ABSTRACT

A piezoceramic (PZT) ultrasonic sensing system based on an optical fiber has been developed for detection of structural damage, in particular, a crack with different dimensions. Firstly, a pure system only using PZTs is investigated as a comparison, and a PZT sensor is located on one end of an aluminum beam as an actuator, the other one is located on the other end of the beam as a sensor. There are two aluminum beams used, i.e. a beam without a crack and a beam with a crack. The two situations correspond to health condition and damage condition of the structure. Secondly, the ultrasonic wave generated from a piezoelectric actuator is guided and propagated in the optical fiber and then sensed by a piezoelectric sensor located at the other end of the fiber. The sensed signal can be influenced by environmental and physical changes around the optical fiber. In this study, the sensitivity of the optical fiber sensor is experimentally studied. The position of the crack was detected by using PZT sensors and optical fiber. The TOF (Time of Flight) was delayed compared to when only PZT sensors were used because of the optical fiber length and crack. Using the wave propagation velocity on the optical fiber and aluminum beam, the crack position was exactly detected. Detection of different cracks with depths from 2mm to 15mm and widths from 0.25mm to 1mm is presented in this paper.

Key Words: Structural health monitoring, PZT patches, optical fiber patches, damage assessment indices

INTRODUCTION

The aging of large structures is a major concern for engineers and scientists. The rapid development of the economy gives rise to much higher and stricter criteria and requirements for SHM (Structural Health Monitoring). The NDE (Nondestructive Evaluation) technique is especially a major concern because it provides convenience for testing and reduces maintenance cost. Also, this technique is generally used in the industry. Non-destructive test with PZT sensor has a lot of advantages. PZT sensors offer special opportunities for structural health monitoring of large structures because the PZT is non-invasive such that it can be set on the structure and easily wired into sensor arrays. Specially, Beam structure is a common element in many large structures. So the real time monitoring and active control of this structure will improve the reliability and safety. In this paper, we developed the damage detection method using the guided lamb wave detection method by PZT sensors and optical fiber.

Damage measurement method using PZT and optical fiber

PZT is one of materials which is suitable for damage evaluation as the prober. PZT is very useful for structural health monitoring because of its ability to convert mechanical to electrical energy and vice-versa making it possible for PZT to function as sensor and actuator.

As one of the measuring method by PZT, there is impedance measurement method. The impedance method is used to detect whether the damage occurs or not and judge the damage extent. Another useful measuring method using PZT is Ultrasonic guided Lamb wave method. The Ultrasonic guided lamb wave is introduced to detect location and shape of damages accurately.

In this paper, the practical structure health monitoring technique, which can detect the damage by predicting its location in a thin and long beam, is developed by using Lamb wave among Ultrasonic guided wave. In the side of application, we compared the simulation and the experimental result from
the generating damage at beam by applying wavelet transformation technique. It was proved usefully available possibility. Finally, the combination of optical fiber and PZT, for damage monitoring of a vulnerable structure by impact, thermal, damage or internal hydraulic, is suggested by the method of the damage evaluation.

EXPERIMENT

Characteristic study of optical fiber

The optical fiber is manufactured by using the glass or plastic. It can transmit light through it from a long distance without loss. The whole size except the protection covering is hundred ~ hundreds µm (1µm is 1/1000mm) and a refractive index of the core part is more higher than the refractive index of the cladding. So that, it doesn't loss light as being close up the core. Also it can transmit the data at up to 12.5Mbyte/s on a line of fiber, it has high economical efficiency and it is not affected by external electromagnetic wave interference.

In this paper, we use 4-single mode optical fibers (SH600, 460HP, SH800, SH980) with core having a diameter of several µm(Fig. 1.2). Also the velocity of optical fiber wave propagation is investigated in the experiment. From the results, 460HP showed the highest wave form after being propagated at the same time and 460HP model was the best also from propagation character of Lamb wave to the aspect of the signal. Structural health conditioning and propagation characteristic of damage conditioning was analyzed successfully using the propagation velocity which was obtained from the experiment.

Damaged detection using PZT

Figure 1.3 - Experimental setup
Table 1 - The property of Al specimen

<table>
<thead>
<tr>
<th>Property of Aluminium beam element</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>1000</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>15</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>2</td>
</tr>
<tr>
<td>Density $\rho [kg/m^3]$</td>
<td>2.70</td>
</tr>
<tr>
<td>Young's Modulus $E [N/m^2]$</td>
<td>7.06</td>
</tr>
</tbody>
</table>

In the experiment we used the aluminum specimen like for example the beam. Tone-burst Lamb-wave of 10 $V_{pe}$ using function generator (Agilent 33250A) was used at excitation signal. Excitation signal was used excited Lamb wave in the center frequency of 56KHz which applied sin signal of seven by Hamming Window. It is executed for doing the comparative analysis from experimental result of interface with optical fiber. After measuring of sensing sensor was analyzed time of flight of sensed waves. The following show the outline of the experiment specimen. The experimental result for the health condition of Fig. 1.4 is depicted in Fig. 1.6.

![Figure 1.4 - Specimen of healthy condition](image)

Next, the experimental result for the health condition of Fig 1.5 is depicted in Fig. 7 from which the position of the damage can be easily evaluated.

![Figure 1.5 - Specimen of damaged condition](image)
Through the above equation (1), position of damage appeared to be 0.2024m and error of 0.24mm was observed. The result of very precise measuring was obtained with distance, time and propagation velocity of Path1 and Path2 through the signal. The precision data is depicted in Table.2.

\[
\text{position of damage} = \frac{(\text{distance of Path2} - \text{distance of Path1})}{2}
\]

\[
= \frac{\left|\text{Path2 TOF} - \text{Path1 TOF}\right|}{2}
\times \text{propagation velocity of beam}/2 \cdots (1)
\]

<table>
<thead>
<tr>
<th>Frequency (㎑)</th>
<th>Velocity (㎧)</th>
<th>Specimen Condition</th>
<th>Real Length (L_1) (m)</th>
<th>Experimental Length (L_2) (m)</th>
<th>Error ((m)) ((L_1 - L_2))</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>4549.8</td>
<td>Healthy</td>
<td>0.95</td>
<td>0.946</td>
<td>0.004</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>2.95</td>
<td>2.957</td>
<td>-0.007</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage</td>
<td>0.95</td>
<td>0.946</td>
<td>0.004</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.35</td>
<td>1.351</td>
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<td></td>
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<td></td>
<td>1.775</td>
<td>1.774</td>
<td>0.006</td>
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</tr>
</tbody>
</table>

Table 2 - Experimental results for healthy and damaged conditions
**Damaged detection experiment and analysis using optical fiber**

**PZT excitation - PZT sensing through optical fiber**

In this experiment, Torn-burst lamb wave of center frequency 84KHz is used as excitation signal through the PZT. The method of PZT sensing through optical fiber is utilized for the experiment. Fig.1.8 and Fig.1.9 show the parameter of the Aluminum specimen used in the experiment.

![Figure 1.8 - Experimental setup for PZT and optical fiber interface (health condition)](image)

**Figure 1.8 - Experimental setup for PZT and optical fiber interface (health condition)**

![Figure 1.9 - Experimental setup for PZT and](image)

**Figure 1.9 - Experimental setup for PZT and**

First, the experiment for the healthy specimen (Fig 1.10) is performed and the result is shown in Fig. 1.11. Signal analysis is performed to establish the frequency of the theoretical wave form in the specimen. And it analyze the signal using group velocity 4549.8m/s of Aluminum specimen and optical fiber group velocity 3546m/s by the distance.

![Figure 1.10 - Wave propagation for the healthy specimen](image)

**Figure 1.10 - Wave propagation for the healthy specimen**

![Figure 1.11 - Response signal and TOF of health specimen](image)

**Figure 1.11 - Response signal and TOF of health specimen**

The result for the damaged specimen illustrated in Fig 1.12 is shown in Fig 1.13 and from it the position of the damage is evaluated.
Through the above equation (1), position of damage appeared to be 0.2005m and error of 0.05mm is observed. It confirmed very accurate measurement result from the measurement result of the Path1 and Path2 distance through the signal. The precision data is depicted by Table.3.

<table>
<thead>
<tr>
<th>excitation frequency (KHz)</th>
<th>propagation velocity (m/s)</th>
<th>specimen condition</th>
<th>real distance (m)</th>
<th>experiment distance (m)</th>
<th>error (m) ($L_1 - L_2$)</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL specimen: 84</td>
<td>4549.8</td>
<td>health</td>
<td>1.215</td>
<td>1.217</td>
<td>0.002</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>optical fiber: 3546</td>
<td></td>
<td>3.215</td>
<td>3.211</td>
<td>-0.004</td>
<td>2</td>
</tr>
<tr>
<td>damage</td>
<td></td>
<td></td>
<td>1.215</td>
<td>1.217</td>
<td>0.002</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.615</td>
<td>1.618</td>
<td>0.003</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.015</td>
<td>2.013</td>
<td>0.003</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3 - Data obtained Health and damaged condition

**PZT and optical fiber excitation - PZT sensing**

Another experiment is carried out wherein one end of the Aluminum specimen is excited by introducing a wave form to the PZT and allowing the wave to propagate through the optical fiber of 24 cm long. The wave propagates through the length of the Aluminum specimen and received by the PZT sensor at the other end. Through signal analysis the damaged in the specimen is determined. Fig. 1.14 and Fig. 1.15 show the schematic representation of the specimen with healthy condition and the result of the experiment, respectively.
The figure above (Fig 1.16) illustrates the specimen with damaged condition and the corresponding result is shown in Fig 1.17.

Comparing the results depicted in Fig 1.17 with Fig. 1.13, although the configuration is reversed, the similarity is easily noticed. The signal where the location of the damage is discovered occurred at exactly the same time for both configurations. This is due to the fact that the distance of the optical fiber from the specimen is the same.

**Comparison of Sensing wave form**
The blue line shows the signal of PZT excitation - PZT sensing and the red line show PZT excitation - PZT sensing signal through optical fiber. When comparing between the two signals, size of damage wave can be confirmed. In the case of sensing, the signal through optical fiber larger and clearer than the signal when sensing directly by PZT without the optical fiber. The waveform enables the evaluation of the position of the damage due to the clear. Also, time delay and decrease phenomenon according kind or distance of optical fiber was sufficiently confirmed possibility of detection through a basic specific experiment. It confirmed usefully available possibility as the detection of the damage through optical fiber and PZT sensor to compare two wave forms.

CONCLUSIONS

It monitored continuatively the health of the structure through the measurement, which graft optical fiber and PZT sensor, and the analysis method considering the flex and the high temperature fitness etc., Also, it presumed accurately the position and a form of damage using Wavelet transformation by Ultrasonic guided wave analysis algorithm.

Analyzied results of characteristic of 4 kinds of single mode optical fibers(SH600, 460HP, SH800, SH980), 460HP shows the highest waveform after being propagated in the same time. The 460HP model is the best for propagating the Lamb wave in the considered experimental setup.

The experiments using only PZT for healthy as well as damaged specimen reveal measurement results with very tolerance.

Using the optical fiber-PZT interface for signal excitation and sensing gives accurate position of the damage.

It requires the algorithm and experimental study for the efficient and precise data management through sensor networking and for the measurement and the analysis of the large-sized and complex structure.

REFERENCES

4) Kazuhisa K., Faculty of Virginia Polytechnic Institute, April,1998.