Measurement of the displacement response of a structure using line detection

S W Kim¹*, B G Jeon¹, D U Park¹ and D W Yun¹

¹KOCED Seismic Research and Test Center, Pusan National University, 49 Busandae-hak-ro, Mulgeum, Yangsan, Kyungnam 50612, Republic of Korea
*corresponding author, Email: swkim09@pusan.ac.kr

Abstract. The shaking table test is required to examine the seismic safety of a structure as well as the structure’s unique functions before and after the occurrence of an earthquake. That is, the data on the displacement responses obtained from the shaking table test are required to assess the seismic performance of a structure. In this study, the shaking table test was conducted to verify the validity of a method of measuring displacement responses using images. In this method, the lines of a structure were detected, and the responses were measured using the amount of change in the intersection of the detected lines. In addition, image filter processing was used to facilitate the detection of the lines of the structure in the shaking table test.

1. Introduction

As strong earthquakes and seismic damage have become more frequent of late, the interest in the seismic design of various social infrastructures is also increasing. Moreover, in the cases of seismic damage, damage and destruction of the structural and non-structural elements of the concerned social infrastructures occurred. Therefore, it is necessary to develop technologies for securing the seismic safety of social infrastructures, and for improving their usability in the global situation where the number of earthquakes is increasing [1]. For the assessment of seismic performance, the shaking table test is currently being conducted on major structures. Data on the displacement responses [2], which represent the overall behavior of a structure, are important for safety assessment, and seismic performance is determined based on these. In general, when the shaking table test is conducted, the displacement responses are measured by installing contact-type sensors like linear variable differential transformers (LVDTs) and ring gauges on a structure or by applying costly laser equipment like the laser Doppler vibrometer (LDV). For LVDTs, the accessibility must be secured, and temporary facilities for fixing them need to be installed. Therefore, they are not economical. In addition, the reliability of the measurements varies depending on the fixing conditions of the temporary facilities. For ring gauges, cables are used instead of temporary facility installation, which is the drawback of LVDTs, and separate facilities capable of minimizing external influences must be installed. When the cables are shaken by external factors, the measurement accuracy is decreased. In the case of LDV [3], it is difficult to apply it to the shaking table test because it is expensive precision equipment despite its outstanding performance.

The method of using images [4-6] is simple, economical, and suitable for extracting the displacement responses of a structure that is hard to access. The existing method of measuring the displacement responses in the shaking table test involves the installation of targets on a structure and measures the
changes in the targets using an image processing method, to measure the displacement responses. In this study, a method of measuring the displacement responses by detecting the lines [7-8] of a structure without installing targets on the structure was proposed. In addition, the shaking table test was conducted to verify the validity of the proposed method.

2. Algorithm for measuring the displacement responses of a structure using line detection

The purpose of the image filter processing [9] is to process the original image and then to convert it in accordance with a specific application purpose. When the test was conducted, the Gaussian filter was used to reduce the noise generated while acquiring optics, lighting, and images. The filter reduces noise and connects the disconnected edges of the image while reducing its sharpness. Due to these characteristics, noise reduction using the Gaussian filter is used in the preprocessing of object recognition sensitive to noise. Figure 1 shows the 7×7 matrix obtained by applying discrete approximation to the Gaussian function with a standard deviation of 0.4, and a weight was given to the image using the convolution mask.

In the shaking table test, unsharp-mask processing was used to sharpen the geometry of the structure. Unsharp-mask processing is the process of removing a blurred image from the image itself. The discrete approximated 7×7 matrix can be expressed as shown in Figure 2, and a weight was given to the image using the convolution mask. The boundary of the structure with an improved geometry is the boundary between two regions with different information, and can be detected by calculating the difference between the two neighboring regions.

\[
\begin{bmatrix}
1 & 1 & 2 & 2 & 2 & 1 & 1 \\
1 & 2 & 2 & 4 & 2 & 2 & 1 \\
2 & 2 & 4 & 8 & 4 & 2 & 2 \\
2 & 4 & 8 & 16 & 8 & 4 & 2 \\
2 & 2 & 4 & 8 & 4 & 2 & 2 \\
1 & 2 & 2 & 4 & 2 & 2 & 1 \\
1 & 1 & 2 & 2 & 2 & 1 & 1
\end{bmatrix}
\]

Figure 1. 7x7 Gaussian function

\[
\begin{bmatrix}
-1 & -1 & -1 & -1 & -1 & -1 \\
-1 & -1 & -1 & -1 & -1 & -1 \\
-1 & -1 & -1 & -1 & -1 & -1 \\
-1 & -1 & -1 & 60 & -1 & -1 \\
-1 & -1 & -1 & -1 & -1 & -1 \\
-1 & -1 & -1 & -1 & -1 & -1 \\
-1 & -1 & -1 & -1 & -1 & -1
\end{bmatrix}
\]

Figure 2. Unsharp-mask processing

\[
\begin{bmatrix}
1 & 0 & 1 \\
-2 & 0 & 2 \\
1 & 1 & 1 \\
1 & 2 & 2 \\
1 & 1 & 1
\end{bmatrix}
\]

Figure 3. Geometry extraction mask

\[
\begin{bmatrix}
-1 & -2 & -1 \\
1 & 1 & 1 \\
1 & 2 & 1
\end{bmatrix}
\]

(a) Horizontal mask

\[
\begin{bmatrix}
-1 & 0 & 1 \\
-2 & 0 & 2 \\
1 & 1 & 1 \\
1 & 0 & 1
\end{bmatrix}
\]

(b) Vertical mask

Figure 4. Dilation structure

The boundary can provide information on the image, such as the position, geometry, and size of the object, and it is the pre-processing stage for enhancing the boundary of the structure. Figure 3 shows the 3×3 mask used for extracting the geometry of the structure. The mask consists of a horizontal mask and a vertical mask.

The dilation structure expands the outermost pixels of the object. The size of the object is expanded, and the background is reduced. To facilitate line detection by expanding the pixels of the structure geometry installed on the shaking table, the outer pixels were expanded using the 3×3 dilation mask structure, as shown in Figure 4.

\[
y = ax + b
\]
The line of the geometry was extracted from the structure geometry improved through the above pre-processing processes using the linear regression equation, as shown in equation (1).

Figure 5 shows a linear regression curve for the center of the pixel line at the pixel position of equation (1). It is possible to obtain equation (1), a first-order regression curve, for the center of the pixel line at the position of the pixel judged to be a line, and the regression curve is expanded to the selected region of interest (ROI) window. The pixel information was set in the ROI window of Figure 6, and the coordinates (displacement responses) were measured using the information on the intersection of the two straight lines. The ROI window represents the square M×M pixel set, and the pixel length detected as a line by the window was set to at least 0.3 M. In addition, to minimize the errors in detecting lines from the image due to noise, the ROI window was set to a minimum of 50×50 pixels and a maximum of 100×100 pixels. Through equation (2), valid lines corresponding to the geometry of the structure as well as various and many lines caused by noise are detected. For the lines that could be judged to be a shape, the pixel length was designated as 0.3 M or longer in the ROI window, which is the square of the M×M pixel set size, in equation (2), and the lines with less than 0.3 M pixels were removed. When such lines are removed, the lines created by noise and other environments are also removed.

\[
\text{Linear regression line} > 0.3 \times \text{ROI window pixel Length} \\
\text{else} = \text{remove} \tag{2}
\]

Figure 7. Calculation of the coordinates of the intersection

In Figure 7, the pixel line was extended from its center for each pixel position using the linear regression curve. In the linear regression curve that was used, the line was extended to the end point of the ROI window, and the coordinates \((x, y)\) of the intersection of the two regression curves were calculated using equation (3).
\begin{align*}
x &= \frac{(x_2 y_2 - y_2 x_2)(x_3 - x_2) - (x_1 - x_2)(x_2 y_4 - y_2 x_4)}{(x_1 - x_2)(y_3 - y_2) - (y_1 - y_2)(x_3 - x_4)} \\
y &= \frac{(x_1 y_2 - y_1 x_2)(y_3 - y_4) - (y_1 - y_2)(x_3 y_4 - y_3 x_4)}{(x_1 - x_2)(y_3 - y_4) - (y_1 - y_2)(x_3 - x_4)}
\end{align*}

Figure 8 shows the displacement response measurement algorithm that uses line detection. The algorithm has a total of eight steps. From the acquired image, a square ROI window is extracted. The luminance plane of the image is extracted from the extracted ROI window. For the information on the extracted luminance plane, the Gaussian filter is used to reduce the noise in the image and to improve the disconnected points. The geometry of the structure is sharpened by applying unsharp-mask processing to the geometry for which the disconnected points were improved and the noise was reduced. Horizontal and vertical masks are applied to the improved geometry for boundary extraction, and the outer pixels are expanded using the dilation structures of the extracted boundaries. In the ROI window of the designated M×M pixel size in the expanded image, the lines with 0.3 M pixels or more are detected and extended while the lines with less pixels are removed. The displacement responses of the structure are measured by calculating the displacement responses in the x- and y-axis of the two-dimensional plane using the changes in the coordinates of the intersections of the extended lines.

![Figure 8. Algorithm summary](image_url)

3. Shaking table test
To verify the algorithm for measuring the displacement responses of a structure using line detection, the shaking table test was conducted. Figure 8 shows the masonry wall installed on the shaking table. The displacement responses were measured at the point using the line detection algorithm. At the point, the table motion measured by the DAQ of the shaking table was compared with the displacement responses measured using the line detection algorithm. To extract the time history of the displacement responses for the intersection of the detected lines, the algorithm presented in Figure 8 was applied. To examine the accuracy and precision of the algorithm for measuring the displacement responses using line detection, error analysis was conducted using the percent error and the root mean square (RMS) error [7]. Figure 9 compares the table motion measured by the DAQ of the shaking table with the displacement responses extracted by the algorithm for measuring displacement responses using line detection. The error rate for the percent error was less than 1%, and the RMS error was less than 1 mm, indicating that the errors were very small. This confirms that the algorithm for extracting displacement responses using line detection has excellent reliability.
Figure 9. Comparison of the table motions

4. Conclusions
The differences between the table motion measured by DAQ in the shaking table test and the displacement responses measured by the line detection algorithm were small, thereby verifying the validity of the image processing data. In addition, it was confirmed that it is possible to measure the displacement responses of a structure using the structure’s geometry, without installing arbitrary targets in the shaking table test. The proposed method of measuring displacement responses in the shaking table test using the line detection algorithm is simple and will make it possible to efficiently measure the displacement responses of a remotely located structure.

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