DEVELOPMENT OF DAMAGE MONITORING SYSTEM USING DIRECTIONAL TRANSDUCERS IN THIN PLATES

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Abstract

This paper develops directional Lamb-wave transducers and applies them to nondestructive inspections for narrow aluminum and CFRP beams. This technique employed the pulse-echo method using two directional piezoelectric elements especially designed for the low-frequency Lamb A_0 mode. Amplitude of the multiple reflected waves in the width direction was significantly reduced and echoes from the damage were clearly detected. We successfully detected damages and evaluated their positions.

1 Introduction

Composite laminates are applied to primary load-bearing structural components in newly developed aircraft because of their superior specific strength and stiffness. Complicated damage from matrix cracks and delamination can be generated in the long operation lifetime of an aircraft. Hence, in-service structural health monitoring techniques have been developed to make inspection more efficient and to reduce maintenance costs.

Ultrasonic Lamb waves are one of the non-destructive evaluation techniques that have potential for long-range inspection because they can propagate a long distance. When a receiving transducer is positioned at a remote point on the structure, the signal received contains information about the integrity of the line between the transmitting and receiving transducers. Many studies have been conducted to detect damage in CFRP laminates using Lamb wave method. Tang and Henneke [1], Dayal and Kinra [2], Seale et al. [3], and Toyama et al. [4] detected transverse cracks in CFRP cross-ply laminates as a reduction in Lamb wave velocity due to a loss of stiffness. Based on their studies, measuring Lamb wave velocity has the potential to quantitatively evaluate in composite laminates. Guo and Cawley [5,6] and Valdes and Soutis [7] detected delamination in CFRP laminates by a reflected wave at the delamination edge, and determined its location using the arrival time of the reflected wave. However, a reflected wave is often not clearly detectable because its amplitude is reduced due to scattering at the delamination edge. The dispersive nature of Lamb waves, as well as attenuation, creates more difficulty in distinguishing the reflected wave from the detected waveform. Tan et al. [8], Birt [9] and Bourasseau et al. [10] detected delamination in CFRP laminates and foam core sandwich structures based on attenuation of the transmitted Lamb wave. Their method is a simple and reliable method to detect damage. However, it is very difficult to quantitatively evaluate the delamination size using from waveform changes, including attenuation.

The purpose of this study is to develop a damage monitoring system for a plate-like structure using Lamb waves. For this purpose, we develop a directional piezoelectric element as a Lamb-wave transducer. We subsequently detect damage in aluminum and CFRP beams and demonstrate the usefulness of the directional transducer.

2 Experimental Procedures

2.1 Development of Directional Transducer

Thin rectangular PZT elements that operate primarily in the longitudinal mode were selected as Lamb wave transducers. The dimensions of element were designed so that the element has directional sensitivity for the 50 kHz A_0 mode propagating in a 1-mm-thick aluminum and CFRP plates. The longitudinal dimension was selected to be sensitive to the 50 kHz A_0 mode in its direction, while the transverse dimension and thickness were intentionally selected to be insensitive to the 50 kHz A_0 mode in their directions.

First, to effectively receive the 50 kHz A_0 mode in the longitudinal direction, the longitudinal dimension was determined to be equal to half the wavelength of the A_0 mode. This determined the longitudinal dimension as 7 mm. Second, the thickness, much thinner than that corresponding to its resonant frequency of 50 kHz, is expected to suitable for the strategy, and was therefore determined as 0.5 mm. Finally, the effect of the element width on the directional sensitivity was experimentally investigated.

Fig. 1 illustrates the experimental set-up to evaluate the directional sensitivity. Elements with widths of 1 mm, 3 mm, and 5 mm were chosen, and their directional sensitivity was compared. The elements were bonded to the surface of an aluminum plate. A commercial transducer with a diameter of 20 mm was used as a transmitter and was placed on the plate surface via coupling gel 100 mm away from center of the sensor, with incident angles steps of 10 degree, from 0 degree to 90 degree. The excitation signal applied to the transmitter was a 50 kHz, five-cycle, sinusoidal tone-burst enclosed in a Hanning window. The peak-to-peak amplitude of the detected A_0 mode was measured as function of the incident angle.

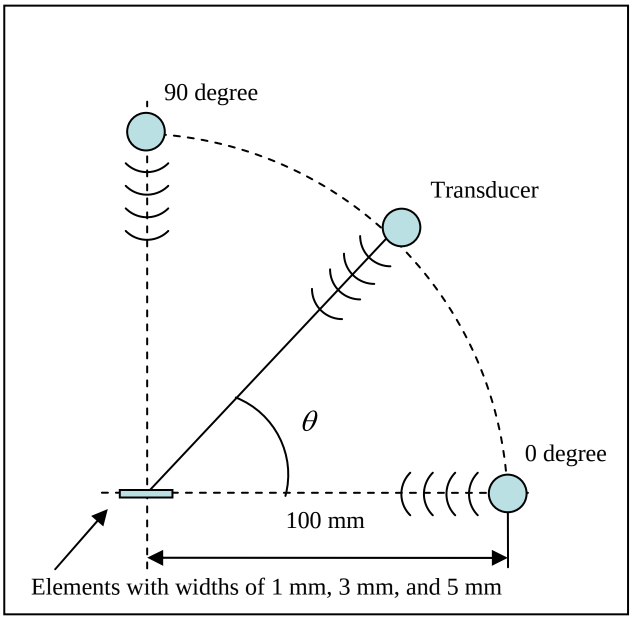

Fig. 1. Directional sensitivity measurement

2.2 Damage Monitoring in Thin Beams

Fig. 2. illustrates the experimental set-up for a damage monitoring system. A slit that simulates a crack was introduced in an aluminum beam (1000×50×1 mm) by a diamond cutter. Impact loading with an energy of 10 J was applied to the center of a cross-ply CFRP beam (1000×50×1 mm) using a weight-drop machine. A pair of surface-bonded directional PZT elements was used as a Lamb-wave transmitter and receiver. The excitation signal applied to the transmitter was a 50 kHz, five-cycle, sinusoidal tone-burst enclosed in a Hanning window.

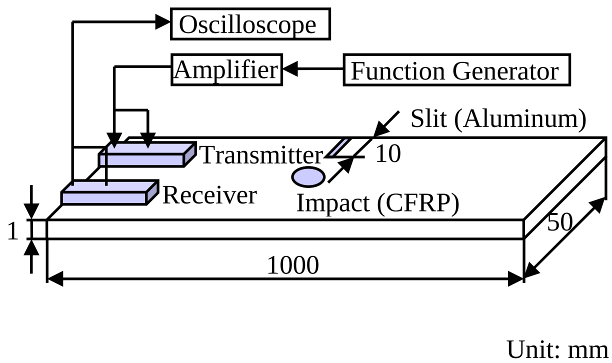

Fig. 2. Experimental set up for damage monitoring system

For comparison, a pair of PZT elements without directivity was also used.

A part of the Lamb waves reflects at the damage position, and is detected by the receiver. Therefore, the damage position is expressed as follows:

$$x = \frac{L}{2} = \frac{Vt}{2} \qquad (1)$$

where x is the distance between the transducer and the damage position, L is the traveling distance of the Lamb wave, V is the group velocity of the Lamb wave and t is arrival time of the echo.

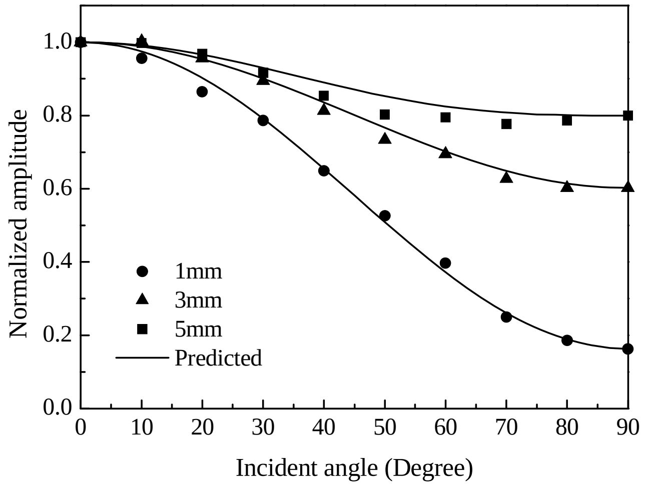

Fig. 3. Experimental and predicted normalized peak-to-peak amplitude detected by piezoceramic elements with different widths as a function of incident angle.

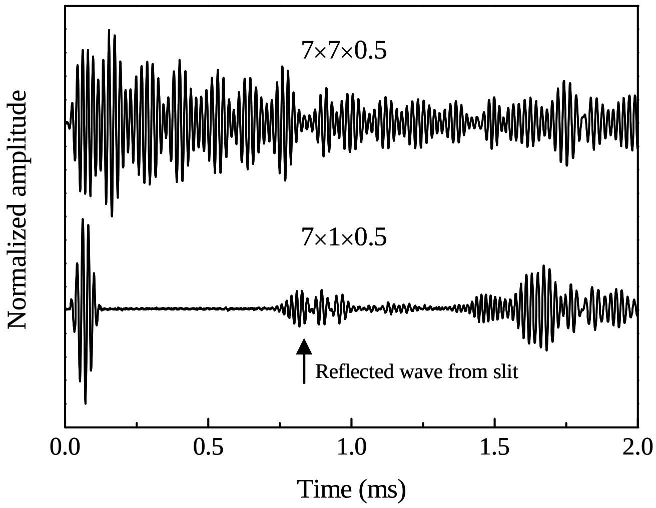

Fig. 4. Comparison of detected waveforms between directional and non-directional transducers for the notched aluminum beam.

3 Experimental Results

Fig. 3. illustrates the normalized peak-to-peak amplitude detected by the three elements as a function of the incident angle. The amplitude nonlinearly decreases with increasing incident angle for all the elements. This confirms their directional sensitivity for the 50 kHz A_0 mode. Furthermore, the directivity becomes shaper with decreasing element width.

Fig. 4. compares the detected waveforms between directional and non-directional transducers for the notched aluminum beam. Numerous wavelets due to multiple reflected waves in the width direction are observed for the non-directional transducers. These wavelets disable us to detect the echo from the slit. In contrast, the amplitude of these wavelets is significantly reduced and an echo from the slit is clearly detected for the directional transducers. The position of the slit was calculated using the arrival time of the echo. Its position was calculated as 520 mm from the transducer, agreeing well with the true one.

Fig.5. illustrates the detected waveforms for the intact and impact-loaded composite beams using the directional transducers. An echo from the impact-induced damage can clearly be detected and damage position could accurately be evaluated. These results demonstrated the usefulness of the developed transducers for damage detection in thin narrow beams.

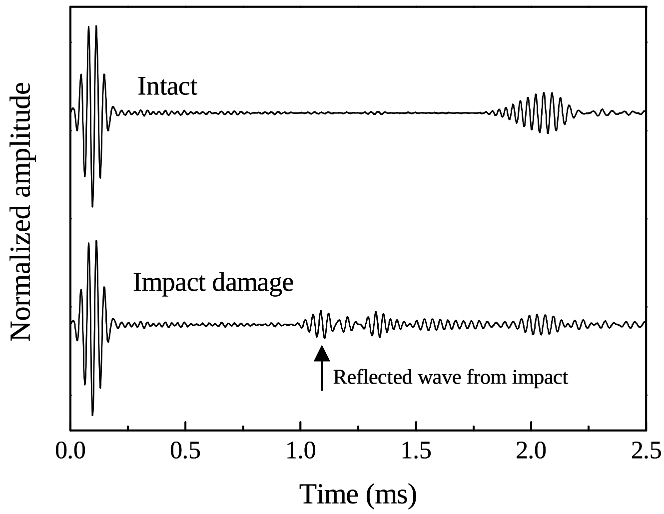

Fig. 5. Detected waveforms for intact and impact-loaded composite beams using directional transducers.

4 Conclusions

In this paper, we developed directional Lamb-wave transducers for detecting of damage in narrow beams.

(1) We successfully developed the directional piezoelectric transducers for the low-frequency Lamb A_0 mode.

(2) Echoes from damage were successfully detected using directional transducers, and we could easily evaluate the damage positions.

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