Damage Identification for Beam-like Structures Using Lamb Waves

NING HU AND HISAO FUKUNAGA

ABSTRACT:

In order to improve the safety, reliability and operational life of structures, it is crucial to monitor the integrity of structures. Lamb waves can propagate a long distance in plate-like and shell-like structures, by virtue of this advantage, in recent years, many researchers employed Lamb wave for the purpose of structural health-monitoring. In this work, a Lamb wave technique is developed for detecting damages in beam-like structures, such as cracks in metallic beams and delamination in composite laminated beams. First, for metallic structures with transverse cracks, A_0 mode in Lamb wave is employed due to its shorter wave length compared with S_0 mode. An excitation technique for generating comparatively pure A_0 mode using piezoelectric actuators is realized experimentally. In this technique, we attach two PZT actuators with out-of-phase applied voltages on both sides of beams to amplify the component of A_0 mode and to reduce the component of S_0 mode. The numerical simulation for the wave propagation in metallic beams with transverse cracks is also carried out. The comparison between the experimental results and computational ones shows the effectiveness of the numerical model. Moreover, the relation between the depth of the crack and the reflection wave from the crack is examined. For composite laminated beams with a delamination, generally it is quite difficult to generate comparatively pure A_0 mode due to its highly heterogeneous material property. In this case, we employ S_0 mode due to its higher propagation speed, which leads to easier identification of reflected wave from damages. From the obtained results for both metallic and composite beams, it can be found that it is possible to identify damages by using only sensor data of damaged structures without benchmark signals, i.e. the sensor data of intact structures. Finally, by using the propagation velocity, and wavelet analysis of wave signals for obtaining the arrival time of reflected signal from damages, the position of damages can be identified accurately.

INTRODUCTION

In order to improve the safety, reliability and operational life of structures, it is an urgent

---

Department of Aerospace Engineering, Tohoku University, Sendai, Japan, hu@ssl.mech.tohoku.ac.jp

task to monitor the integrity of structures. Generally, the availability of some efficient techniques for non-destructive detection is essential. However, many existing nondestructive inspections such as ultrasonic wave, X ray and thermography need to suspend the operation of structure, and have possibilities of human carelessness. Therefore, it is difficult to guarantee the integrity of structures with high reliability in aspect of real-time. Accordingly, in recent years, the concept called as structural health monitoring has drawn much attention of researchers. Structural health monitoring is a technology that automatically monitors structural conditions from sensor information in real-time, by equipping sensor network and diagnosis algorithms into structures. Lamb wave can propagate by a long distance in plate-like and shell-like structures, by virtue of this advantage, many researchers build up structural health-monitoring systems using Lamb wave [1]. Generally, Lamb wave has two fundamental modes, i.e., symmetric mode (S mode), and anti-symmetric mode (A mode). Most of researches use S_0 mode for damage detection. The propagating velocity of S_0 mode is higher than that of A_0 and other lamb wave mode so that it is comparatively easy to pick up the reflected waves from damages in experimental data. On the other hand, the wavelength of S_0 mode is larger than that of A_0 mode so that it is insensitive to some small damages.

In this study, for metallic beams, we attach two PZT actuators with opposite applied voltages on both sides of aluminum beams to amplify the component of A_0 mode and to reduce the component of S_0 mode. In this case, by employing comparatively low excitation frequency with low noises, we can detect the transverse cracks on aluminum beams accurately. The numerical simulation using FEM is also carried out. The numerical results agree with the experimental ones very well. For cross-ply laminated beams with a delamination, it is very hard to generate comparatively pure A_0 mode. The reason may be from that there is higher nonuniformity in this kind of materials. When both A_0 mode and S_0 mode exist simultaneously, it is easier to pick up the reflected wave of S_0 mode from damages due to its faster propagation speed. Therefore, we employ S_0 mode to identify the delamination in composite laminated beams. The group speeds of wave propagation for both materials are also experimentally measured. By virtue of wavelet transformation, highly accurate wave propagation speeds can be obtained. These experimentally obtained speeds are further verified by those theoretical predicted wave speeds using Rayleigh-Lamb equation for metallic materials and transfer matrix method for composites. Finally, by using the wave propagation speeds and the arrival time of reflected waves from damages, the position of damages can be identified accurately. Compared with some existing techniques using Lamb waves, an important merit of the present technique is that there is no need for the benchmark data or the data of intact structures before damages if the locations of actuator and sensor are properly determined.

METALLIC BEAMS

First, an aluminum beam with surface transverse cracks, which are modeled by notches with a very narrow width (around 0.1 mm) in experiments are shown in Figure 1. The material properties of cantilevered aluminum are shown in Table 1. The dimensions of beam are shown in Figure 1. Two kinds of beam thicknesses are considered, i.e. 3 mm

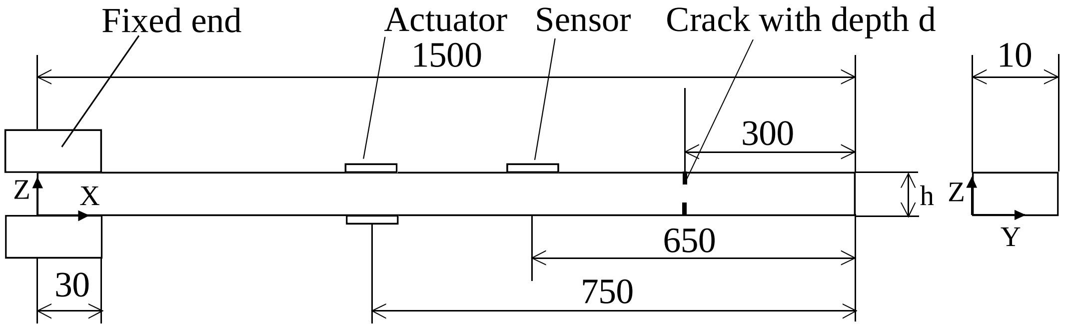


Figure 1: Schematic view of aluminum beams with cracks (length unit: mm).

Table 1. Material properties of aluminum

E [GPa]	ν	ρ [kg/m^3]
73	0.3	2770

Table 2. Material properties of piezoelectric

Young's Modulus [GPa]	Piezoelectric Coefficient [pC/N]
E_{11}=62 E_{33}=49	d_{33}=472 d_{31}=-210

and 5 mm, respectively. For transverse cracks, two kinds of damage patterns are considered. One is a single crack on one side, and another is double cracks on both sides. Also, as shown in Figure 1, by attaching two actuators on both sides of structures with out-of-phase applied voltages, an excitation technique for generating comparatively pure A_0 mode using piezoelectric is realized experimentally. The dimensions of square PZT actuator are 10 mm×10 mm×0.5 mm. The excitation frequency is 50 KHz in our beam experiments. Usually, A_0 mode is more easily generated when the actuator is thin and excitation frequency is low. The A_0 mode is used for its shorter wave length and higher sensitivity to damages, such as small cracks. By employing the above technique with dual actuators on both sides of beam, comparatively very pure A_0 mode can be produeced.

With the same actuator configuration, by using a square aluminum plate of 5 mm thickness as shown in Figure 2, we have measured the prorogation group speed of A_0 mode when excitation frequency ranges from 10 KHz to 300 KHz. The circular actuator and sensor are of 10 mm diameter and 0.5 mm thickness. The signals of sensor 1 and sensor 3 are shown in Figure 3. From it, we can find that very pure A_0 mode can be generated. Also, the reflected waves from bounary of plate can be identified clearly. By employing the wavelet technique, the arrival time of incident A_0 mode can be determined exactly. Finally, the arrival time delay and distacens between 3 sensors are used to calculate the group velocity of A_0 mode. The average group velocity of A_0 mode determined by experiments and theoretical group velocity evaluated from Rayleigh-Lamb equation [3] with the material properites in Table 1 are plotted in Figure 4. From this figrue, we can find that both results agree to each other very other, the maximum error

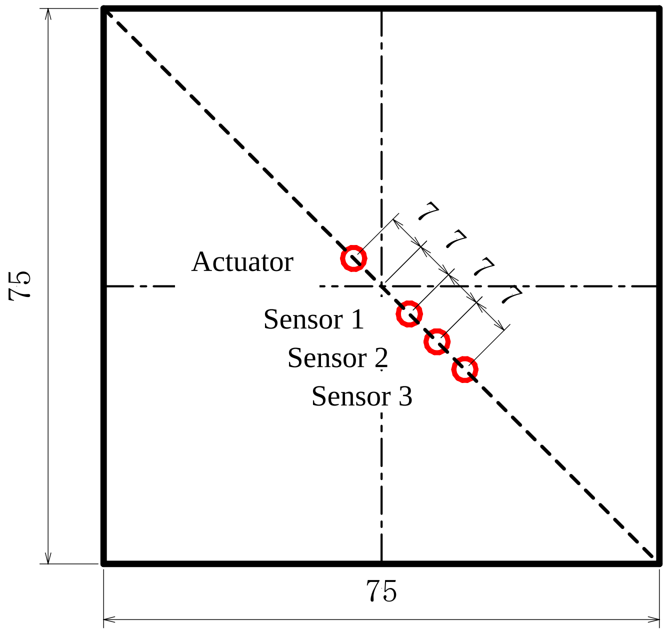
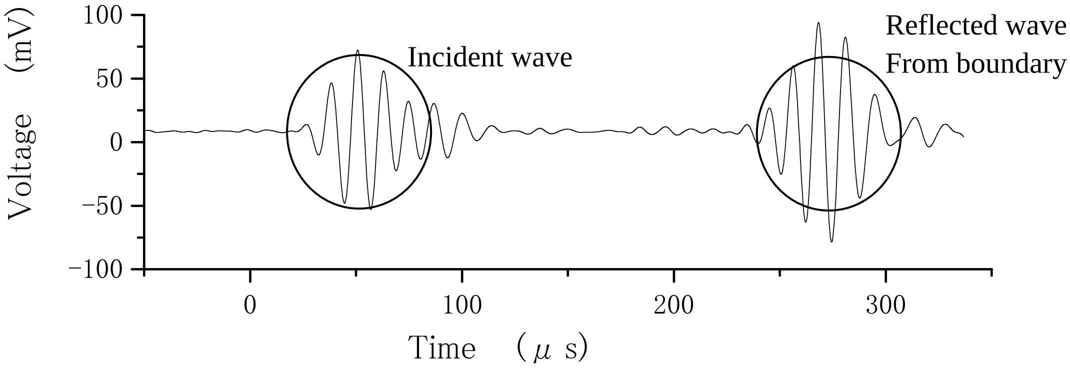
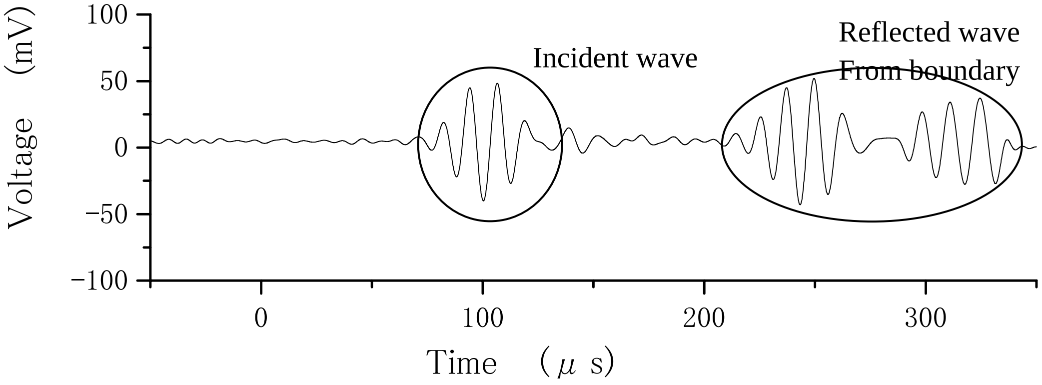


Figure 2: A square plate of acuators and three sensors (length unit: cm).



a) Signal of sensor 1



b) Signal of sensor 2

Figure 3: Signals of sensor 1 and sensor 3.

between the experimental results and theoretical ones is 5.4%.

For aluminum beams in Figure 1, besides the experiments, numerical simulations by

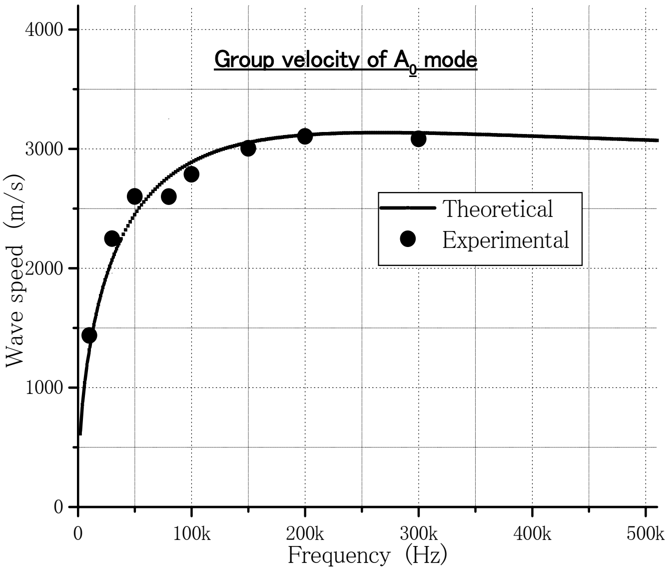
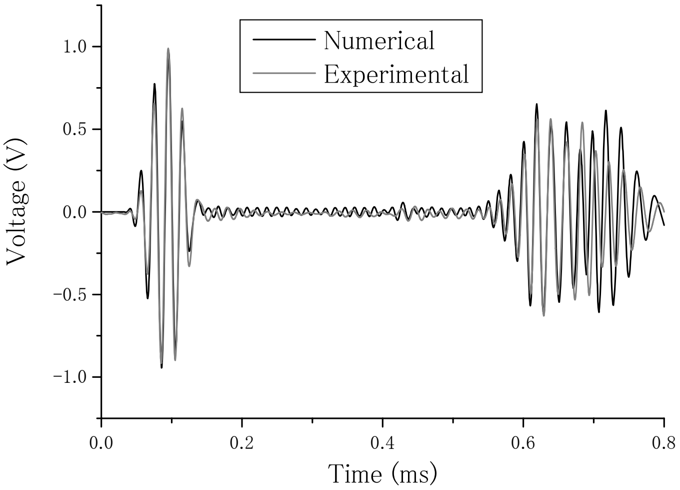
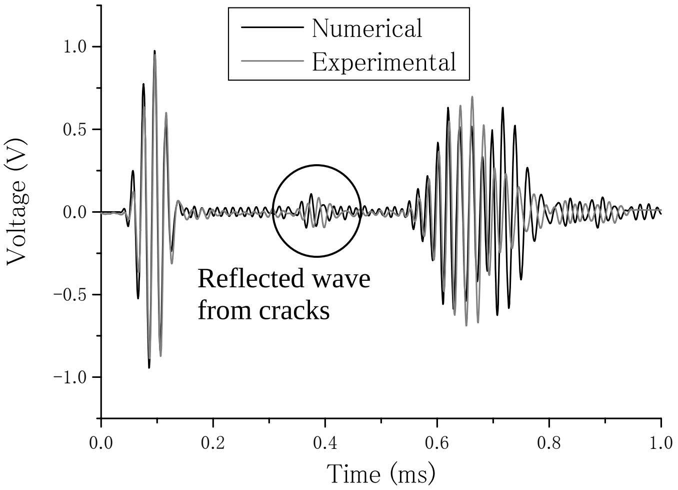


Figure 4: Group velocity of aluminum plate of 5 mm thickness.

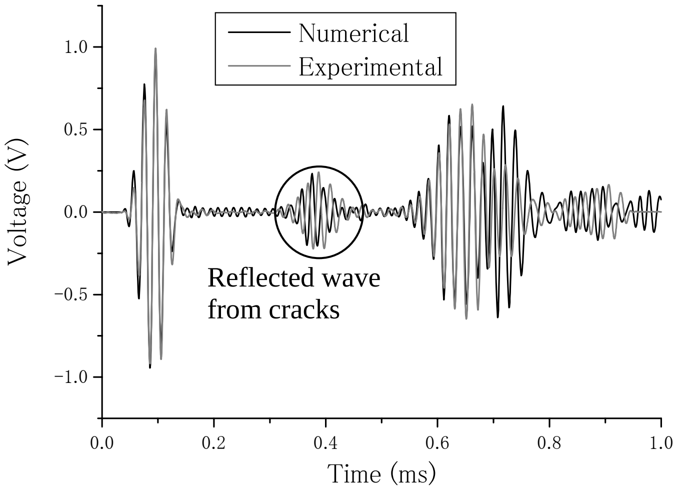


a) Numerical and experimetnal results of wave form of intact beam of 5 mm thickness

using a hybrid 3D finite element proposed by the authors [2] and the explicit time integration algorithm have also been performed. In computations, within one wave length, at least ten elements are used. The exicitation signal is of frequency of 50 KHz and 5 cycles. For intact beam of 5 mm thickness, the comparsion between the numerical results and experimental ones is shown in Figure 5(a), where the damping coefficient used in numerical model is obtained by comparing the almplitude of reflected waves from two ends of beam. From this figure, we can find that the numerical results agree with experimental ones very well. The effectiveness of numerical model is verified. For beams with 1.25 mm single crack on one side and 1.25 mm double cracks on both sides, the comparison of numerical and experimental results are shown in Figures 4b) and c). From them, both results are coincident to each other well. Also, by checking Figure 1, in this case, the wave propagation path is shown in Figure 6. From Figures 4b) and c), we can identify the reflected waves from damages between the incident wave and reflected waves from boundary very clearly. The reflected waves from damages are



b) Numerical and experimetnal results of wave form of beam of 5 mm thickness and 1.25 mm single crack on one side



c) Numerical and experimetnal results of wave form of beam of 5 mm thickness and 1.25 mm double cracks on two sides

Figure 5: Comparison bewteen numerical and experimental results of 5 mm beam.

marked in Figure 6 as path 2. To investigate the influence of crack depth d on the almplitude of reflected waves of crack, for 5 mm thickness beam of double cracks on both sides, the experimental results are shown in Figure 7. From this figure, it can be found that when the crack depth is 0.25 mm, there is no obvious reflection from damages. When the crack depth is larger than 0.75 mm, very clear reflections from cracks can be identified. Also, with the increase of crack depth, the almplitude of reflected waves from damages increases too. The same results can also be found for for single crack, i.e. 0.75 crack depth is a limit for generating sufficient reflected waves from damages. For 3 mm thickness beam, the same conclusion can be made.

Finally, by employing the wavelet transformation technique to determine the arrival time of reflected wave from cracks and the theoretical group velocity for 50 KHz shown in Figure 4, the identified position of cracks for both numerical and experimental models are shown Table 4. From this table, we can find that the position of cracks can

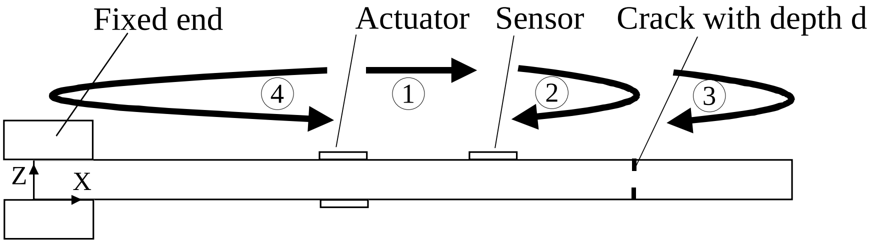


Figure 6: Wave propagation path in aluminum beam.

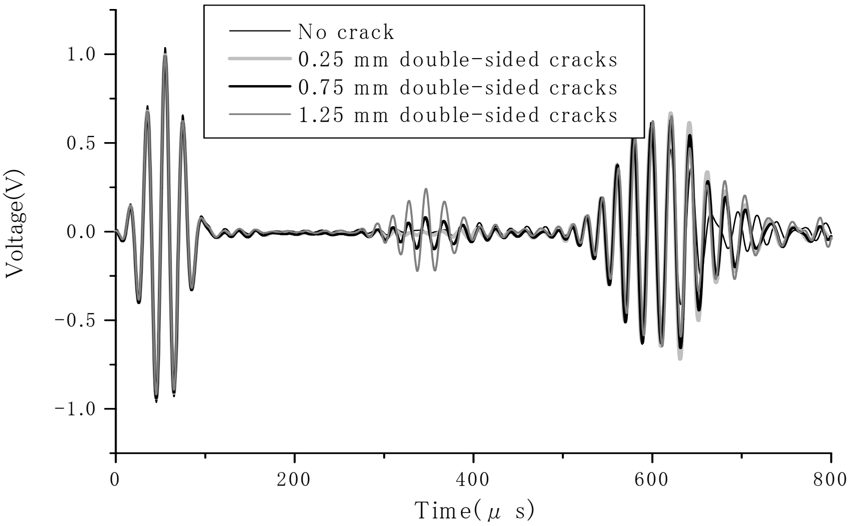


Figure 7: Influence of crack depth on reflected waves from cracks for 5 mm beam.

be identied very accurately. Compared with case of 5 mm thickness beam, the comparatively errors of positions of cracks in 3 mm thickness beam are a little higher.

COMPOSITE LAMINATED BEAMS

Second, a composite laminated CFRP beam with a delamination is shown in Figure 8. The dimensions of beam of lay-up of $[0_{10}/90_6/90_6/0_{10}]$ are 1005 mm×10 mm×4.8 mm as shown in Figure 8. A delamination with length of 30 mm is made by inserting a 25 μm Teflon sheet between 10th and 11th plies. In our experiemnts, it was found that it is very hard to generate the pure A_0 mode using the excitation technique in metallic beams. In the obtained signals, both S_0 mode and A_0 mode always exist. The reason is unclear, but perhaps from that there is higher heterogeneous or ununiform material properties. In this case, we employ only one actuator and S_0 mode for identifying the delamination due to its higher propagation speed and easier detection of reflected waves from damages. To avoid the complex wave form including reflection waves from both ends, one actuator is attached at the left end. In this case, the generated wave of actuator and reflected wave sensor from the left end will be duplicated and become one wave form.

The experimental results of intact beam and delaminated beam are compared in Figure 9 when excitation signal is of frequency of 100 KHz and 5 cycles. From this figure, it can be found that there is a clear reflected wave from the delamination. For the

Table 3. Results of identified crack position for 3 mm and 5 mm beams

	Thickness	Group velocity [m/s]	Arrival time [ms]	Position [mm]	Error [%]
Calculate	3mm	2068.5	0.354	1216.1	1.3
	5mm	2449.5	0.285	1199.1	0.1
Experimental	3mm	2068.5	0.349	1211.0	0.9
	5mm	2449.5	0.291	1206.4	0.5

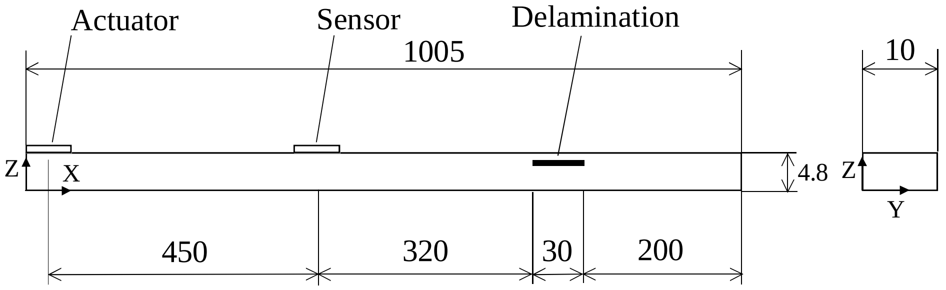


Figure 8: Schematic view of laminated beam with delamination (length unit: mm).

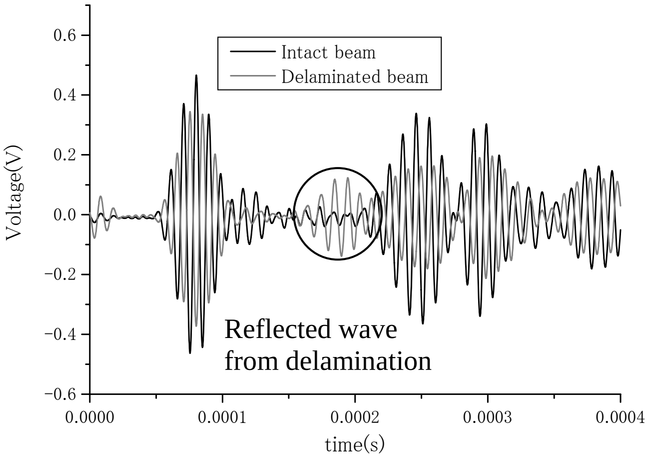


Figure 9: Comparison of signals of intact and delaminated beams.

intact beam, we measured the group speed of S_0 mode as 6225.7 m/s for 100 KHz. By identifying the arrival time of reflected wave from the delamination using the wavelet transformation technique and employing the above speed, the central position of delamination from sensor is calculated as 336.8 mm, where the true central position is 335 mm. It can be found that the delamination position can be identified accurately.

REFERENCES

1. Z.Q. Su, L. Ye, Y. Lu. Guided Lamb waves for identification of damage in composite structures: A review. *J. of Sound & Vibration*, (2006) (in press)
2. Y.P. Cao, N. Hu, J. Lu, H. Fukunaga and Z.H. Yao. A 3D brick element based on Hu-Washizu variational principle for mesh distorsion. *Int. J. Numer. Meth. Engrg.*, 53, 2529-2548. (2002)
3. I.A.Viktorov. Rayleigh and Lamb Waves, *Plenum press*, New York, (1967).