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구조물의 손상에 대한 추정방법의 실험적 비교

Experimental Comparison of Structural Damage Detection Methods

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Experimental Comparison of
Structural Damage Detection Methods

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Experimental Comparison of Structural Damage Detection Methods
Recently, Structural health monitoring and damage detection has received a considerable amount of interest. Also many detecting techniques have been developed for a few decades. In order to use these various damage detection methods in real structures, it is important to know the characteristics and applicability of them. In this study, methods using natural frequency, mode shape and wave propagation are compared experimentally for their application.

For the experimental comparison, three damage detection methods are tested with the same damage cases and environmental conditions. Aluminum beams, 40mm wide and 4mm thick with a clear span of 600mm under fixed-free boundary conditions are used. Damages are given at three different locations, 1/4, 2/4, 3/4 of the beam length starting from the fixed end. The damage sizes are 5%, 10%, 20% and 30% at each damage location.

Unlike numerical calculation of the compared methods, it is hard to detect small damages by any compared method because of practical and technical problems. Some errors are unavoidable and some others can be reduced by changes of experimental setup. These factors of errors are also discussed in this study.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td><strong>CHAPTER 1 INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Backgrounds</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Literature Review</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Objectives and Scope</td>
<td>4</td>
</tr>
<tr>
<td><strong>CHAPTER 2 COMPARED DAMAGE DETECTION METHODS</strong></td>
<td>6</td>
</tr>
<tr>
<td>2.1 Frequency Domain Method</td>
<td>6</td>
</tr>
<tr>
<td>2.1.1 Natural Frequency Method</td>
<td>6</td>
</tr>
<tr>
<td>2.1.2 Frequency Response Function (FRF) Curvature Method</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Mode Shape Method</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 Mode Shape Method using Wavelet Transforms</td>
<td>7</td>
</tr>
<tr>
<td>2.2.2 Mode Shape Sensitivity Method</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Wave Propagation Method</td>
<td>9</td>
</tr>
<tr>
<td><strong>CHAPTER 3 EXPERIMENTAL SETUP</strong></td>
<td>11</td>
</tr>
<tr>
<td>3.1 Setup</td>
<td>11</td>
</tr>
<tr>
<td>3.2 Experimental Procedures</td>
<td>13</td>
</tr>
<tr>
<td>3.2.1 Frequency Domain Method</td>
<td>13</td>
</tr>
<tr>
<td>3.2.2 Mode Shape Method</td>
<td>13</td>
</tr>
</tbody>
</table>
CHAPTER 4 NUMERICAL AND EXPERIMENTAL RESULTS ………………… 15

4.1 Frequency Domain Method ……………………………………………………... 15
  4.1.1 Numerical Result ……………………………………………………………… 15
  4.1.2 Experimental Result …………………………………………………………… 17

4.2 Mode Shape Method ……………………………………………………………….. 22
  4.2.1 Numerical Result ……………………………………………………………… 22
  4.2.2 Experimental Result …………………………………………………………… 25

4.3 Wave Propagation Method ………………………………………………………… 29
  4.3.1 Numerical Result ……………………………………………………………… 29
  4.3.2 Experimental Result …………………………………………………………… 33

4.4 Discussion ………………………………………………………………………….. 36

CHAPTER 5 CONCLUSIONS …………………………………………………………….. 39

SUMMARY (IN KOREAN) ………………………………………………………………… 40

REFERENCES …………………………………………………………………………. 42

ACKNOWLEDGEMENTS
CURRICULUM VITAE
# LIST OF TABLES

3.1 Specification of accelerometer ................................................................. 11
4.1 Differences in natural frequencies between damaged and undamaged beam (%) .. 15
4.2 Differences in natural frequencies between damaged and undamaged beam (%) .. 18
4.3 Computed and measured arrival time ......................................................... 36
4.4 Factors of experimental error ................................................................. 37
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Experimental setup</td>
<td>12</td>
</tr>
<tr>
<td>3.2</td>
<td>A schematic of a uniform beam containing a damage</td>
<td>13</td>
</tr>
<tr>
<td>4.1</td>
<td>Comparison of natural frequencies</td>
<td>16</td>
</tr>
<tr>
<td>4.2</td>
<td>Comparison of natural frequencies</td>
<td>19</td>
</tr>
<tr>
<td>4.3</td>
<td>FRF curvature differences</td>
<td>21</td>
</tr>
<tr>
<td>4.4</td>
<td>Comparison of second mode shape: damage location 2/4 (MIDAS model)</td>
<td>22</td>
</tr>
<tr>
<td>4.5</td>
<td>Wavelet coefficient plot</td>
<td>23</td>
</tr>
<tr>
<td>4.6</td>
<td>Relationship between wavelet coefficient and damage size</td>
<td>24</td>
</tr>
<tr>
<td>4.7</td>
<td>Mode shape sensitivity</td>
<td>25</td>
</tr>
<tr>
<td>4.8</td>
<td>Comparison of second mode shape</td>
<td>26</td>
</tr>
<tr>
<td>4.9</td>
<td>Mode shape slope differences</td>
<td>28</td>
</tr>
<tr>
<td>4.10</td>
<td>Input load and response of undamaged bar</td>
<td>30</td>
</tr>
<tr>
<td>4.11</td>
<td>Response at free end of damaged bar</td>
<td>31</td>
</tr>
<tr>
<td>4.12</td>
<td>Influence of impact time on response</td>
<td>32</td>
</tr>
<tr>
<td>4.13</td>
<td>A schematic of the experimental setup for wave propagation</td>
<td>33</td>
</tr>
<tr>
<td>4.14</td>
<td>Experimental input load and response of undamaged beam (fixed-fixed)</td>
<td>34</td>
</tr>
<tr>
<td>4.15</td>
<td>Response of damaged beam (fixed-fixed)</td>
<td>35</td>
</tr>
</tbody>
</table>
1.1 Backgrounds

Civil structures, such as long span bridges, large dams and tall buildings etc, often have a long-term service period. During this time, they are inevitable to have structural damages from various environmental influences. These damages generally degenerate the performance of the structures, and consequently threaten the safety of life and property. Detection of damages at the early stages of growth is one of the most important requirements for the proper maintenance of civil structures. This leads to the necessity of developing damage detection techniques that are both practical and accurate. Therefore the health monitoring systems and damage detection techniques are becoming important issues.

In the past 20 years a lot of works has been published in the area of damage detection, where various methods have been proposed. The premise of these detection methods is that damages in a structure will cause changes of structural response. Classical methods, such as those based on frequency and stiffness analysis, extract damage information from variations in structural stiffness and natural frequency relative to undamaged structures. Since damage alters the dynamic characteristics of a structure, namely its eigenproperties, several techniques based on modal analysis have been developed in recent years. Among all sorts of methods developed from changes in dynamic parameters, some are based on mode shape
changes. The main idea of this method is identifying local perturbations caused by
damages such as cracks. Recent studies proposed structural models based on wave
propagation, which are well suited for detecting small defects since they are
sensitive to changes in local dynamic impedance. However, there are still many
challenges and obstacles before these methods to be implemented in practice, even
though they are accurate and robust theoretically.

To be able to find and locate damages accurately, collecting quality data is important.
Because of the importance of the data acquisition, various smart sensors have received a
lot of interest, and their installation in real structures has been studied recently. Due to the
improvement of these smart materials, health monitoring and data acquisition systems for
civil structures have been advanced dramatically. Recent advances in materials and signal
processing technology must be taken advantage of to make further progress in practical
non-destructive evaluation (NDE) technique. However, still the application of damage
detection methods in reality has a lot of practical and technical problems. These methods
need experimental verification in many ways for better reliability.

1.2 Literature Review

A large number of studies about non-destructive evaluation (NDE) have been
carried out on conventional and modern approaches. The conventional methods have
been well developed, and accepted by industry as practically applicable damage
detection methods. The modern NDE methods are still under development,
implemented in limited area, and not fully accepted as a verified tool for detecting
damages. One of these modern methods is the vibration-based inspection
methodology.
A comprehensive survey of structural health monitoring was carried out by Sohn et al. at Los Alamos national laboratory. (2003). It determines the current state of the damage detection and health monitoring technology. Salawu (1995) presented a literature review about detection of structural damage through changes in natural frequency. As pointed out in these studies, damage in a structure results in a reduction in stiffness and an increase in damping, which in turn leads to a decrease in the natural frequencies of the structure. It was also argued that a localized damage would affect each mode differently, and this enables one to find the location of the damage. Owolabi et al. (2002) tested the method using changes in natural frequencies with both simple-simple and fixed-fixed aluminum beam for experimental verification. They show the relationship between damage location and natural frequency changes.

The method based on mode shape has also been investigated in many recent studies, including those by Wang et al. (1998), Chukwuojekwu et al. (2000), Ovanesova et al (2003), which mostly deal with damage detection using wavelet transform. Parloo et al. (2001) also suggested damage localization using mode shape sensitivities. Mode shape and frequency response function methods were compared and discussed by Maia et al. (2002). Over the years many analytical techniques have been developed for treating wave propagation problems. Magdalena et al. (2002) introduced a new finite spectral element of a cracked rod for damage detection. Wieslaw et al. (2003) presented a method of wave propagation, which can be further used to detect small delaminations in beam-like structures. Bart et al. (2000) discussed two very relevant practical issues in the application of vibration-based health monitoring: the excitation source and the effect of temperature. These kinds of studies are necessary because not only the health of a structure, but also the applied excitation and the changing temperature influence the measurable dynamic
characteristics.

A large number of researches related to structural damage detection have been published, however there are few studies focused on the experimental comparison of various methods. Also details about practical and technical problems need to be discussed for reliable application of the methods.

1.3 Objectives and Scope

The purpose of this study is to compare structural damage detection methods experimentally. Comparison of the experiment is focused on the applicability and feasibility of the proposed detecting techniques. To perform the test, three typical and possible methods, such as frequency domain, mode shape and wave propagation method were chosen. The approach based on natural frequency changes is more conventional, but this could provide an inexpensive structural assessment technique, since frequency measurement can be acquired cheaply. Mode shape method has gained increasing attention because it does not need any prior knowledge about states of the structures. Recent advances in smart materials lead the improvement of wave propagation method which is effective for detecting delamination and cracks in composite structures.

An actual aluminum cantilever beams were used for this experimental investigation. To see the effect of damage size and location, various damage cases were given to the beams. The size of damage was restricted up to 30% stiffness reduction, because large damages can be detected by visual inspection without any equipment in practice. In a sense, complicated damage detection methods should be able to find small defects. In a real test, there are a lot of factors of errors, and it is
important to reduce these inaccuracies for real application of the methods. Factors which could limit successful application of vibration monitoring for damage detection and structural assessment are also discussed. Numerical calculation using finite element model, which has the same dimensions as the experimental beams, is performed to verify the result of the experiment.
CHAPTER 2

COMPARED DAMAGE DETECTION METHODS

2.1 Frequency Domain Method

2.1.1 Natural Frequency Method

Existence of structural damage in an engineering system leads to modification of the vibration modes. In other words, damage in a structure results in a reduction in stiffness, and generally that causes a decrease in natural frequencies. Local or distributed changes in stiffness produce changes in natural frequencies, which affect each mode differently depending on the damage location. This is because the damage event is local phenomenon in most cases. This effect offers the possibility of using data from dynamic testing to detect, locate and quantify damages.

As only frequency information is required, this approach can provide cost effective structural assessment technique. Another advantage of measuring vibration responses is the global nature of the derived natural frequencies. However, natural frequency changes alone may not be sufficient for a unique identification of the structural damage, since frequency shifts due to changes in ambient conditions (e.g. temperature, humidity) is considerable.

2.1.2 Frequency Response Function (FRF) Curvature Method

Basically, this method is an extension of the Pandey et al. method, and suggested by Sampaio et al. It uses FRF data rather than just using natural frequency. The method uses the frequency response at different locations of the structure.
The curvature for each frequency is given by

\[ \alpha^*(\omega)_{i,j} = \frac{\alpha(\omega)_{i+1,j} - 2\alpha(\omega)_{i,j} + \alpha(\omega)_{i-1,j}}{h^2} \]  \quad (1) \]

where \( \alpha_{i,j} \) is the FRF measured at location \( i \) for a force input at location \( j \), and \( h \) is \( \Delta \omega \).

The absolute difference between the FRF curvatures of the damaged and undamaged structure at location \( i \), along the chosen frequency range, is calculated, for an applied force at point \( j \), by

\[ \Delta \alpha^*_{i,j} = \sum_{\omega} \left| \alpha^*(\omega)_{i,j}^{d} - \alpha^*(\omega)_{i,j} \right| \]  \quad (2) \]

where, \( \alpha^*(\omega)_{i,j}^{d} \) is the FRF curvature of damaged structure. Finally, one can sum up for several force location cases.

\[ FRF_{-C_j} = \sum_{j} \Delta \alpha^*_{i,j} \]  \quad (3) \]

As you can see in these formulas, the method can detect and localize defects by comparing undamaged with damaged state.

2.2 Mode Shape Method

2.2.1 Mode Shape Method using wavelet transforms

The premise of the technique is that damage (e.g. cracks) in a structure will cause structural response perturbations at mode shape curves. The extent of the irregularity of the curve depends on the size and location of defects. Generally, such local perturbation
cannot be observed from visual inspection, but they are detectable from the distribution of
the wavelet coefficients obtained by wavelet transform. This method does not require any
knowledge of the material properties nor prior states of the structure.

### 2.2.2 Mode Shape Sensitivity Method

Several mode shape sensitivity methods are presented in Maia et al and Parloo et al’s
paper. The simplest one is mode shape (MS) method; its damage index is written below.

\[
\Delta \psi_{ij}^d = |\psi_{ij}^d - \psi_{ij}^u| \quad (4)
\]

where \( \psi_{ij}^d, \psi_{ij}^u \) are the damaged and undamaged \( j^{th} \) mode shape vectors of location \( i \). If
more than one mode is used, the index is the sum of damage indices from each mode.

\[
MS_i = \sum_j \Delta \psi_{ij} \quad (5)
\]

Mode shape slope (MSS) method seeks the change in the squared mode shape slope.
Its damage index is written below

\[
MSS_i = \sum_j [\psi_{ij}^{d^2} - \psi_{ij}^{u^2}] \quad (6)
\]

Mode shape curvature (MSC) method was first presented by Pandey et al. The
location of the damage is assessed by the largest absolute difference between the mode
shape curvatures of the damaged and undamaged structure, as follows:

\[
MSC_i = \sum_j |\psi_{ij}^d - \psi_{ij}^u| \quad (7)
\]
Another possible way for localizing damage is using the modal assurance criterion (MAC) and co-ordinate modal assurance criterion (COMAC). For damage identification purposes, differences between mode shapes of the structure in a reference condition and a damaged condition are assessed:

\[
MAC_{jk} = \frac{\sum_{i=1}^{N_0} (\psi_{ij} \psi_{ik})^2}{\left(\sum_{i=1}^{N_0} (\psi_{ij})^2\right) \left(\sum_{i=1}^{N_0} (\psi_{ik})^2\right)}
\]  
(8)

\[
COMAC_i = \frac{\left(\sum_{j=1}^{N_m} \psi_{ij} \psi_{ij}^d\right)^2}{\left(\sum_{j=1}^{N_m} (\psi_{ij})^2\right) \left(\sum_{j=1}^{N_m} (\psi_{ij}^d)^2\right)}
\]  
(9)

The values are calculated for all \(N_m\) modes as well as all \(N_0\) dofs. The diagonal values of the MAC matrix indicate which modes are most affected by the damage. In some cases, the COMAC values are able to localize damage.

### 2.2.3 Wave Propagation Method

This method is based on the known fact that material discontinuities affect the propagation of elastic waves in a structure. The change in certain material characteristics, such as a local change in stiffness caused by a crack, will affect the propagation of transmitted elastic waves and will modify the received signal. More simply, by calculating arrival time and size of the wave reflected from damage, one can estimate its location as well as its size. The wave speed can be easily achieved theoretically or experimentally.
Chapter 2. Compared Damage Detection Methods

The phase speed $c$ is given by $\omega / \gamma$ (Graff 1975) where $\gamma$ is wavenumber and $\omega$ is frequency. Phase speed-frequency ($c$-$\omega$) relationship is written bellow.

$$
\bar{c}^2 = \frac{1 + \frac{E}{G\kappa} \pm \sqrt{\left(1 - \frac{E}{G\kappa}\right)^2 + \frac{4E}{G\kappa\bar{\omega}^2}}}{2(1-1/\bar{\omega}^2)} \quad \text{for} \quad \bar{\omega}^2 \neq 1 
$$

$$
\bar{c} = \frac{E}{\sqrt{E + G\kappa}} \quad \text{for} \quad \bar{\omega}^2 = 1
$$

where, $E$ is Young’s modulus, $G$ is shear modulus, $\kappa$ is Timoshenko beam theory,

$\bar{\omega} = \sqrt{\rho I / (G\kappa)} \omega$, \quad $\bar{c} = c / c_s$, \quad $c_s = \sqrt{G\kappa / \rho}$ which is the propagation velocity of shear waves accounting for shear deformation.

The significance of this method is that wave propagation is simple matter. By using this phenomenon, damage can be detected with simple experiment.
CHAPTER 3
EXPERIMENTAL SETUP

3.1 Setup

Experimental setup used to obtain dynamic response data is shown in figure 3.1. Aluminum beams (6061-T6), 40mm wide and 4mm thick with a clear span of 600mm under fixed-free boundary conditions are used. The beams have the following material properties: Young’s modulus $E=70$Gpa, density $\rho=2710$kg/m$^3$, the Poisson ratio $\nu=0.33$. An impact hammer (PCB Piezotronics Model 086C03) with a hard tip is employed. Accelerometer (B&K type 4507) is used and table 3.1 shows its specification. Data are acquired using FFT analyzer (B&K type 3560C) which has a maximum acquisition rate of 70 thousand samples per second. Shaker is equipped as a source of excitation.

<table>
<thead>
<tr>
<th>Table 3.1 Specification of accelerometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Sensitivity</td>
</tr>
<tr>
<td>Frequency Range</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Measuring Range</td>
</tr>
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</table>

The fixed-free beam model is clamped at one end, between one thick square steel plates and heavy steel support shown in figure 3.1. Total 13 identically manufactured aluminum beams are used; one is for an undamaged case and the others are for 12
different damage cases. Damages are generated to the desired width using a thin saw cut (around 0.8 mm thick). Damages are given at three different locations, 1/4, 2/4, 3/4 of the beam length starting from fixed end. The damage sizes are 5%, 10%, 20%, 30% (=2d/40mm; see figure 3.2) at each damage location. A schematic of a beam containing damage is shown in figure 3.2.

Figure 3.1 Experimental Setup
3.2 Experimental procedures

3.2.1 Frequency Domain Method

Impact load is given near fixed end of the cantilever beam, and acceleration is measured at free end. Autospectrum can be obtained from the measured acceleration data, which shows resonant frequencies (natural frequency) apparently. In this paper, first three natural frequencies are considered for comparison. Before damages are given to the beams, natural frequencies of all 13 aluminum beams are measured. Ideally, all the beams, produced identically, should have same natural frequencies, however they have a little difference. This could be caused by experimental error. To measure more accurate natural frequency, measuring duration and averaging of data is also important.

To obtain frequency response function (FRF), impact hammer is used. FRF can be calculated by FFT analyzer with input force (impact) and response of the beam. In this test, impact load is given near fixed end, and acceleration of 15 different locations along the beam is measured to get FRF at each location. Finally, Damaged and undamaged FRF at each point are compared to localize damages.

3.2.2 Mode Shape Method

In order to get the mode shape of the beam, shaker needs to be attached stably. While the shaker is giving an excitation at a natural frequency to the beam, the response
of the beam was measured. In this test, responses of 60 different points (10mm interval) along the beam are obtained for mode shape. First and second mode shape of each beam are measured.

### 3.2.3 Wave Propagation Method

Like natural frequency change method, this method is easy to perform the experiment. Short impact load is given near fixed end of the beam, and acceleration is measured at free end. Theoretically, between arrival of direct wave and wave reflected from the boundary, there should be a small signal caused by a damage. The objective of this method is to find the signal reflected from damage. Even though the basic idea of this method is quite simple, there are many factors of errors. This will be discussed later in this paper.
CHAPTER 4
NUMERICAL AND EXPERIMENTAL RESULTS

4.1 Frequency Domain Method

4.1.1 Numerical Result

Numerical calculation of damaged beam model was performed using eigenvalue analysis. Table 4.1 shows numerical comparison of changes in natural frequency, and figure 4.1 shows the comparison graphically. Natural frequency changes increase depending on the size of damages. Local changes in stiffness produce changes in natural frequencies, which affect each mode differently depending on the damage location. The first natural frequency was most affected when the damage is at 1/4 location. The third natural frequency decreases the most when the damage is at 3/4 location. According to numerical result, effect of damages can be observed clearly, so this method seems to be very promising technique for damage identification.

<table>
<thead>
<tr>
<th>Damage case</th>
<th>1\textsuperscript{st} natural frequency</th>
<th>2\textsuperscript{nd} natural frequency</th>
<th>3\textsuperscript{rd} natural frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>10% 20% 30%</td>
<td>10% 20% 30%</td>
<td>10% 20% 30%</td>
</tr>
<tr>
<td>1/4</td>
<td>0.1 0.2 0.3</td>
<td>0.03 0.05 0.08</td>
<td>0.02 0.03 0.02</td>
</tr>
<tr>
<td>2/4</td>
<td>0.005 0.01 0.02</td>
<td>0.01 0.04 0.11</td>
<td>0.005 0.01 0.015</td>
</tr>
<tr>
<td>3/4</td>
<td>0.1 0.15 0.2</td>
<td>0.03 0.06 0.11</td>
<td>0.04 0.1 0.2</td>
</tr>
</tbody>
</table>
### Chapter 4 Numerical and Experimental Results

#### a) Comparison of first natural frequency

#### b) Comparison of second natural frequency
Chapter 4 Numerical and Experimental Results

17

0
0.1
0.2
0.3
0.4

1/4                      2/4                      3/4

(%) Differences

10% Damage
20% Damage
30% Damage

Damage location

4.1.2 Experimental Result

Before damages are given to the beams, natural frequencies of all 13 aluminum beams were measured. The beams were produced identically, however they had maximum of 0.2% differences in natural frequency each other. Practical irregularity of the beams could be one reason of the errors. Changes of environmental conditions (e.g. boundary condition, temperature, external load etc) also affect the accuracy of the test. In that sense, it is necessary for natural frequencies to change by more than 0.3% for damage to be detected with confidence.

From the experimental results, the following observations were made for all the cases considered. Table 4.2 shows comparison of damaged and undamaged beam in terms of changes in natural frequency (%). In the case of 10% damages, most of the natural
frequency differences are smaller than error level. In other words, at least 20% stiffness reduction is meaningful in this experiment. Due to the experimental errors, differences are entirely larger than those of numerical result. The fundamental natural frequency was most affected when the damage located at 1/4 length of the beam from the fixed end. The second natural frequency decreased the most when the damage was at 2/4 location. Damage at 3/4 location most affected the third natural frequency. This could be explained by the fact that the decrease in frequencies is greatest for a crack located where the bending moment is greatest. The nodal point of the second mode and third mode is near 3/4 and 2/4 locations each. When damage locates near this nodal point, natural frequency is less affected. Generally, the larger the damage is the more natural frequency decreases. This is the same result with the simulation data. Based on this fact, damage size can be inferred roughly.

Table 4.2 Differences in Natural Frequencies between Damaged and Undamaged Beam (%)

<table>
<thead>
<tr>
<th>Damage case</th>
<th>1st natural frequency</th>
<th>2nd natural frequency</th>
<th>3rd natural frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Size</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>1/4</td>
<td>0.1</td>
<td>0.3</td>
<td><strong>0.4</strong></td>
</tr>
<tr>
<td>2/4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>3/4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

This natural frequency change method was easy and cost effective to perform the test. However, there are somewhat differences between two results. Experimental errors could be one reason of this difference. These errors make this method impractical. Even in the limited and strict experiment condition, small damage cannot be detected. Temperature change caused relatively large (more than 1%) natural frequency differences. It is the main obstacle in application of the method in a real structure, even though it is
not a big problem in the test. Boundary condition caused the biggest error. Weight of the sensor and irregularity of the beams were also the factor of errors.

For FRF curvature method, FRF were obtained from 15 different sensor positions, and curvature was calculated using the formula written in chapter 2. 30% damage size and 1/4, 2/4, 3/4 damage locations were considered, and comparisons are illustrated in figure 4.3 The existence of damage is not obvious from the observation of figure 4.2. Because of practical errors, it was unable to find damage clearly by this method. FRF should be robust to the ambient conditions, however, in practice, it was more sensitive to the magnitude of impact than damage changes.

![Graph showing comparison of first natural frequency](image-url)
Chapter 4 Numerical and Experimental Results

b) Comparison of second natural frequency

c) Comparison of third natural frequency

Figure 4.2 Comparison of natural frequencies
Chapter 4 Numerical and Experimental Results

Figure 4.3 FRF curvature differences

a) Damage size: 30%, location 1/4

b) Damage size: 30%, location 2/4

c) Damage size: 30%, location 3/4
4.2 Mode Shape Method

4.2.1 Numerical Result

Aluminum beams were modeled using MIDAS finite element method. The beam type models have exactly same dimension, boundary condition and damage cases with the experimental beam. The beam model was divided into 120 elements and damage was simulated by reduction in stiffness of one element.

![Graph comparing second mode shape](image)

Figure 4.4 Comparison of second mode shape: damage location 2/4 (MIDAS model)

Figure 4.4 shows the simulation result of second mode shape when damage locates at 1/4 of the beam length. There is no observable difference between the undamaged and the damaged mode shape. However, on application of the wavelet transformation method, even 10% damage is clearly visible as seen in figure 4.5. It is observed that wavelet coefficients near the location of the damage are highest in magnitude, except near the boundaries.
Figure 4.5 Wavelet coefficient plot

a) Damage size: 10%, location 1/4

b) Damage size: 10%, location 2/4

c) Damage size: 10%, location 3/4
All the damaged cases analyzed by this algorithm located the damage accurately. The magnitude of the coefficient at the damage area is observed to increase almost linearly with damage extent as seen in figure 4.6. Using this method, damage size and location is detected without any prior knowledge of undamaged state.

Results of various damage detection methods using mode shape vectors are represented in figure 4.7. These methods were calculated numerically using the formula written in chapter 2. The methods are different from mode shape with wavelet transform method in term of using undamaged data of the beam. According to the result, all of the methods are capable of pinpointing the correct damage location.

Figure 4.6 Relationship between wavelet coefficient and damage size
Chapter 4 Numerical and Experimental Results

4.2.2 Experimental Result

To get an experimental mode shape, responses of sixty different points (10mm interval) of a beam were measured, while giving an excitation at a natural frequency using the shaker. Figure 4.8 shows comparison of the second mode shape, and there is a little difference between damaged and undamaged state. In the case of smaller than 20% damage, the mode shapes were almost matched with undamaged case. When the damage is bigger than 20%, the normalized amplitude is observed to increase with damage extent as seen in figure 4.8. On application of the wavelet transformation method, even 30% damage couldn’t be found regardless of various damage locations.
Figure 4.9 shows the result of mode shape slope method. As one can see in this result, it is totally impossible to find the damage. This isn’t the matter of detecting method but the accuracy of the data. Because all of the mode shape sensitivity methods deal with mode shape vectors, there is no way to find damages with incorrect data. In the numerical result, small damages can be found obviously, due to accurate data. Theoretically, this method seems to be effective as well as reasonable. In reality, number of sensor is limited and even small measuring errors make damage localization difficult. Furthermore, this is the most difficult, and time consuming among the compared methods. In this test, shaker instability was the biggest problem.
Figure 4.8 Comparison of Second Mode Shape
Chapter 4 Numerical and Experimental Results

Figure 4.9 Mode shape slope differences

(a) Damage size: 30%, location 1/4

(b) Damage size: 30%, location 2/4

(c) Damage size: 30%, location 3/4
4.3 Wave Propagation Method

4.3.1 Numerical Result

Changes of wave propagation process due to a crack appearance are examined by comparing the difference between the responses from damaged and undamaged beams. The influence of the impact time increment for wave propagation is also examined.

A bar, which has the same dimension and material property with the experimental beam, is modeled for numerical calculation of wave propagation effect. Figure 4.10 (a) shows impact load given near the fixed end, and (b) shows the acceleration at free end of modeled bar. In this figure, direct wave and wave reflected from the boundary are observed clearly. Wave velocity can be calculated with given material property, and by using calculated velocity, arrival time of direct wave can be obtained easily. Impact load is given for 0.01ms which is very short time relative to the wave arrival time. In the figure 4.11, there are additional signals between direct and reflected wave. These are the waves reflected from damages. By calculating the wave arrival times, one can estimate the damage location.

When impact load is given for 0.05ms, flat area between the direct and reflected wave becomes shorter as seen in the figure 4.12 (b). Because of this effect, the location of the wave reflected from damage is not clear. With longer impact time, in the case of 0.1ms, wave propagation effect cannot be observed, because of overlapped waves. Consequently, there is no difference between damaged and undamaged response. In order to find damages by the wave propagation method, impact time should be short enough relative to arrival time.
a) Input load (impact time : 0.01ms)

b) Response at free end

Figure 4.10 Input load and response of undamaged bar
Chapter 4 Numerical and Experimental Results

Figure 4.11 Response at free end of damaged bar

(a) Damage size: 20%, location: 1/4

(b) Damage size: 20%, location: 2/4

(c) Damage size: 20%, location: 3/4
Chapter 4 Numerical and Experimental Results

Figure 4.12 Influence of impact time on response
4.3.2 Experimental Result

Short impact load is given near fixed end of the cantilever beam, and acceleration is measured at free end. In this test, beam length is 60cm, and experimentally measured wave velocity is 1.4m/ms. Practically, it was impossible to give an impact load shorter than 0.6ms. This impact time is not short enough relative to wave arrival time 0.4ms. Because of this long impact time damage localization was difficult, even by using wavelet transform.

To make arrival time longer, 1.1m aluminum beams with two boundary conditions, fixed-free and fixed-fixed, were tested. In the case of fixed-free B.C., wave propagation effect was not clear because of flexibility of the beam and large deflection at free end. The location of accelerometer was changed in the experiment of fixed-fixed beam. The schematic of the experiment is shown in figure 4.13.

![Figure 4.13 A schematic of the experimental setup for wave propagation](image)

By changing the boundary condition, arrival time of wave reflected from boundary could be elongated to 1.6ms which is about three times longer than the impact time. Wave velocity and arrival time can be measured experimentally with the acceleration data shown in figure 4.14 (b). In this test, smaller than 40% damage could not be detected because of technical problem (e.g. impact time, sensitivity of the sensor etc.). With 50%
damage, an additional signal can be observed between direct and reflected signal which is shown in figure 4.15. This is the wave reflected from the damage.

Figure 4.14 Experimental input load and response of undamaged beam (fixed-fixed)
Chapter 4 Numerical and Experimental Results

Figure 4.15 Response of damaged beam (fixed-fixed)

a) Damage size : 50%, location : 80cm from the accelerometer

b) Damage size : 50%, location : 65cm from the accelerometer
Table 4.3 shows the comparison of computed and measured arrival time related to the damage location. There are some errors between the two results because the location of the additional signal is not clear in the experimental data. In a sense, the location of the damage is well matched with that of calculation. However, to detect damage with this method, damage should be in limited area, because of the relatively long impact time. If damages locate near the boundaries, the wave reflect from the damage is overlapped with impact or reflected signal. In this case, damages are not detected with either visual inspection or wavelet transform.

Wave propagation method is easy and cost effective to perform the experiment, but there are some problems to be solved for its application. In the experiment, long impact time is the biggest problem. Depending on the location of impact and sensor, the response shows different result. Also, the weight of sensor and wire could be the factor of error.

<table>
<thead>
<tr>
<th>Damage location from the sensor</th>
<th>Arrival time of wave reflected from damage</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Computed</td>
<td>Measured</td>
</tr>
<tr>
<td>65cm</td>
<td>1ms</td>
<td>1.1ms</td>
</tr>
<tr>
<td>80cm</td>
<td>1.2ms</td>
<td>1.3ms</td>
</tr>
</tbody>
</table>

### 4.4 Discussion

The factors of error for each method are presented in table 4.4. The biggest problem of the natural frequency method was the fixed condition of boundary. Weight of the accelerometer and irregularity of the beams also affect the accuracy of the result. However, these don’t cause errors in application to a real structure. The main obstacle is
temperature changes. Instant comparison of natural frequency change is meaningless because frequency change due to temperature changes is more significant than existence of damage. Continuous monitoring is necessary for this reason. In this case, natural frequency also changes according to the sources of external load. Bart et al. (2000), presented an experimental study about excitation sources and temperature effects.

<table>
<thead>
<tr>
<th>Factors of experimental error</th>
<th>Methods</th>
<th>Frequency domain</th>
<th>Mode shape</th>
<th>Wave propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary condition</td>
<td>⬤</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Shaker instability</td>
<td>×</td>
<td>⬤</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Impact load</td>
<td>○</td>
<td>×</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>Weight</td>
<td>○</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Noise</td>
<td>△</td>
<td>○</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>Resolution</td>
<td>○</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Temperature changes</td>
<td>○</td>
<td>△</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Inequality of the beams</td>
<td>○</td>
<td>○</td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>

Practical problem related to the shaker instability made the majority of error in mode shape method. Attachment of the beam to the shaker is an important matter in high frequency excitation. In a real structure, this excitation source is also a problem too. The price of a shaker, a large number of sensors, and the additional manpower for installation make it very expensive. Moreover, if a structure has low-frequency (below 1 Hz) mode, it may be difficult to excite. A lot of well-organized mode shape related methods (e.g. wavelet transform, sensitivity, neural network etc.) have been studied recently. However, before using those methods, the fact that mode shape data is reliable should be premised.

In wave propagation method, impact load is the most important matter. Depend on the impact time, intensity and location, the result shows big differences. Theory and
experiment are very simple, however this is not robust method. Damage near boundaries is hard to be detected. It might be difficult to apply this method to a real structure with a changing cross section or heterogeneous material.
CHAPTER 5
CONCLUSIONS

In this study, various damage detection methods were compared experimentally to find their characteristics and applicability. Conclusions of this study are summarized as follows;

(1) Natural frequency method is effective to find the existence of damages, even though exact location cannot be detected. Mode shape method shows good performance with numerical results. In the experiment, it is hard to obtain exact mode shape, which make mode shape method impractical. Wave propagation method is effective to find the location of the damage, however only large damages in limited area could be found because of sensitiveness of wave.

(2) Various unexpected errors occurred during the experiment. Some factors of error cannot be removed and some can be reduced by small changes of experimental setup. Knowing the reason of error is important to improve the performance of the methods.

(3) Small damages cannot be found by any of the compared methods even in the strict experimental condition. Unlike the theory and numerical study, obtaining accurate data, which is important to find damages, is difficult in practice. Study about accurate experimental procedure is necessary as well as numerical algorithms.
요 약 문

구조적 손상추정 방법의 실험적 비교

최근 구조물의 손상추정 방법에 관한 관심이 높아지고 있고, 이에 따라 많은 기법들이 연구, 개발되어 왔다. 이러한 기법들을 실제 구조물에 적용하기 위해서는 각 기법들의 장단점 및 특성을 파악하는 것이 중요하다. 본 논문에서는 실제 적용에 중점을 두고 여러 가지 손상추정 방법을 실험을 통해 비교 하게 된다. 일반적으로 널리 알려져 있고, 실험이 가능한 대표적인 3 가지 방법인 고유 진동수를 이용한 방법, 모드형상을 이용한 방법, 파동의 전파를 이용한 방법을 선택하여 실험을 수행하고, 그 결과로 세 방법의 성능을 비교한다.

길이 600mm, 폭 40mm, 두께 4mm인 알루미늄 켄틸레버 빔이 실험에 사용되었다. 손상의 형태는 빔 폭의 감소(강성의 감소)로 주어지며 그 크기는 5%, 10%, 20%, 30%이다. 손상의 위치는 고정단에서 빔 길이의 1/4, 2/4, 3/4 위치에 주어진다.

고유진동수를 이용한 방법은 간단한 실험으로 결과를 얻을 수 있다. 그러나 20% 이내의 작은 손상은 찾아내기 어려울 뿐더러, 큰 손상이라 하더라도 위치를 정확히 찾아낼 수 없다는 단점이 있다. 실제 구조물에 적용 할 경우에는 온도 변화에 의한 오차가 큰 문제점으로 작용한다. 모드형상을 이용한 방법은 이론적으로는 미세한 손상의 위치도 정확히 찾아낼 수 있다. 그러나 실제 실험에서는 많은 시간과 노력으로 투자하더라도 정확한 손상을 찾아내기가 어렵다는 단점이 있다. 실제 구조물의
모드형상을 구하는 것 또한 쉽지 않으므로 비경제적인 방법이다. 과동의 전파를 이용한 방법은 지지조건이나 외부 하중에 민감하다는 단점이 있다. 그러나 아주 간단한 실험으로 큰 손상의 위치를 정확히 찾아 낼 수 있었다.
REFERENCE


Reference

2003
Reference