One sensor linear location using dispersive A_0 mode in thin plates

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Composite laminates have recently been used for primary components of aircraft structures because of their superior specific strength and stiffness. Composite structures in these safety-critical applications must be inspected frequently to ensure structural integrity. However, inspection for a large structure is costly, labor intensive, and time consuming. Internal damage from low-velocity impact is the most prevalent type of damage found in composite structures. Hence, in-service structural health monitoring techniques for identifying impact location have been developed to make inspection more efficient [1, 2]. Knowing the approximate impact location can allow for a localized search, saving time and expense. To be economically viable in such applications, the monitoring system must add as little extra weight and cost to the structure as possible. Therefore, it is important to reduce the number of sensors needed for identifying the impact location in thin plates.

For this purpose, linear location with one sensor using the arrival times of two Lamb modes (S_0 and A_0) has been proposed [3–5]. Furthermore, one author [4] demonstrated that planar source location was possible with two sensors using this technique. However, a Lamb wave originating from an out-of-plane impact contains a predominant A_0 mode and little S_0 mode. Thus, measuring the arrival time of the S_0 mode is always difficult, resulting in large errors in estimating the location. To overcome this difficulty, we propose a linear location method with one sensor, using only the A_0 mode for a source with out-of-plane motion.

The new linear location method is explained below. The distance between a sensor and a source can be calculated by measuring the arrival times of two or more waves, which originate from the same source and propagate with different velocities. Only the S_0 and A_0 modes can propagate through thin plates below 1 MHz, and the A_0 mode is highly dispersive at low frequencies (the S_0 mode is non-dispersive), i.e., the A_0 mode at different frequencies propagates with different group velocities. If the group velocities of the A_0 mode are known at all frequencies, one-sensor linear location becomes possible, if the arrival times of the A_0 mode at different frequencies can be measured.

The materials used were a cross-ply CFRP (TR380, Mitsubishi Rayon Co., Ltd.) plate with a lay-up of $[0/90]_{2S}$ and an aluminum plate. The plate dimensions were $1000 \times 1000 \times 1$ mm. Fig. 1 plots the predicted dispersion curves of the A_0 mode for both plates. These curves were calculated using an interactive Windows program called "Disperse," developed by Pavlakovic and Lowe [6]. The material properties of the unidirectional CFRP laminate used for the calculation are listed in Table I. Fig. 1 demonstrates that highly dispersive regions are below 100 kHz for the CFRP plate, and below 200 kHz for the aluminum plate. Consequently, we used the A_0 mode in these frequency ranges for the linear location.

Thin rectangular PZT elements (C-6, Fuji Ceramics Corporation) that operate in the longitudinal mode (d_{31}) were selected as the Lamb-wave sensors. These surface-bonded thin sensors have significant potential to be adopted for built-in structural health monitoring compared with conventional transducers. The longitudinal dimension of the PZT element was designed to effectively receive the dispersive A_0 mode. Grondel *et al.* [7] demonstrated that the amplitude of a given mode was maximal when the longitudinal dimension of the piezoceramic element was equal to its half wavelength. Fig. 1 also plots the calculated half wavelength of the A_0 mode as a function of frequency. The half wavelength at 50 kHz is 7.5 mm for the CFRP plate and 6.9 mm for the aluminum plate. This determined the longitudinal dimension as 7 mm to enable the PZT element to detect the A_0 mode in the frequency ranges focused on with sufficient sensitivity.

Group velocity was measured as a function of frequency before the linear location to verify the predicted dispersion curves. Fig. 2 illustrates the experimental setup for the group velocity measurement. Three PZT elements ($7 \times 7 \times 1$ mm) were bonded to the surface of the plate in a line (in the 0 ° direction for the CFRP plate) with intervals of 150 mm. Pencil lead breaks, normal to the surface were performed to generate a

TABLE I Material properties of unidirectional CFRP laminate.

Properties	
Longitudinal Young's modulus, E_{11} (GPa)	129
Transverse Young's modulus, E_{22} (GPa)	9.70
In plane shear modulus, G_{12} (GPa)	4.36
In plane Poisson's ratio, ν_{12}	0.34
Out-of-plane Poisson's ratio, ν_{23}	0.50
Ply thickness (mm)	0.117
Density, ρ(kg/m^3)	1537

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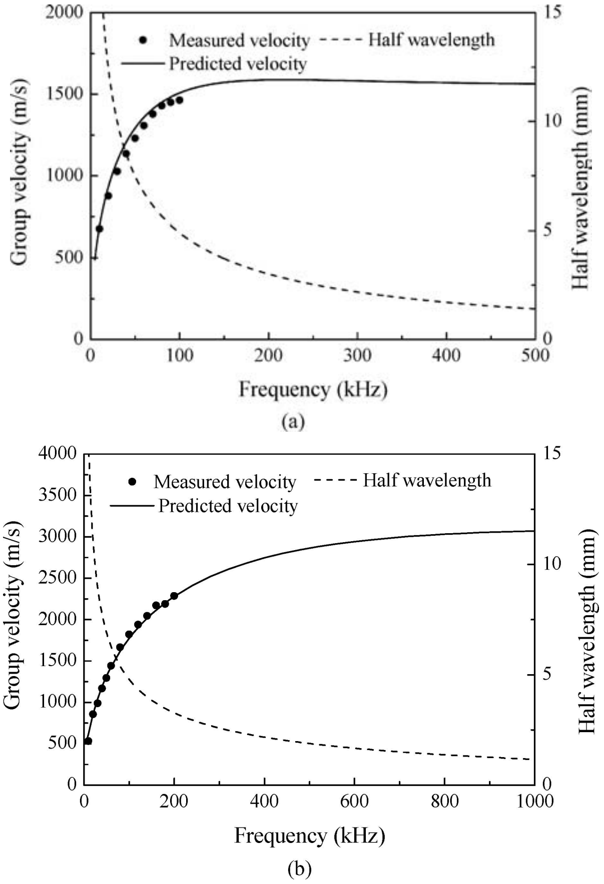

Figure 1 Calculated group velocity and half wavelength as functions of frequency for A_0 mode: (a) CFRP plate and (b) Aluminum plate. Dots indicate measured group velocities

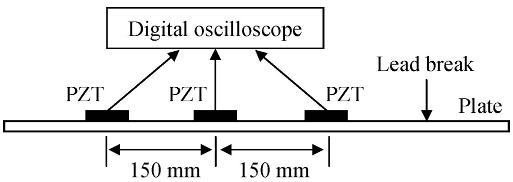

Figure 2 Experimental setup for group velocity measurement.

broad-band A_0 mode. The detected signals were transmitted directly to a digital oscilloscope (without amplifier), and acquired at a sampling interval of 400 ns with 2500 sampling points. Kishimoto *et al*. [8] reported that the arrival time of the wave propagating with the group velocity could be determined as the peak time of the wavelet coefficient. The waveforms detected at the three sensors were thus subjected to wavelet transform using the Gabor function, and the arrival times of the A_0 mode as a function of frequency were measured. A linear least-squares fit from a plot of arrival time and distance was performed to obtain the group velocity. Fig. 1 plots the measured group velocity as a function of frequency. The measured group velocities agree well with the predicted ones.

Linear locations with one sensor using dispersive A_0 mode were performed. The PZT elements were bonded to the edge surface of the plates, and pencil lead breaks normal to the plate surface were performed at 100–600 mm from the sensor in steps of 100 mm. The detected waveforms were subjected to the wavelet

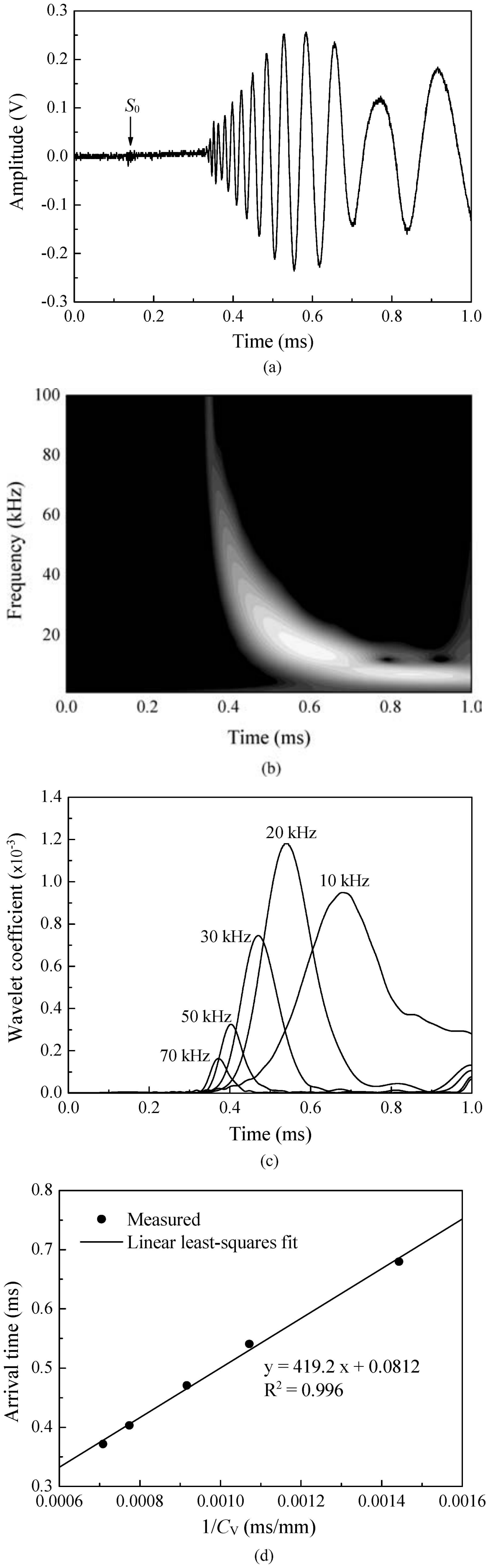

Figure 3 Results of linear location for source 400 mm from sensor in CFRP plate: (a) waveform detected at sensor, (b) wavelet contour map, (c) variations of wavelet coefficient with time at five frequencies, and (d) plot of $1/C_V$ versus arrival time.

TABLE II Summary of linear location results

True distance (mm)	Estimated distance (mm)	
	CFRP	Al
100	111	104
200	227	201
300	281	293
400	419	419
500	524	486
600	567	594

transform, and the peak times of the wavelet coefficients for five frequencies (10, 20, 30, 50, and 70 kHz for the CFRP plate and 40, 80, 120, 160, and 200 kHz for the aluminum plate) were measured. Fig. 3a illustrates the waveform detected by the sensor 400 mm from the source for the CFRP plate. The arrow indicates the arrival time of the S_0 mode, which was calculated using the group velocity of the non-dispersive S_0 mode of 6746 m/s. Since the source had out-of-plane motion, the amplitude of the S_0 mode was very low with a low signal-to-noise ratio; it was therefore difficult to distinguish the S_0 mode from the noise. In contrast, the typical waveform of the A_0 mode, the highest frequency components arriving first, followed by lower frequency components, was detected with enough signal-to-noise-ratio. Fig. 3b depicts the contour map of the time-frequency analysis using the wavelet transform. The highly dispersive nature of the A_0 mode below 100 kHz was clearly identified. Fig. 3c illustrates the variations of the wavelet coefficient with time for the five frequencies, extracted from the data denoted in the contour map. The peaks are clearly identified and measuring the arrival times of the A_0 mode was easy. A linear least-squares fit from a plot of $1/C_V$ (C_V: predicted group velocity) and arrival time was performed to obtain the slope of the curve, which corresponds to the distance between the sensor and the source. As indicated in Fig. 3d, the measured plots were well fitted by a line with a correlation coefficient better than $R^2 = 0.99$. The estimated distance is 419 mm, which agrees well with the true distance of 400 mm. Table II summarizes the results obtained by the proposed linear location method. The estimated distances for both plates were in good agreement with the true ones.

This study proposed a new linear location method with one sensor using the dispersive nature of the A_0 mode propagating in thin plates, and demonstrated its usefulness for identifying the distance between the sensor and the source with out-of-plane motion. This technique does not use the S_0 mode, overcoming the difficulty in the previously proposed method, and can contribute to reducing the number of sensors needed in source locations.

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