Displacement of Bridge Monitoring Techniques with Strain Measurement

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Abstract— General methods of displacement measurement are to use LVDT, tiltmeter, or laser deflection meter. But these methods can’t be applied effectively if bridge height is so high that the installation of sensor is difficult. So the great part of these cases, the reliability and accuracy of measured results are uncertain usually. To overcome this problem, in this paper, the two techniques for calculation of displacement from measured strain are proposed, the one is iteration of data averaging, and the other is lowpass filtering of measured strain. To verify these techniques, laboratory and field tests are carried out, and it is concluded that lowpass filtering technique is effective for calculating displacement by measured strain.

Keywords—Displacement, Bridge, Monitoring, lowpass filter, Strain.

I. INTRODUCTION

The security of bridges requires periodic monitoring, maintenance, and restoration. Preventive maintenance and structural safety of bridges may be guaranteed by the application of health monitoring system, which can provide valuable information for detailed inspection, repair and rehabilitation of bridges. For that reason, long term monitoring systems are largely constructed and various kinds of sensors are used in bridge monitoring system. Especially, the strain sensors are greatly applied because strain value is useful and important to identify healthy status of bridge.

The monitoring displacement of bridge allows estimation of input dynamic excitation characteristics and has an important role in evaluation of structure status determination.

In many bridges, the vertical displacements are the most relevant parameters to be monitored in both short and long term.

Inaudi D. [1] calculated displacement from measured strain by the relationship between curvature and displacement, and KICT [2] analyzed the classical beam theory and the displacements of structure are calculated using measured strain. The applicability of this algorithm was verified by simple type reinforced concrete beam test, and data were acquired by LVDT, embedded and attached strain gauge.

In this paper, to calculate displacement, data averaging method and lowpass filtering on measured data are employed and also verified from laboratory and field test.

II. RELATIONSHIP BETWEEN STRAIN AND DISPLACEMENT

Inaudi. D. [1] proposed the displacement calculation algorithm by relationship between curvature and displacement, and this algorithm is available in the case of static loading to evaluate load carrying capacity of bridge, so it is difficult to real-time monitoring of displacement occurred from passage on the bridge of vehicle by this method. But, if the structure has linear behavior, and simple span, displacement can be calculated from measured strain by Hook’s law, and the equation is expressed as

\[ f = \frac{My}{I} = E\varepsilon \Rightarrow EI = \frac{My}{\varepsilon} \]  (1)

in which,

- \( f \) : stress
- \( M \) : Moment
- \( I \) : Moment of Inertia
- \( y \) : Distance from neutral axis to sensor position
- \( E \) : Elastic Modulus
- \( \varepsilon \) : Measured Strain

As shown in Eq. (1), the equation for calculation can be the function of applied load, \( P \). And applied load, \( P \), and stiffness, \( EI \) can be eliminated by the relation of strain \( (\varepsilon) \) and displacement \( (\nu) \). Therefore, to calculate displacement from strain, distance from neutral axis to sensor position \( (y) \), span length \( (L) \), and the factor calculated during elimination of loaded force \( P \), and stiffness \( EI \).

If load, \( P \) are applied to center which makes large displacement of structure, the span length are 500 cm, and distance from neutral axis to sensor position, \( y \) are assumed to 4.44 cm, the displacement function at a distance 225 cm from left support are given as follows.
\[ v = \frac{PL^2}{48.7EI} \]  

(2)

in which,

\[ P \] : load

\[ L \] : span length

Substitution of \( EI \) from Eq. (1) into Eq. (2) gives

\[ v = \frac{\varepsilon P L^3}{48.7 \times \frac{P L}{4.44} \times y} = \frac{\varepsilon L^2}{11y} \]  

(3)

III. LABORATORY TEST

To verify the displacement calculation technique using measured strain, laboratory test was performed. The results are analyzed by the iteration of data averaging, and lowpass filtering of measured strain.

A. Lab Test Details

In this study, dynamic tests on steel pipe are performed using dial gauge for displacement and strain gauge for strain measurement. Steel pipe has a length of 500 cm, height of 5 cm, width of 10 cm, 0.32 cm thick, and the data acquisition sampling rates of this test are 2,048 Hz.

Applied accelerometer were Kistler 8452A(±50 g), strain gauge are Tokyo Sokki in Japan, FLA-5L-11-5L, MEGADAC and AD 684SH-1 module of OPTIM Electronics were employed for data acquisition system.

The experimental setup is presented in Figure 1. The dynamic vibration of specimen was achieved by means of rubber hammer at optional position to simulate real-time in the case of vehicle crosses the bridge, and the measuring times were 7 minutes at 4 times.

Substitution \( y \) (=2.5 cm), \( L \) (=500 cm) into Eq. (2) gives

\[ v = \frac{\varepsilon L^2}{11y} = \frac{\varepsilon \times 500^2}{11 \times 2.5} = 9.090\varepsilon \]  

(4)

Figure 1: Schematic of Test Specimen

B. Data Averaging

During laboratory test using electronic strain gauge, white noise induced by measurement equipment and condition of test site are occurred severely. To reduce this white noise, data averaging procedures are performed for several times. Hereby, data averaging means the half of two measured values as times gone at the same point.

Figure 2 provides the result of displacement calculation from measured strain as data averaging times and measured time varied, and they were compared to measured displacement by dial gauge. The numbers of data averaging are 0, 5, 10, 20, 30, 40, and 100. In this figure, to show data clearly, the ranges of time history are limited from 18 to 24 sec of total 100 seconds. As data averaging times to reduce the effect of white noise are increased, the calculated displacements are more and more similar to measured displacement as shown in Figure 2.

Figure 2: Calculated Displacement Per Data Averaging Numbers
Table 1 provides maximum displacement as data averaging times are increased, and Figure 3 shows the measured error rate from comparing calculated displacement to measured displacement. Hereby, error rates are calculated from Eq. (5).

\[
\text{Error Rate} = \left( \frac{\text{Measured Max Displacement} - \text{Estimated Max Displacement}}{\text{Measured Max Displacement}} \right) \times 100
\] (5)

<table>
<thead>
<tr>
<th>Averaging Times To Calculate Displacement</th>
<th>Measured Displacement</th>
<th>Max Value(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.4055</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.8720</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.7941</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.7538</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.7289</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.7137</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.7029</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>0.6932</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.6854</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>0.6793</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.6739</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.6289</td>
<td></td>
</tr>
</tbody>
</table>

As shown in Figure 3, if a criterion of error rate is assumed at 10%, available averaging number to reduce white noise is 20 times. Therefore, it is concluded that setting up the criteria of error rate and after that, performing averaging value is more effective in the side of times saving and economical effect. However, if electronic strain gauge are applied and the measurement results has larger white noise, several times averaging are needed to eliminate white noise. Because it’s time-consuming, it is impossible to apply electronic strain gauge to calculate displacement. Therefore, before monitoring, the reason of induced white noise should be eliminated and it is the effective step to calculate displacement. To do this, fiber optic sensor, which is almost independent of white noise are effective to calculate displacement from measured strain.

C. Low Pass Filtering

As mentioned before, elimination of white noise by iterative averaging is time-consuming, so executing lowpass filtering on measured strain and apply these values to Eq. (3) is the other effective method. Hereby, the results from lowpass or bandpass filtering were calculated and compared to measured displacement.

FFT analysis on data before averaging was performed, and from this analysis, the ranges of frequency occurred are from 6 to 8 Hz. Therefore, on this data, bandpass filtering was applied including the range from 4 to 10 Hz to calculate displacement, and these values are compared to measured displacement as shown in Figure 4.
IV. FIELD TEST

To verify the filtering method in the field, the measured data from steel box girder bridge which is located in national highway in South Korea were applied to calculate the displacement by filtering. The dimension, shape, and the view of bridge are as Table 2, Figures 5 and 6.

<table>
<thead>
<tr>
<th>Item</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstructure</td>
<td>Steel Box Girder</td>
</tr>
<tr>
<td>Length</td>
<td>3@50+(50+2@80+50)+3@50=560m</td>
</tr>
<tr>
<td>Lane</td>
<td>Up 2 Lanes/ Down 2 Lanes</td>
</tr>
<tr>
<td>Width</td>
<td>20.5m</td>
</tr>
<tr>
<td>Year</td>
<td>1998</td>
</tr>
<tr>
<td>Design Load</td>
<td>DB24</td>
</tr>
</tbody>
</table>

As shown in table and figure, the measured spans are the 3 continuous steel box girders which are located in start point of bridge, and the sections are limited to 18.75 m point from abutment and the center point of 3 continuous spans (center of 2nd span). In the Figure, “Dis” means Dial Gauge, and “St” means strain gauge.
V. RESULTS

To analyze the relationship between strain and displacement, measured strain are substituted into Eqs. (1), (2) and (3), and the result are as these.

(1) Section A-A

\[
\delta = \frac{0.01369PI^3}{EI} \Rightarrow \frac{EI}{\delta} = \frac{0.01369PI^3}{\delta}
\]

\[
M = 0.20215Pl
\]

\[
\varepsilon = \frac{My}{EI} = \frac{l}{0.013694Pl^3} = \frac{14.761\delta y}{l^2}
\]

\[
* \delta = \frac{\varepsilon l^2}{14.761} \times 10^{-6} \times 10^3
\]

(2) Section B-B

\[
\delta = \frac{0.0114583Pl^3}{EI} \Rightarrow \frac{EI}{\delta} = \frac{0.0114583Pl^3}{\delta}
\]

\[
M = 0.11719Pl
\]

\[
\varepsilon = \frac{My}{EI} = \frac{l}{0.0114583Pl^3} = \frac{10.228\delta y}{l^2}
\]

\[
* \delta = \frac{\varepsilon l^2}{10.228} \times 10^{-6} \times 10^3
\]

in which,

\(\delta\): Displacement

\(\varepsilon\): Measured Strain

\(l\): Span Length

\(y\): Distance from neutral axis to bottom of bridge

Figure 7 provides the comparison of measured and calculated displacement, which is acquired from measured strain and the relationship between strain and displacement of Eq. (3) in the case of loaded vehicle are driving at the speed of 65 km/h.

![Figure 7](image_url)

Figure 7: Measured Displacement vs. Calculated Displacement (Before filtering).
In this calculation, \( y \), the distance from neutral axis to bottom of bridge, are applied to two values, the one is theoretical value (Section A-A: 1.6 m, Section B-B: 1.7 m), and the other is calculated value from measured strain at compressive and tension range. Applied displacement is average of measured value, and the measured points are 2 points at each steel box girder.

As shown in Figure, calculated displacement from strain at section A-A is similar to measured displacement, and at section B-B, calculated displacement from strain is above measured displacement. Measured strain has noise by various causes, so calculated displacement would be more accurate if noise are eliminated by filtering. Figure 8 provides the relationship between measured and calculated displacement by lowpass filtering at 1 Hz on the measured strain.

If calculated displacement from measured strain with noise is above the real measured displacement, it is not problem in the side of safety of structure. So it would be more effective to calculate displacement of steel bridge with sound condition. But, this method has limitation in case of the bridge has varied section or damages are occurred at the measured point or support, so additional researches are needed in this field.

**Figure 8**: Measured Displacement vs. Calculated Displacement (After filtering).

**VI. CONCLUSION**

In this study, the effective techniques for the displacement of bridge calculation using measured strain are proposed, and the results are as follows.

1. Data averaging and lowpass filtering techniques are performed to calculate real-time displacement from measured strain, and to verify these method, the measured and calculated displacement of bridge are compared.

2. Data averaging method is time-consuming, and lowpass filtering method has simpler than data averaging. If FFT analyzing and filtering on measured strain can be performed simultaneously in the field, it is possible to calculate displacement using measured strain without dial gauge or LVDT.

3. Proposed technique would be more effective to calculate displacement of steel bridge with sound condition. But, this method has limitation in case of the bridge has varied section or damages are occurred at the measured point or support, so additional researches are needed in this field.
REFERENCES


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