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Multi-point Dynamic Response Measurements Using Digital Image Processing from Image Signal

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ABSTRACT

Recently, a concern for maintenance of civil structure has been increased. In addition, the number of civil structures for evaluating structural safety due to natural disaster and structural deterioration is rapidly increasing. It is common that the structural characteristics of the existing structures are different from those at initial design stage, and changes in dynamic characteristics may result from stiffness reduction due to cracks on the materials and deterioration process of the structures allow to detect the damaged location as well as quantitative evaluation. One of the typical measuring instruments used for monitoring of civil structures is the dynamic measurement system. The conventional dynamic measurement systems require cabling works considerable for directly connecting between sensor and DAQ logger. Therefore, a method to measure dynamic responses of structures in a remote distance without the mounted sensors is needed. In this study, a method to measure multi-point dynamic responses by using a digital image processing technique is suggested. The image processing technique was used with the template matching method, which enhanced the resolutions of the dynamic responses of structures through the utilization of an image transformation function that corrected geometric errors between the undeformed and deformed images. Therefore, in this study, several tests were carried out to verify the algorithm for measuring multi-point dynamic responses by using digital image processing.

1. INTRODUCTION

Recently, the concerns regarding the technologies for the maintenance and management of civil structures are rising because of the rapid increase in the number of structures, which requires examinations on the structural safety due to performance

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deterioration, aging, etc. The performance of a structure primarily deteriorates due to the defects caused by the design or construction errors, the aging of the acting weights and construction materials, the changes in the external environments, etc. When the stiffness is reduced due to the aging of the structure, member cracks, etc., changes occur to the dynamic characteristics of the structure; therefore, the precise determination of the damaged parts and the degree of their damage by analyzing the dynamic characteristics at the actual behavior of the structure is considered an important issue. Therefore, to estimate the changes in the dynamic characteristics of a structure, an effective system that can monitor the actual behavior of the structure, and an analysis technique, are needed.

Inspections and safety diagnoses of civil structures are currently conducted. The displacement response is an important datum that shows the overall behavior of a civil structure, and is a basis for determining the structure's level of deterioration and aging degradation. Typical methods of diagnosing the safety of civil structures include the use of contact sensors such as the linear variable differential transformers (LVDT) and the ring gauge for the structure, and the measurement of the displacement using relatively expensive laser equipment such as the laser dropper vibrometer (LDV). In the case of LVDT, easy accessibility is required, and support for fixing sensors is necessary. Accordingly, the additional cost and the difficulty of precisely fixing the support reduce the reliability of the measured values. As for the ring gauge, the support that is the weakness of LVDT is not necessary, but a cable is needed. An additional equipment to protect the ring gauge from wind is necessary because the accuracy of the measurements is affected by the cable movements due to the wind. In the case of LDV, its application at construction sites is difficult despite its excellent performance, because it is very expensive. Therefore, the equipment that is currently used for safety diagnosis is impractical, and there is a very high demand for equipment that can efficiently measure the displacement response of a civil structure. Therefore, measurement equipment for displacement response using image signals have been attracting much attention to overcome the drawbacks of the typical contact sensors and laser equipment for displacement response measurement.

Many studies have been conducted using image signals instead of conventional mounted sensors. However, these studies have been focused on measuring displacement response by an image processing technique after recording a position of the target mounted on the structure, in which the number of measurement targets may be limited. Therefore, in this study, it conducted shaking table test and field test to verify the validity of the method that can measure multi-point displacement responses of structures using image processing technique.

2. DYNAMIC RESPONSE MEASUREMENT USING DIGITAL IMAGE PROCESSING

2.1 Template Matching

Template matching (Bruk 1986) is a method that calculates the similarity between a template and an image given in a particular space. It is applied mainly to a single characteristic of the image. Similar patterns inside the image are found based on the previously learned template, and such template is a kind of model image. The template matching method registers the random template in the target window, and finds the most similar target window at the region of interest (ROI) window that change over time. Fig. 1 shows the basic concept of the template matching method, which can use the cross correlation to find the positions of the image regions that correspond to each template. The normalized cross correlation $\gamma(u,v)$ of the i^{th} template at the original image position (x, y) can be calculated using Eq. (1). The maximum normalized cross correlation (Lewis 1995) coefficient $\gamma_{\max}$ value appears at the point where the target window optimally matches the ROI window.

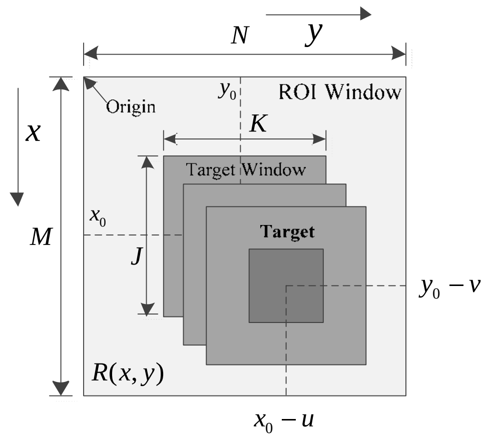

Fig. 1 Template matching process

$$\gamma_{u,v} = \frac{\sum_{xy}\left[T(x,y)-\overline{T}\right]\left[R(x-u,y-v)-\overline{R}_{u,v}\right]}{\sqrt{\sum_{xy}\left[T(x,y)-\overline{T}\right]^2\left[R(x-u,y-v)-\overline{R}_{u,v}\right]^2}} \quad (1)$$

2.2 Subpixel Estimation

To correct the geometric errors that occur due to the displacements and deformations of a structure, the coordinates of the control points of the undeformed and the deformed images could be calculated by the mathematical transformation function between the two images. Using such transformation function, the pixel positions of the displaced or deformed image are changed based on the undeformed image. The functions that can be used as the transformation function include the affine function, which can represent only linear movements; the projection function, which is suitable for small transformations; and the polynomial function, which is applicable to nonlinear deformations and movements. In this study, a quadratic polynomial function such as Eq. (2) was used to calculate subpixel appropriate for nonlinear movements such as deformations.

$$x = \sum_{i,j=0}^{2} a_{i,j} x'^i y'^j, \quad y = \sum_{i,j=0}^{2} b_{i,j} x'^i y'^j \quad (i+j<2) \quad (2)$$

2.3 Outline of Algorithm

The acquired video files were converted to image files and chronologically arranged, and the point where the response of a target window was to be found, i.e., the control point, was designated in the undeformed image. To effectively establish the ROI, the maximum movement of the target was calculated and its correlation was determined. To obtain the information on the place where the target window optimally matched the ROI window, the normalized cross correlation was calculated. To correct the geometric errors, the quadratic polynomial function was applied to rearrange the pixel positions to correct the geometric error. The power spectral density (PSD) function was applied to the dynamic responses to extract the natural frequencies. The dynamic responses and their characteristics at various points can be calculated by applying the aforementioned algorithm to various target windows and ROI windows.

3. EXPERIMENTAL VERIFICATIONS

3.1 Vision-based System

The vision-based system is a sensor for measurements. It consists of a portable digital camcorder and a tripod with transportability and convenience for the installation of the system. The system is economically constructed without the need to attach additional equipment to it because it uses the original optic zooming, recoding, and saving functions of portable digital camcorders.

3.2 Shaking Table Test

Fig. 2 Sensor installation position

In this study, to verify the applicability of the algorithm for measuring the displacement responses using the image processing technique, the shaking table test was conducted on a friction pendulum bearing system. The friction pendulum system (FPS) is a seismic isolation system that has been widely used for separating architectural structures, telecommunication devices, electronic equipment, etc. from seismic loads. Among FPS, the shaking table test was conducted on a cone-type friction pendulum bearing system (CFPBS) that can adjust the acceleration responses and relative displacement responses in a seismic load using the slope of the friction surface designed in a cone shape. The targets were installed at each position to estimate the table motions and the displacement responses of the CFPBS, as shown in

Fig. 2, and the table motions measured using Target0 and DAQ were compared. The conventional sensors for verifying the measurement precisions of other targets, however, could not be installed because of the difficulties in installing the temporary facility for fixing the LVDT due to the small upper part of the CFPBS and in measuring the displacement responses using a LDV due to the long distance. The size of the Target0 on structure was 25 mm, and the number of corresponding pixels was 10. Therefore, the resolution of unit pixel was 2.50mm.

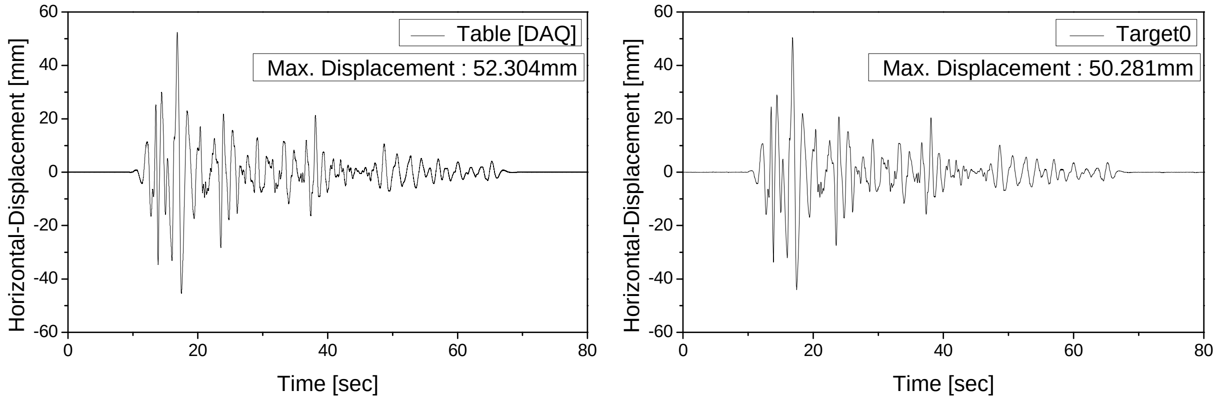

Fig. 3 Comparison of displacement response on table motion

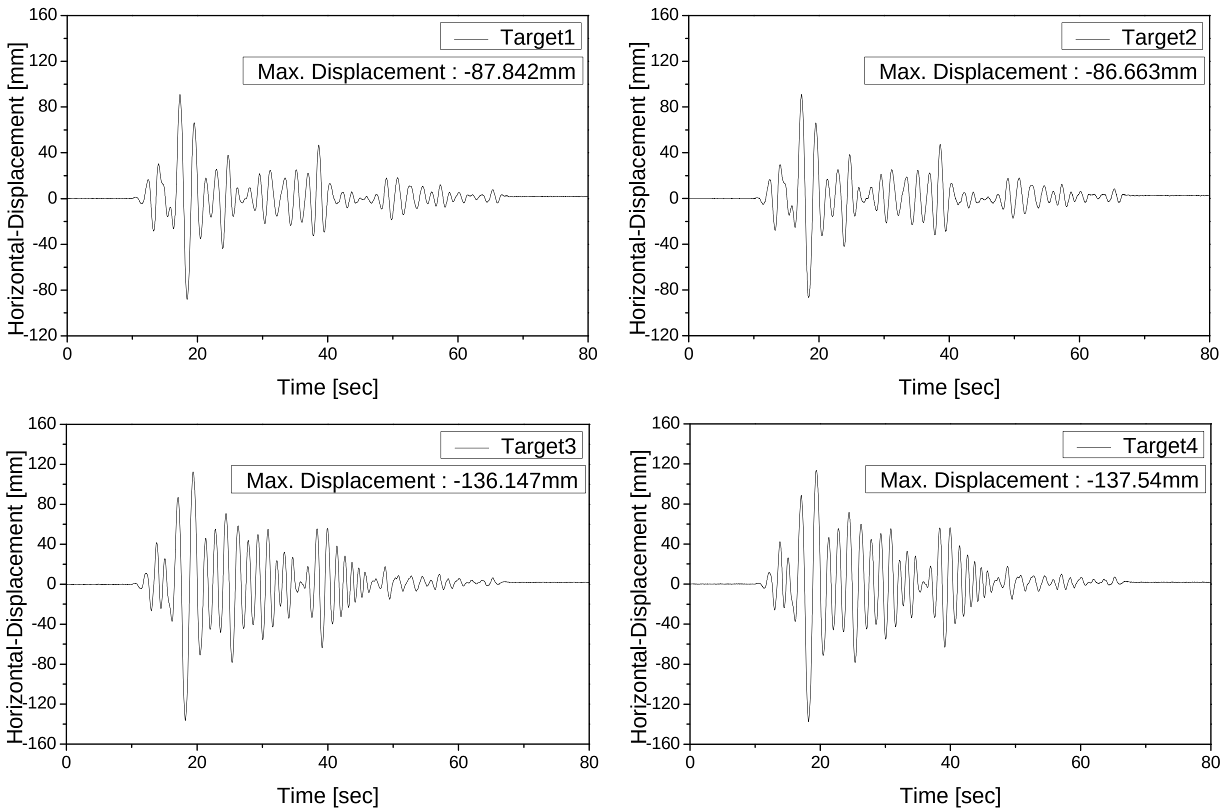

Fig. 4 Relative displacement response at other position

Table 1 Error analysis on table motion

Target	Percent Error(%)	RMS Error(mm)	System Error(%) RMS error / Max. Displacement
0	0.989	0.496	0.009

Fig. 3 shows the comparison between the table motions measured by the DAQ and the displacement responses estimated using the image processing technique algorithm. Table 1 shows a percent error rate within a 1% difference between the displacement responses of Target0 and those measured via DAQ, a less than 0.5 mm RMS error, and a system error within a 0.01% difference, which are considered minor. Thus, the reliability of the displacement responses estimated using the image processing technique appeared favorable. Fig. 3 shows the relative displacement responses estimated using the image processing technique at other positions.

3.3 Field Test

In this study, to verify the accuracy of the estimation of the dynamic characteristics of the hanger cables of a suspension bridge using the image processing technique, a test was conducted at Namehae Bridge, which is currently in traffic use and connects Seolcheon-myeon in Namhae-gun, Gyeongnam to Geumnam-myeon in Hadong-gun, Gyeongnam in South Korea, as shown in Fig. 5. The Bridge has a total span length of 660m (404m-long middle span, and 128m-long spans at both sides) and consists of two H-shaped main towers, each with 49 hangers and parallel main cables at both the east and west sides.

Fig. 5 Namhae Bridge

The sensors installed the cable shapes (Kim 2013) as the target window, without the need to install the targets on the hanger cable, to estimate the dynamic responses. The accelerometer was installed on cable A but not on cable B due to difficulties in the accessibility of cable B. Before the ambient vibration test, the pixel values that corresponded to the cable diameters were measured. The results showed that the diameter of cable A was 48mm and it had 138 corresponding pixels. Therefore, the resolution of a pixel was 0.348mm. In addition, the region marked with a square in Fig. 6 is the ROI window, in which the hanger cables were established at 130x130 pixels to prevent interferences with each other, and the target window was set at 50x50 pixels. Furthermore, because no fixed objects appeared in the image backgrounds of the Namhae Bridge, unlike at Gwangan Bridge in Busan, South Korea, the motion of the vision-based system (Kim 2003) was not corrected but was removed using a band pass filter.

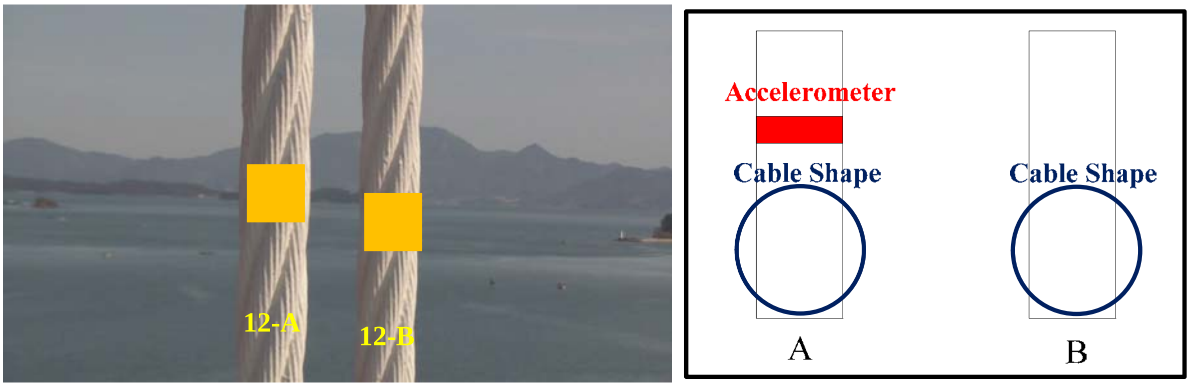

Fig. 6 Sensor installation position

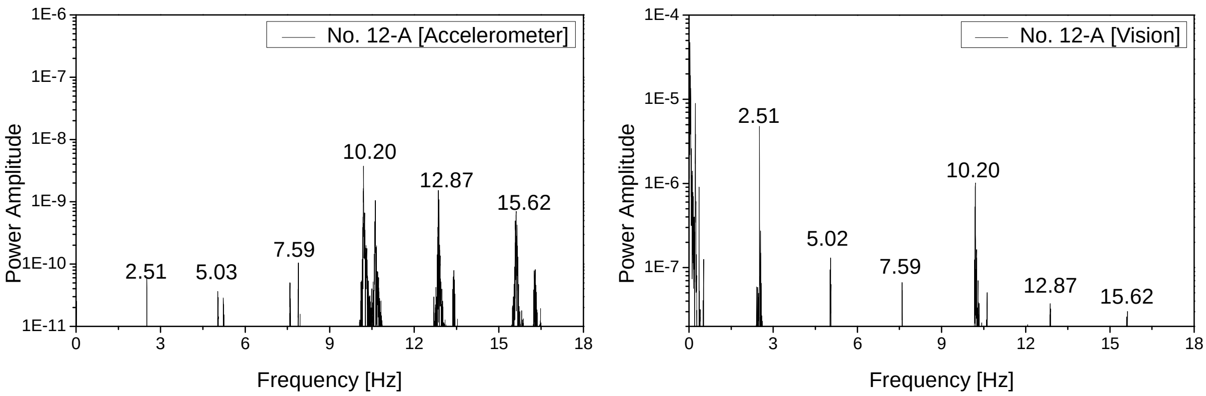

Fig. 7 PSD Functions of No. 12-A hanger cable

Table 2 Error analysis on table motion

Cable	Sensor	Frequency (Hz)						Tension (kN)	Error (%)
		1st	2nd	3rd	4th	5th	6th		
12-A	Accelerometer	2.51	5.03	7.59	10.20	12.87	15.62	133.27	0.24
	Vision-based System	2.51	5.02	7.59	10.20	12.87	15.62	132.95	
12-B		2.51	5.02	7.59	10.20	12.87	15.62	132.95	-

Fig. 7 shows the PSD functions that corresponded to each response on the No. 12-A hanger cable. The motion of the vision-based system at 11 - 12.5Hz was removed using the band pass filter. The natural frequencies and the tensions estimated using the vibration method (Shimada 2000) of each hanger cable are presented in Table 2. The results confirm the precision (differences within 1%) of the natural frequencies and the tensions measured using the accelerometers and the image processing technique. Thus, the possibility of estimating the dynamic characteristics of cables through the cable shapes, without installing targets, was verified.

3. CONCLUSIONS

In this study, it can be suggested that a non-contact displacement response measurement method using digital image processing based on a commercial digital camcorder in measuring point and multi-point displacement responses of structures.

The validity can be confirmed by the result that the displacement responses estimated by analyzing digital image processing data in the shaking table test have an insignificant error with the displacement responses measured by using DAQ. The natural frequencies estimated by analyzing the image processing data at Namhae Bridge presented errors within 1% difference compared with the natural frequencies that were measured using accelerometers. Thus, the validity of the image processing data was confirmed. Therefore, the proposed dynamic response measurement method using the image processing technique is considered more appropriate for structures, the dynamic characteristics of which need to be estimated, and is likely to enable more economical and effective estimations of the dynamic characteristics of the structures.

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