ACTA MECHANICA SOLIDA SINICA 30 (2017) 65–74

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/CAMSS

Nondestructive testing method based on lamb waves for localization and extent of damage☆

Jianlin Chen, Zheng Li, Kezhuang Gong*

State Key Laboratory of Turbulence and Complex System, College of Engineering, Peking University, Beijing 100871, PR China

ARTICLE INFO

Article history:
Received 6 May 2016
Revised 3 June 2016
Accepted 14 June 2016
Available online 10 February 2017

Keywords:
Lamb wave
Damage detection
Cross correlation
PZT wafer
Aluminum plate

ABSTRACT

Based on Lamb wave analysis of propagation in plate-like structures, a damage detection method is proposed that not only locates the position of the damage accurately but also estimates its size. Similar damage detection methods focus only on localization giving no quantitative estimation of extent. To improve detection, we propose two predictive circle methods for size estimation. Numerical simulations and experiments were performed for an aluminum plate with a hole. Two PZT configurations of different sizes were designed to excite and detect Lamb waves. From cross-correlation analysis, the damage location and extent can be determined. Results show that the proposed method enables a better quantitative resolution in detection, the size of the inspection area influences the accuracy of damage identification, and the closer is the inspected area to the damage, the more accurate are the results. The method proposed can be developed into a multiple-step detection method for multi-scale analysis with prospective accuracy.

1. Introduction

Non-destructive testing (NDT) is a comprehensive technique used in industry to evaluate the mechanical properties of materials and the integrity of structures without causing damage. Depending on developments of NDT methods, dozens of detecting methods are widely applied in industry, although those based on Lamb waves have been drawing increasing attention. The reason is that Lamb waves can propagate long distances with low attenuation in plate-like structures, and are highly sensitive to small imperfections. Therefore, Lamb waves have a great potential for fast damage detection of plate-like structures.

Since Lamb's derivation in 1889 of the dispersion equation for wave propagation for an infinite free plate [1], much effort has been spent to obtain the frequency dispersion curves numerically [2]. For applications of Lamb waves in NDT, Rose studied the propagation of ultrasonic Lamb waves in plates [3]. Thereafter, NDT methods based on Lamb wave analysis have advanced significantly in damage detection of plates [4]. Like guided waves in structures, Lamb waves have multiple modes and complicated dispersive characteristics [5]. Hence, many techniques have been developed to detect damage in plates based on baseline data, which includes the signal acquired from the intact plate. Plumbum–zirconate–titanate (PZT) patches or wafers are widely used as actuators and receivers of Lamb waves for its effective signal control and design as well as light weight [6]. For better accuracy from the method, the key is either to excite an appropriate mode in a non-dispersive region [5,7] or to choose an appropriate signal processing method with good time-frequency resolution. Li et al. [8] proposed a combined method employing

☆ Project supported by the National Natural Science Foundation of China (Nos. 11172003 and 11521202).

* Corresponding author.
E-mail address: lizheng@pku.edu.cn (Zheng Li).

http://dx.doi.org/10.1016/j.camss.2016.06.001

empirical mode decomposition (EMD) and wavelet analysis to attain good time resolution of the response signals. Gangadharan et al. [9] proposed a time reversal technique using Lamb waves to detect damage in an aluminum plate; despite no baseline, they achieved good results. Cai et al. [10] provided a time–distance domain transform (TDDT) method to interpret the dispersion of Lamb waves, which can result in high spatial resolution images of damage areas. Although there are some NDT methods based on Lamb waves, most are focused on determining the location of the damage; only a few identified quantitatively the extent of the damage. Su et al. [11] proposed a Lamb-wave-based damage imaging approach with an active sensor network to reveal the overall health status of an entire structure under inspection. They could determine the presence of damage visually, but could not provide its exact extent. Recently, Devivier et al. [12] proposed an approach to image the full-field ultrasonic flexural waves in a spatially and temporally resolved manner, but they did not develop this method for damage detection.

This paper proposes an NDT approach based on Lamb wave analysis to identify both the position and the size of plate damage. PZT wafers are used in a square test configuration; the cross-correlation function is applied in signal processing. Numerical simulation and experimental testing were performed on aluminum plates with simulated damage. The results are presented below. The effectiveness of identification methods and testing ranges are discussed regarding detection accuracy.

2. Damage identification based on Lamb waves

Consider a large plate with free boundaries; an excitation signal acts at its center and spreads out across the plate by wave propagation. If testing sensors are set at certain distances around the excitation point, direct wave signals can be recorded as well as reflected waves from the plate periphery or from damage sites within the plate. For an intact plate, the received signals only contain wave propagation data without any distortion from damage. Hence, comparing the received data from a damaged plate with those of an intact plate, a difference would obviously show the presence of damage. We choose a square configuration for the PZT wafers (Fig. 1); its centered wafer (PZT0) is the actuator, and the other four corner wafers (PZT1, PZT2, PZT3, PZT4) are receivers. If we denote by S_n the intact signal and S'_n the signal with damage information, then their difference $\Delta S_n = S'_n - S_n$ gives the response signal reflecting the damage. From a non-vanishing ΔS_n, we can determine the presence of damage.

Beyond the determination of damage, we need to accurately locate the damage. Assuming that damage appears in the plate (Fig. 1), PZT2 receives signal S_n propagating only along path d_2 in the intact plate; it receives signal S'_n propagating along paths d_2 and $d_0 + d_{02}$ in the damaged plate. Hence, ΔS_n is the signal propagating along path $d_0 + d_{02}$. This difference in the signals spreading along paths d_2 and $d_0 + d_{02}$ depends on the time delay Δt between ΔS_n and S_n. Using signal processing analysis, we can obtain this time delay. Similarly, time delays for the other three receivers, PZT1, PZT3, and PZT4

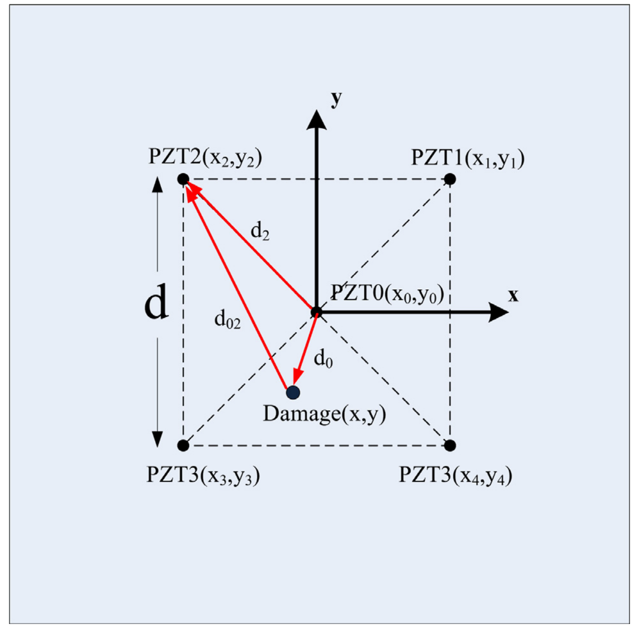

Fig. 1. – Square configuration of the PZT wafers.

can be obtained. To get an accurate time of flight, we choose the cross-correlation function to process the data.

If we set (x_0, y_0) as the coordinates of the actuator PZT0, (x_i, y_i) as the coordinates of the receivers PZTi ($i = 1,\ldots,4$), and (x, y) as the coordinates of the center of the damage (Fig. 1), we can obtain the time delay for PZT2 from

$$\frac{d_0 + d_{02}}{v} - \frac{d_2}{v} = t_0 + t_{02} - t_2 = \Delta t_2, \quad (1)$$

where v is the wave velocity, t_0 the time of flight from PZT0 to the damage, t_{02} and t_2 are time-of-flights from the damage and from PZT0 to PZT2, respectively. Δt_2 can be obtained by comparing the response signals of the intact and damaged plates. By elementary geometry (Fig. 1), $d_0 = \sqrt{(x - x_0)^2 + (y - y_0)^2}$ and $d_{02} = \sqrt{(x - x_2)^2 + (y - y_2)^2}$, and hence Eq. (1) can be expressed as

$$\sqrt{(x - x_0)^2 + (y - y_0)^2} + \sqrt{(x - x_2)^2 + (y - y_2)^2} = \frac{\sqrt{2}d}{2} + v \cdot \Delta t_2, \quad (2)$$

where d is the side length of the square PZT configuration. Therefore, from Eq. (1), we can obtain the equations for each of the corner PZT wafers

$$\frac{d_0 + d_{0i}}{v} - \frac{d_i}{v} = t_0 + t_{0i} - t_i = \Delta t_i \,. \quad (3)$$

Similarly, with $d_{0i} = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ ($i = 1, 2, 3, 4$), we have from Eq. (2)

$$\sqrt{(x - x_0)^2 + (y - y_0)^2} + \sqrt{(x - x_i)^2 + (y - y_i)^2} = \frac{\sqrt{2}d}{2} + v \cdot \Delta t_i. \quad (4)$$

From the dispersion curves for Lamb waves in a plate (Fig. 2), we note that in the low-frequency range there are