMC samples for parameters; (a) x-coordinate (x_d) and (b) y-coordinate (y_d)

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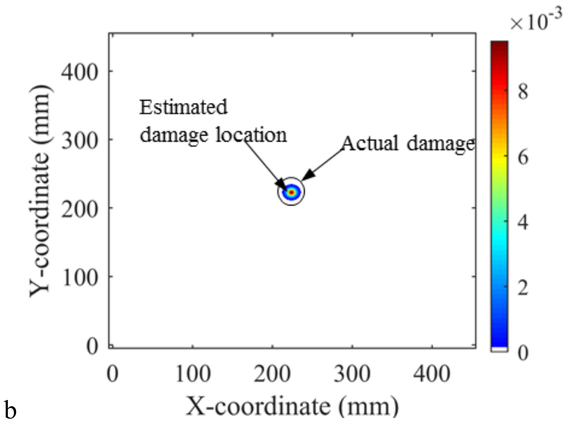

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Figure 6. Joint PDF of possible damage location

4. CONCLUSION

This article focuses on damage localization in composite materials using Lamb wave method. The Bayesian method is proposed to fuse the ToF-based ellipse localization and RAPID localization. Numerical results obtained with delamination damaged quasi-isotropic composite plate validate the ability of the proposed algorithm. Results highlight accuracy and robustness of the new method.

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