Lamb Wave Detection Using PZT and Fiber Optic Sensor

Chun-Gon Kim[1], Dae-Hyun Kim[1] and Young-Han Kim[2]

1. *Division of Aerospace Engineering, KAIST, Daejeon, Korea*
2. *Agency for Defense and Development, Daejeon, Korea.*

Abstract: The surface mounted piezoceramic transducers and fiber optic sensor can detect signals in both symmetric and antisymmetric Lamb wave modes. Hanning windowed sine torn bursts were used for the piezoceramic transducer excitation signals. In order to overcome the difficulties in the signal processing of the simultaneous modes, the symmetric and antisymmetric modes were separated by using the two sensors bonded on the opposite surfaces at the same planer location. Spectral analyses of the separated symmetric and antisymmetric Lamb waves showed that each mode propagated with different frequency characteristics in the exciting frequency band range. In case of a fiber optic sensor, its geometric characteristics induce sensing directivity of Lamb wave. In this paper, the directivity of a fiber optic sensor was investigated using EFPI (extrinsic Fabry-Perot interferometer) sensor.

Key words: *Lamb wave, Piezoceramic transducer, spectral analysis, fiber optic sensor, directivity*

1. Introduction

A lot of researches [1-3] have been carried out on structural damage evaluation in composite and metallic structures using Lamb wave as one of structural health monitoring techniques. The structural damage evaluation method using Lamb wave has several advantages. Lamb wave needs little power and covers large structural areas because the waves travel a long distance. Also this technique reduces signal processing time to extract damage information from the sensor signals because it does not require continuous monitoring during operations. However, the sensor signals are very complex and difficult to be interpreted because Lamb wave has multiple modes and the individual mode is usually dispersive. Therefore many studies have been conducted to develop transducers such as the interdigital transducer (IDT) and transducer arrays for generating a single Lamb wave mode.

The application of Lamb wave to the health monitoring of composite materials began in late 1980s. Liu [4] presented the analytical-numerical approaches for the optimization of IDT and transducer arrays to improve the excitability of specific wave modes in composite materials.

Badcock [5] investigated that the embedded 0-3 piezocomposite elements were identified as good candidates for generating and receiving Lamb wave. Giurgiutiu [6] presented practicalities of surface mounted sensors for structural damage detection by showing that cracks on an aluminum aircraft skin specimen were detected using surface mounted PZT wafer transducers. He focused on the surface mounted transducers because they could be commonly applied to metallic and composite materials.

Piezoceramic transducers (PZT) of the surface mounted type generate both symmetric and antisymmetric Lamb wave modes simultaneously. Also, if the specimen size is small, then the received signals include a lot of reflected waves. In this case, the received signals are very complex and it is difficult to extract damage information from the signals in time-domain because of the interference of the modes and reflected waves. Recently, a lot of researches have been carried out to detect Lamb wave using several fiber optic sensors. Especially, an interferometric fiber optic sensor is a good candidate to detect Lamb wave because it has excellent sensitivity. However, the fiber optic sensor has a geometric characteristic, which induces directivity. To evaluate the Lamb wave detected by the fiber optic sensor, the directivity should be investigated.

In this paper, we detected Lamb wave, which was propagated through an aluminum plate, using PZT and fiber optic sensor. An easy method was proposed to separate symmetric mode from antisymmetric one. Each characteristic of both modes was investigated in order to extract the damage information from the complicated signals that cannot be interpreted in time-domain. Moreover, the directivity of fiber optic sensor was also investigated using EFPI (extrinsic Fabry-Perot interferometer) sensor.

2. Lamb wave propagation

Lamb wave is one of the guided waves which are constrained by free surfaces of plate, shell and tube, and propagates along the directions of length and width. Distinctive features of Lamb wave are that the propagation velocity varies with the exciting frequency times thickness and that there are symmetric and antisymmetric Lamb wave modes in the same frequency. Also, each mode has several orders in some frequency ranges. The propagation velocity of Lamb wave is calculated with Rayleigh-Lamb frequency relation derived from the displacement potential of an elastic body and Newton's equations of motion. Equation (1) is for the symmetric Lamb wave mode in which the particle motion of the plate occurs symmetrically about the symmetric axis of the plate. Equation (2) is for the antisymmetric Lamb wave mode in which the particle motion occurs asymmetrically about the symmetric axis of the plate [7].

$$\frac{\tan(qh)}{\tan(ph)} + \frac{4k^2 pq}{(q^2 - k^2)^2} = 0 \tag{1}$$

$$\frac{\tan(qh)}{\tan(ph)} + \frac{(q^2 - k^2)^2}{4k^2 pq} = 0 \tag{2}$$

where the parameters p and q are defined as follows;

$$p^2 = \frac{\varpi^2}{c_L^2} - k^2, \quad q^2 = \frac{\varpi^2}{c_T^2} - k^2, \text{ h= t/2}$$

where c_L and c_T are the longitudinal and transverse propagation velocities of bulk wave and wavenumber $k = \frac{\varpi}{c_p}$.

From Equations (1) and (2), the phase velocity dispersion curves can be plotted. The other useful plot is group velocity dispersion curves which can be derived from the phase velocity curves using Equation (3). The group velocity dispersion curves are shown in Figure 1.

$$c_g = \frac{d(kc_p)}{dk} = c_p + k\frac{dc_p}{dk} \tag{3}$$

The phase velocity(c_p) is the propagating velocity of the wave with a single frequency, and the group velocity(c_g) is the propagation velocity of the wave packet with adjacent multi frequencies. Therefore it is appropriate to compare the wave propagation velocity measured from Lamb wave propagation tests using the torn burst wave of a certain frequency band with the group velocity. Changes in the waveform amplitude and duration are caused by the difference between the group and phase velocities. This phenomenon is called as dispersion. The waveform dispersion is proportional to the velocity difference. The waveform pattern cannot be identified for a large velocity difference.

3. Lamb wave detection in aluminum plate using PZT

3.1 Experimental Setup and Procedure

Figure 2 shows the test setup. PZT transducers were actuated by a function generator (SONY, model AFG-320) with the amplitude of 10V. PZT signals were obtained with a 4 channel digital oscilloscope (Tektronix, model TDS 420) and saved into a computer by GPIB. The specimen plate is 1000×1000×2.1mm in size and made of AL6061-T6. Bar type PZT(50×20×0.4mm) of Fuji Ceramics Co. was cut into pieces of 10×10mm. Seven square pieces were mounted by adhesives as shown in Figure 3. PZT (No. 7) was mounted at the opposite side of PZT (No. 3) in order to identify the symmetric mode and antisymmetric mode from the sensor signals.

3.2 Experimental Results

Since the particle displacements at the same place of the upper and lower surfaces are antisymmetric about the mid-plane of the plate, waveforms of antisymmetric Lamb wave mode have 180° phase difference. But waveforms of symmetric Lamb wave mode have the same phase. Therefore each sensor signal can be expressed as Equation (4).

$$U_f = u_s(t) + u_a(t) \quad \text{for sensor on upper surface ,}$$

$$U_b = u_s(t) - u_a(t) \quad \text{for sensor on lower surface} \tag{4}$$

where the subscripts s and a represent symmetric and antisymmetric mode, respectively.

The symmetric and antisymmetric mode signals can be separated by signal processing of Equation (5) from sensor signals of the upper and lower surfaces given in Equation (4).

$$u_s(t) = (U_b + U_f)/2 \quad \text{for signal of symmetric mode}$$

$$u_a(t) = (U_f - U_b)/2 \quad \text{for signal of antisymmetric mode} \tag{5}$$

The signal processing of Equation (5) was coded by using MATLAB®. Figure 4 shows signals obtained from PZTs by exciting PZT (No. 2). Signals from PZT (No. 3) and PZT (No. 7) were obtained at the same location of the upper and lower surfaces. Figure 5 shows the signals of symmetric and antisymmetric Lamb wave modes as the results of signal processing of Equation (5). In the signal processing the normalized signals were used to correct the differences in the signal amplitude caused by the differences in the electric capacity of PZT transducers. The waveform path and time of flight reflected from the plate boundaries were calculated using Snell's law. In order to make sure that the signals of each mode were accurate, these results were compared with those measured from the tests. The time of flight was calculated to be 270μsec for the symmetric waveform reflected at the top edge and 266μsec for the antisymmetric waveform reflected at the left edge from PZT2 to PZT3 transducers, respectively. According to the calculation, it was predicted that the two waveforms were superposed in sensor signals. Figure 5 shows that the signal waveforms obtained from the upper and lower surfaces are a bit different to each other due to the superposition of the two waveforms. Figure 5 shows also the two separated waveforms of the symmetric and antisymmetric modes from the PZT signals. This experimental results show that Lamb waves with only single mode can be easily extracted from the sensor signals with multi modes because the surface mounted PZT transducers were used. From these experiments with aluminum plates, it was shown that the amplitudes of antisymmetric mode waveforms were smaller than those of symmetric mode waveforms, and that the amplitudes of waveforms reflected normally from the boundary were bigger than those of waveforms reflected less than 90 degrees. The mode changes could not be found by these differences in waveform amplitudes due to the mode and reflected angle.

Figure 6 shows the results of the spectral analysis to investigate the frequency features of signals in the symmetric and antisymmetric modes. The symmetric mode signal has a peak at 293 kHz and the antisymmetric mode signal at 332 kHz. These results show a deviation from the exciting frequency of 300 kHz. These results are consistent with those of spectral analyses with the most typical waveform of each mode. The consequent spectral analyses can be successfully used to obtain the structural damage information because of the feature that Lamb wave propagates in various frequencies dependent upon the modes in the exciting frequency band.

4. Lamb wave detection in aluminum plate using fiber optic sensor

4.1. Manufacture of Sensors and Specimens

The other sensitive sensor to detect the Lamb wave is a G-EFPI (gold-deposited EFPI) [8]. The manufactured gage length and the cavity length of a G-EFPI were 9.26mm and 190μm, respectively. A piezoceramic actuator of 10mm in diameter and 0.6mm in thickness (Fuji Ceramics Co. Ltd., Japan) was prepared to use for a wave actuator. An aluminum (Al 6061-T6) plate was finally prepared for propagation medium of Lamb waves. The size of the plate was 1000×1000×2.1mm, which is large enough so that the excited Lamb wave first arrived to the fiber optic sensor is not amassed with the Lamb waves reflected and returned from edges of the plate.

As in Figure 7, seven piezoceramic actuators were attached at each different positions having 15 degree intervals each from 0 to 90 degrees and located 200mm from the center point of the plate, at which the manufactured G-EFPI sensor was attached, in order to simulate the same effect as in the case that the G-EFPI sensor changes its angle from 0 to 90 degree with respect to the piezoceramic actuator. The distance between the G-EFPI sensor and the actuator was determined as the length which is possible to classify between the two modes of symmetric and antisymmetric one. Shear stress of the piezoceramic actuator was satisfactorily delivered to the plate by sanding the adhesion surface of the aluminum plate with #600 emery paper before attaching the piezoceramic actuator to the aluminum specimen.

4.2 Evaluation of Directivity of fiber optic sensor

The G-EFPI sensor was attached at the center of the aluminum specimen as shown in Figure 7. The attached sensor was connected to the stabilization controlling sensor system [9] to watch in real time whether the sensitivity of the sensor changes due to the external thermal or quasi-static change during the test. As shown in Figure 7, one of the 7 piezoceramic actuators was connected to a function generator, and in order to save the input signal, the output channel of the function generator and the fiber optic sensor system were connected to oscilloscope (Tektronix TDS 420, USA). Since the large number of digitization of a signal results in the precise measurement of the sensitivity of the signal, the sampling frequency of the oscilloscope was tuned to as high as 10MHz. The sine tone burst wave of 250 kHz, which was shaped beforehand using the function generator, was input into the piezoceramic actuator. After the signals corresponding to each frequency were obtained, the remaining 6 piezoceramic actuators acquired the signals with the same method. The S/N ratio was improved by increasing the number of acquisition of the signals as many as 128, and 5 averaged signals from 128 acquisitions were obtained to measure the deviation of the measured signals.

4.3 Experimental Results

Figure 8 presents the signals from the Lamb waves induced by the exciting frequency of 250 kHz, acquired by using the G-EFPI sensor. It is known from the figure that the amplitude of symmetric mode of Lamb waves decreases as the angle of piezoceramic actuator increases. The maximum amplitude was observed when the sensor was placed perpendicular to the propagating direction of the Lamb waves, because the G-EFPI sensor is more sensitive in its longitudinal direction. In order to investigate more precisely the change of sensitivity with respect to the change of direction of the sensor, the sensitivity corresponding to each angle was normalized through the measured values using the commercial AE sensor from the prior experiment. Figure 9 shows that the reduction of the signals with increasing directivity angle was significant. From the results, it is confirmed that the sensitivity changes with respect to the direction of the sensor while measuring ultrasonic Lamb wave with the G-EFPI sensor. Using the directivity characteristics of G-EFPI signal, the direction of the source of wave can be known by calculating the sensitivity ratio according to the direction. In order for more precise analysis using the results of above experiment, an approximate function can be determined using Boltzman approximation method as in Figure 9. Moreover, it can be seen that the G-EFPI sensor is more sensitive than the commercial AE sensor to detect the symmetric mode of Lamb wave because the sensitive of the G-EFPI is more dependent on longitudinal direction than transverse direction.

5. Conclusion

In this paper, the signal processing techniques were proposed to simplify the Lamb wave signals which is complicated due to the use of the surface mounted PZT transducer. The signals were easily separated into the symmetric and antisymmetric modes by two sensors mounted on the upper and lower surfaces at the same planer point. From the spectral analysis of the separated signals, it was shown that the symmetric and antisymmetric modes of Lamb wave propagated respectively with the different frequency bands in the exciting frequency range. Moreover, Lamb wave was successfully detected using the G-EFPI sensor. As the result, it was known that when the G-EFPI sensor was set as parallel to the propagation direction of the wave, it had the most sensitivity. The sensitivity decreased in cosine function as the relative angle between the source and G-EFPI increased. Thus, it was able to be suggested that the direction of the source of wave could be found using the directivity of fiber optic sensor.

References

[1] Ye, L., and Su, Z., A Damage identification technique for CF/EP composite laminates using distributed piezoelectric transducers. Composite Structures, 57(2002) 465-471

[2] Kessler, S., Spearing, M., Damage detection in composite materials using Lamb wave methods. Smart Materials and Structures 2002;(11):269-278.

[3] Lemistre, M., and Balageas, D., Structural health monitoring system based on diffracted Lamb wave analysis by multiresolution processing. Smart Materials and Structures 10 (2001) 504-511

[4] Liu, T, Veidt, M. Kitipornchai, S. Single mode Lamb wave in composite laminated plates generated by piezoelectric transducer. Composite Structures 2002;(58):381-396.

[5] Badcock, R., Birt, E., The use of 0-3 piezocomposite embedded Lamb wave sensors for detection of damage in advanced fiber composites. Smart Material Structures. 2000;(9):291-297.

[6] Giurgiutiu, V., Bao, J., and Zhao, W., Active sensor propagation health monitoring of beam and plate structures. Proceeding of the SPIE's 8th Int'l symposium on Smart structures and material, 4-8 March 2001.

[7] Rose, J., Ultrasonic Waves in Solid Media. Cambridge University Press, 1999

[8] D. H. Kim, H. K. Kang, J. W. Park, C. S. Hong and C. G. Kim, "Measuring Dynamic Strain of Structures Using a Gold-Deposited EFPI," Smart Materials and Structures, Vol. 12. No. 1. pp. 1-5, 2003.

[9] Dae-Hyun Kim, Bon-Yong Koo, Hyung-Joon Bang, Chun-Gon Kim and Chang-Sun Hong, “A Phase Stabilization System of EFPI for Damage Detection of Composites,” The Korean Society for Aeronautical and Space Science, Vol. 31, No. 8, pp. 44-50, 2003.

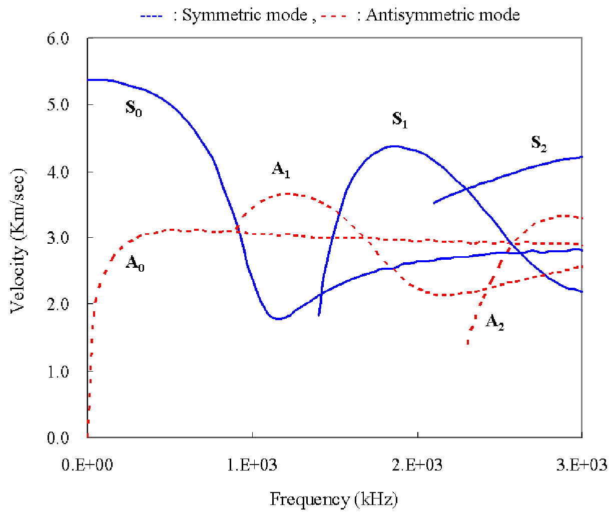

Figure 1. The calculated group velocity dispersion curves for an aluminum plate (AL6061-T6, t=2.1mm)

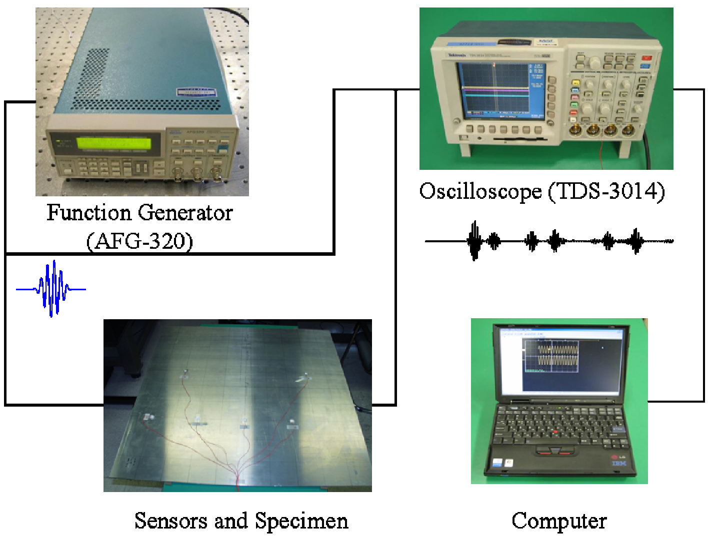

Figure 2. Experimental setup for Lamb wave propagation

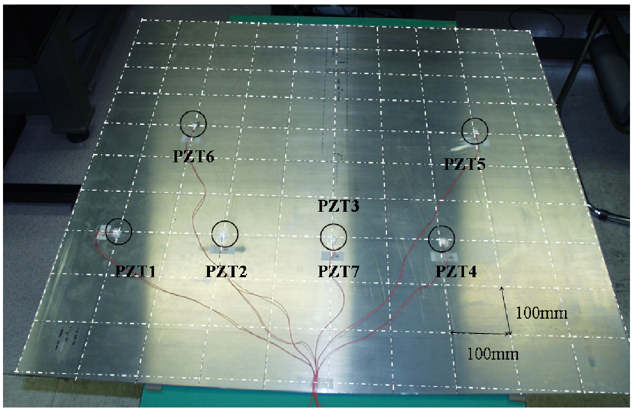

Figure 3. Sensor arrangement on the aluminum plate

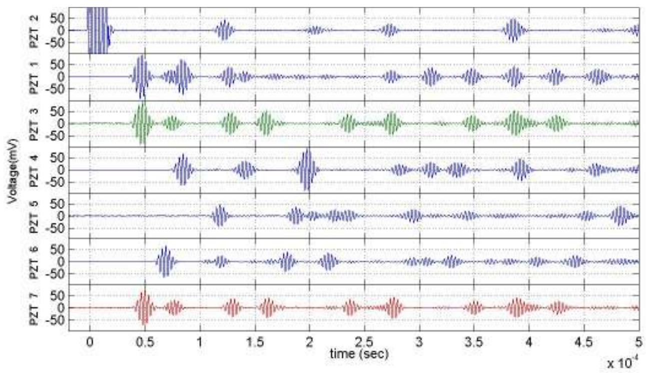

Figure 4. PZT Signals obtained by actuating PZT no.2

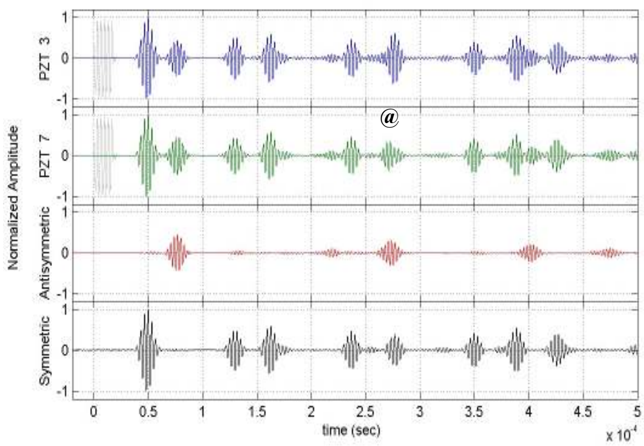

Figure 5. Symmetric and antisymmetric mode Lamb waves extracted from signals of PZT no.3 and no. 7.

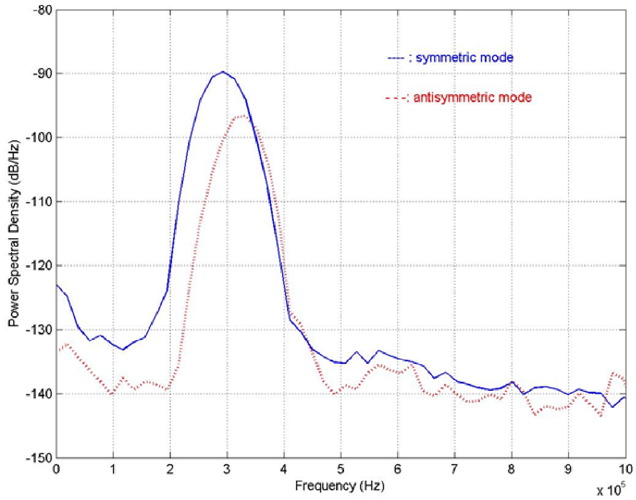

Figure 6. Frequency features of the signals in the symmetric and antisymmetric mode

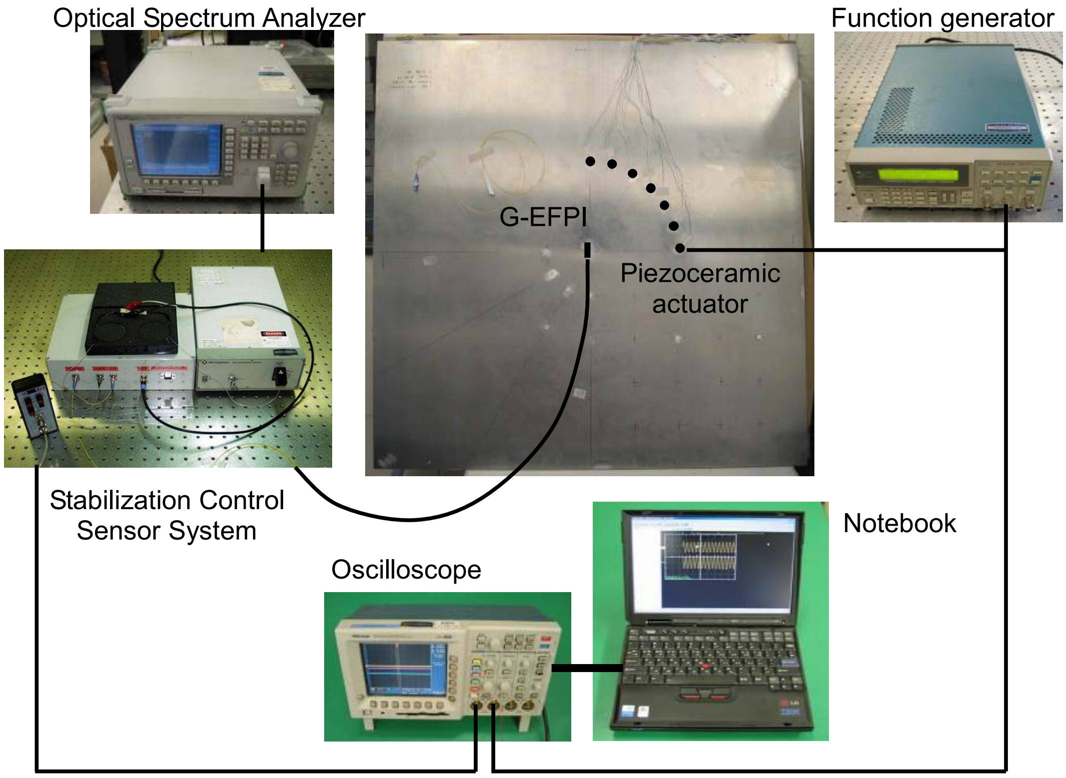

Figure 7. Experimental Setup for detecting of Lamb wave with the stabilization controlling sensor system

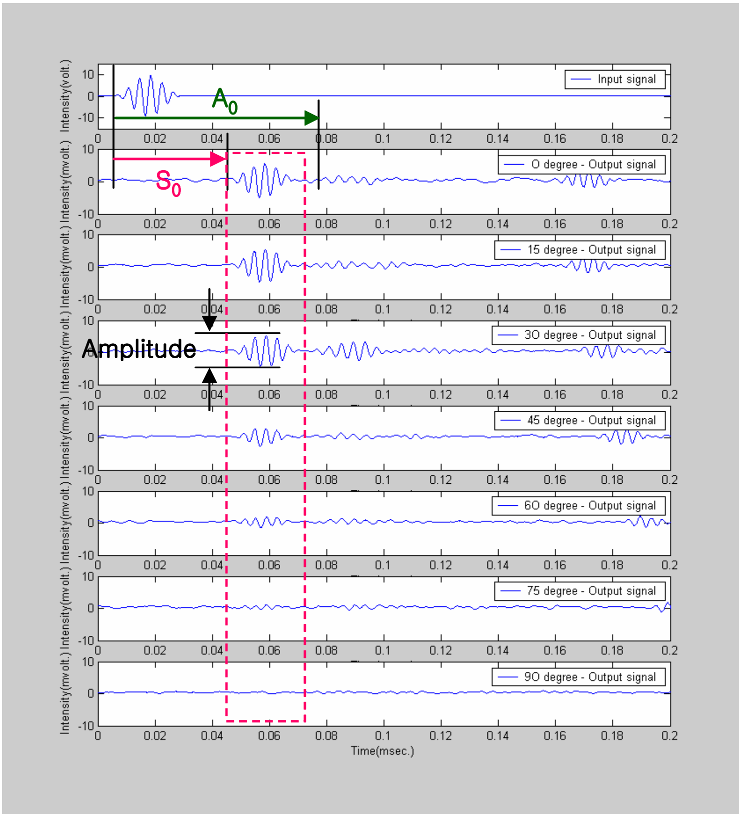

Figure 8. Lamb waves detected by a G-EFPI under the excited frequency of 250kHz

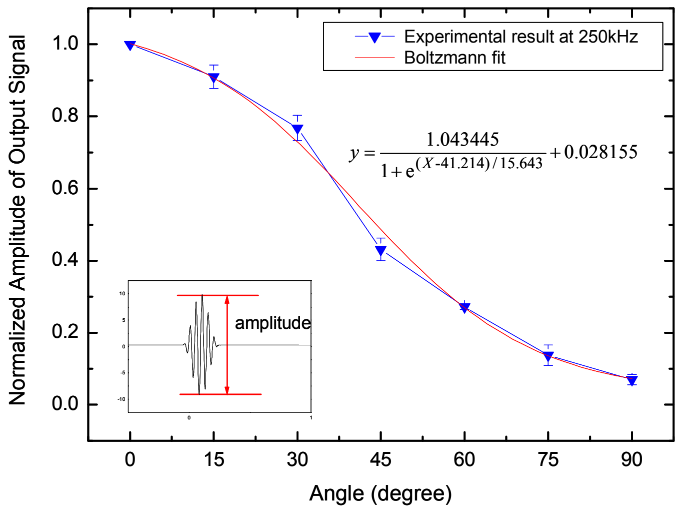

Figure 9. Sensitivity change according to the angle of EFPI sensor to detect Lamb wave at the exciting frequency of 250kHz