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A scanning spatial-wavenumber filter and PZT 2-D cruciform array based on-line damage imaging method of composite structure

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ABSTRACT

The spatial-wavenumber filtering technique of Lamb wave is gradually applied for damage inspection of composite structure in recent years because it is an effective approach to distinguish the wave propagating direction and mode. But for on-line damage monitoring of composite structure by using spatial-wavenumber filter, the problem is how to realize the spatial-wavenumber filtering of Lamb wave when the wavenumber response cannot be measured or modeled. This paper proposes a scanning spatial-wavenumber filter and piezoelectric sensor (referred to as PZT) 2-D cruciform array based on-line damage imaging method of composite structure. In this method, a 2-D cruciform array constructed by two linear PZT arrays is placed on composite structure permanently to acquire Lamb wave damage scattering signal on-line. For one linear PZT array, a scanning spatial-wavenumber filter which does not rely on any modeled or measured wavenumber response is designed to filter the damage scattering signal at a designed wavenumber bandwidth to give out a wavenumber-time image. Based on the image, the wavenumber of the damage scattering signal projecting at the array can be obtained. The same process can be also applied to the other linear PZT array to get the wavenumber projecting at that array direction. By combining with the two projection wavenumbers, the damage can be localized without blind angle. The method is validated on an aircraft composite oil tank of variable thickness. The validation results show that the damage direction estimation error is less than 2° and the damage distance estimation error is around 20 mm in the monitoring area of nearly 600 mm × 300 mm. It indicates an acceptable performance of the damage imaging method for complex composite structure.

1. Introduction

Modern structures on aircraft make increasing use of composite materials. However, the inner damage of composite structure can reduce the strength and even cause an air crash [1]. Hence, the damage monitoring of composite structure is an important research topic in the field of Structural Health Monitoring (SHM) [1–3].

Among the existing SHM methods for composite structure, much attention has been paid to the piezoelectric sensor (referred to as PZT in the rest of the paper) and Lamb wave based SHM technology because it is sensitive to small damage and long detection range, and it can be also applied to on-line damage monitoring [1–4]. In recent decade, PZT array and Lamb wave based damage imaging methods have been widely studied, such as delay-and-sum imaging [5–8], time reversal focusing imaging [9–12], damage probability imaging [13–16], ultrasonic phased array [17–20] and multi-signal classification [21]. They utilize a large number of actuator-sensor channels from a network of PZTs to map the structure that is monitored based on the measurement of Lamb wave damage scattering signal, producing a visual indication of damage location, with the advantages of high signal-to-noise ratio, high damage sensitivity and large scale structure monitoring.

However, most of the methods mentioned above process Lamb wave signal in time domain or frequency domain. Comparing with that, the spatial-wavenumber filtering technique performed in spatial-wavenumber domain is an effective approach to distinguish Lamb wave propagating direction and mode. Thus, this technique has been gradually studied and applied to ultrasonic imaging based Non-Destructive Testing (NDT) in recent years [22–27]. In most of these studies, the spatial response of Lamb wave propagating on an inspected structure is measured by using a Scanning Laser Doppler

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Vibrometer (SLDV) to scan all the spatial measuring points on the whole structure first. Then, 3D Fourier Transform is used to convert the spatial response to wavenumber response. Finally, a wavefield image constructed by the spatial-wavenumber response can be obtained. Based on the wavefield image of the whole structural plane, a spatial-wavenumber filter can be set to extract damage features for damage evaluation. Although all these studies show a high damage inspection accuracy of the spatial-wavenumber filter, they are time-consuming and can be only used to off-line damage inspection because they are limited to point-by-point measurements of Lamb wave spatial-wavenumber response by using the SLDV. It is inconvenient to apply them to on-line damage monitoring.

Considering on-line damage monitoring by taking the advantage of the spatial-wavenumber filtering technique, Purekar and Pines et al. [28,29] propose a spatial-wavenumber filter based on-line damage imaging method. In this method, a linear PZT array is placed on a monitored structure permanently to acquire Lamb wave damage scattering signal. But comparing with using the SLDV, the PZT array cannot be moved. It can be only used to obtain the spatial response of the damage scattering signal at the structural area covered by the PZT array. Therefore, a finite element simulating method is adopted to get the wavenumber of Lamb wave propagating on the structure. After that, a spatial-wavenumber filter is designed based on the modeled wavenumber and the obtained spatial response to search the damage direction. Wang et al. [30] also develop this method for on-line damage imaging of composite structure. These previous studies show a high computational efficiency and damage direction estimation accuracy of the spatial-wavenumber filter. However, the accurate wavenumber response of Lamb wave signal propagating on composite structure is difficult to be modeled, especially on complex composite structure. Therefore, the problem of applying the spatial-wavenumber filter to on-line damage imaging of composite structure is how to realize the spatial-wavenumber filtering of the damage scattering signal when the wavenumber response of Lamb wave cannot be measured or modeled accurately. In addition, the blind angle and near field blindness problem of the linear PZT array should be further studied.

In this paper, a new damage imaging method of composite structure based on a scanning spatial-wavenumber filter and PZT 2-D cruciform array is proposed. The scanning spatial-wavenumber filter which does not rely on only modeled or measured wavenumber response is proposed first. And then, a damage imaging method based on the filter is proposed, and the corresponding damage localization method of no blind angle is given as well. Finally, the damage monitoring performance of the method for complex composite structure is validated on an aircraft composite oil tank of variable thickness.

2. The scanning spatial-wavenumber filter

In this section, Lamb wave time domain sampling and spatial sampling, and the theoretic fundamental of spatial-wavenumber filter are discussed. After that, the scanning spatial-wavenumber filter is proposed.

2.1. Lamb wave time domain sampling and spatial sampling

There is a linear PZT array placed on a structure as shown in Fig. 1. It consists of M PZTs and the distance between the centers of each two adjacent PZTs is Δx. The PZTs are numbered as $m = 1,2,\ldots,M$. A Cartesian coordinate is built on the array. The center point of the linear PZT array is set to be the original point.

There is a damage located at (x_a, y_a). The direction (angle) and distance of the damage relative to the linear PZT array are supposed to be θ_a and l_a respectively. To obtain the damage scattering signal, a frequency narrowband excitation signal of central frequency ω is input to the PZT at the original point to excite Lamb wave of frequency narrowband. When the Lamb wave propagates to the damage, the damage scattering signal is generated and it can be acquired by the array. According to some previous studies [4,9,17], the amplitude of Lamb wave A_0 mode is dominant at low excitation frequency. Thus, the damage scattering signal can be approximated to be single-mode signal when the excitation frequency is low. The wavenumber of the damage scattering signal is denoted as k_a. It is wavenumber narrowband and it can be considered to be constructed by two components. The first component is the wavenumber projecting at the array direction (X-axis projection wavenumber) $k_x = k_a \cos\theta_a$ and the second component is the Y-axis projection wavenumber $k_y = k_a \sin\theta_a$.

Fig. 2 gives an example of the damage scattering signal acquired by the linear PZT array. It is expressed as a waterfall plot. The horizontal coordinate of the waterfall plot is sampling time and the longitudinal coordinate is sampling distance which is corresponding to the location of the PZTs.

Ordinarily speaking, the linear PZT array is seen to be a time domain sampling device. Each PZT can output a time domain sampling signal as shown in Fig. 2 when looking the waterfall plot from the time direction (blue line). The sampling dots (length) and the sampling rate are denoted as L and f_s respectively.

The linear PZT array can be also regarded as a spatial sampling device to acquire spatial response of the damage scattering signal at the area covered by the array when looking the waterfall plot from the distance direction (red line). The spatial sampling rate is $2\pi/\Delta x$. The spatial response acquired by the linear PZT array at time t_r can be represented as Eq. (1).

$$f(x, t_r) = [f(x_1, t_r), f(x_2, t_r), \cdots, f(x_m, t_r), \cdots, f(x_M, t_r)] \quad (1)$$

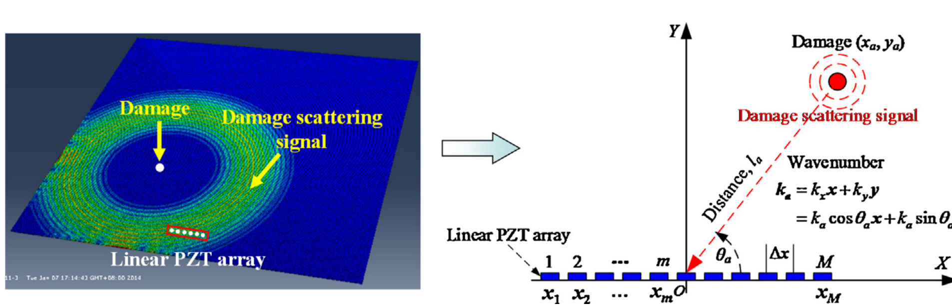

Fig. 1. Schematic diagram of Lamb wave spatial sampling.