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Dynamic characteristics of suspension bridge hanger cables using digital image processing

Sung-Wan Kim, Nam-Sik Kim*

Department of Civil and Environmental Engineering, Pusan National University, 30 Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea

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ABSTRACT

In this study, a non-contact measurement method is proposed to estimate the tension in hanger cables by using digital image processing. Digital images were acquired through a vision-based system using a portable digital video camera (camcorder), which was used to remotely measure the dynamic responses and was chosen because it is convenient and cost-efficient. Digital image correlation technique, as one of digital image processing algorithms, was applied to develop an image processing algorithm. An image transform function was used to correct the geometric distortion between the deformed and undeformed images and to calculate the subpixels. The motion of the vision-based system caused by external wind or vibration at camera location was corrected considering a fixed object in the image without any additional sensors. Using this algorithm, the dynamic response of the hanger cable and the resolution of the modal frequencies were improved. It was also confirmed that the dynamic characteristics of the hanger cables can be estimated with only the cable shape not attaching any target.

1. Introduction

Because of recent developments in civil infrastructures, the demand for long-span bridges has increased. The interest of long-span cable-supported bridges such as suspension and cable-stayed bridges has been rapidly increasing with recent advances in material, design and construction technologies. Long-span bridges could be considered as a statically indeterminate structure wherein the main stiffening girders are supported by stay cables, main cables and hanger cables. In cable-supported bridges, the cable members are critical to the safety of the entire bridge system, and so the tension in the cable estimated from its dynamic characteristics needs to be monitored carefully [1–4]. To estimate the tension in the cable, which is continuously excited by traffic and wind loads, first of all, the dynamic characteristics of the cable should be identified.

The cable tension could be estimated either by directly measuring the stress on the cable by using a load cell or hydraulic jack [5] or through the vibration method [6,7], which uses the cable shape conditions and measured dynamic characteristics to estimate the tension. Electromagnetic sensors [8] have recently been used to detect the changes in the magnetic field created by changes in the stress of the cable. Generally, accelerometers [9] have been used to estimate the tension of cable by using the vibration method. Conventional accelerometers may require a considerable amount of cabling work to facilitate a direct connection between the sensor and the data acquisition logger. For this reason, a non-contact sensing method to measure the dynamic responses of the cable from a remote distance without attaching any sensors is needed. Currently, non-contact sensing methods applicable for measuring the dynamic responses of the cable are laser Doppler, Global Positioning System (GPS) and image processing techniques. The laser Doppler effect method [10] is relatively accurate, however, it is not economically efficient because the measurement of dynamic response of only one point requires expensive instrumentation. The GPS [11,12] method is also uneconomical and is not suitable for cable response measurements because of signal errors and its limited data sampling rate. On the other hand, image processing techniques are simple, economical and suitable for measuring the vibration of structures that are difficult to access. The displacement response of a flexible bridge may also be measured using light-emitting diode targets [13] and a texture recognition algorithm and system [14]. The small cable vibration was measured using an optical flow method without attaching any target [15], whereas the displacement responses of structures under shaking table tests and vehicle loading tests were estimated by using an image correlation technique [16]. The bridge deflection was measured by applying digital image correlation (DIC) and by eliminating camera motions that occur owing to external factors such as wind, using perspective transformation [17]. The deflection measurement of larger-scale structures was also carried out using the sampling Moiré method [18].

* Corresponding author. Tel.: +82 51 510 2352; fax: +82 51 513 9596.
E-mail address: nskim@pusan.ac.kr (N.-S. Kim).

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However, in the measurement of image signals from the cables of a long-span bridge, it may be not easy to obtain accurate dynamic responses and modal frequencies because of the motion of vision-based system. Camera support vibration or external wind may cause the motions of vision-based system, which can cause an image analysis error. In this study, a correction algorithm for eliminating the camera motion caused by external vibration in a vision-based system by considering a fixed object in the image was developed to reduce errors in the health monitoring assessment and to improve the cable recognition rate. Thus, an ambient vibration test was carried out on Gwangan Bridge in South Korea to verify the validity of the method used to measure the dynamic characteristics of the hanger cable and the camera motion correction algorithm for the vision-based system employing digital image processing. It was also tested to check the possibility of non-contact sensing of cable structures by using the cable shape not attaching any target.

2. Estimating dynamic characteristics using digital image processing

2.1. Vision-based system

A portable and easy-to-install digital camcorder (SAMSUNG VM-HMX 10A), which does not require additional cable installation or devices to store signals, was used in this study. The test was conducted cost-efficiently, without the use of additional devices, because the video recording and saving functions inherent in the camcorder were used.

2.2. Digital image correlation

When an illuminated object is deformed, the digital image of the object surface can be seen as a record of the discontinuous light intensity data. The light intensity is determined by the number of signal bits and is represented as a value of unit pixels. The commonly used light intensity of an 8-bit signal has a gray level between 0 and 255; the object size that corresponds to the specific pixels is determined by the focal distance of the lens.

The DIC technique [19–23] is widely used in the field of experimental mechanics to measure the deformation of an object's surface. Its basic principle is to find the maximum correlation between deformed and undeformed images. Cross-correlation in the DIC technique is used to compare a deformed image with an undeformed image to find the differences between two images. The cross-correlation method determines the correlation between the image and the registered pattern by using the Euclidean distance, and then normalizes the pattern through noise removal, zoom-in, zoom-out, and rotation. However, the matching rate changes with changes in the image intensity; therefore, the resulting value changes according to the registered pattern size. In this study, normalized cross-correlation (NCC) was used, which is insensitive to changes in light and lighting, maintains its characteristics regardless of changes in the ratio and rotation, and allows the setting of a threshold limit.

NCC is a simple matching method used to determine the position of the required pattern presented target-window function TW in a two-dimensional region of interest (ROI) window. When the deformed and undeformed images are matched, a pixel set of the target-window function is used instead of the unit pixel, as shown in Fig. 1. The reason for this is that if the unit pixel is used to determine the deformation of the structure, many unit pixels with the same gray level are likely to exist in the deformed image, making an analysis difficult.

The target window, (x, y) in the ROI window of the deformed image is moved by the pixels; the target window of the deformed image has the coordinate transformation of $(x-u,\ y-v)$ which forms the correlation used to provide the optical ROI window matching point information. During pattern matching, the undeformed and deformed images are compared pixel by pixel. A rectangular pixel set, which is a target window using any gray level pattern, is made from the undeformed image, and a pixel set with a similar pattern is found from the deformed image based on the correlation, to determine the change in the control point in the target window. The correlation of the pixel set with the target window in the ROI window is determined by calculating the NCC coefficient by

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

where

$$\overline{TW} = \frac{1}{N_x N_y}\sum_{x=0}^{N_x-1}\sum_{y=0}^{N_y-1} TW(x,y) \tag{2}$$

$$\overline{R}_{u,v} = \frac{1}{N_x N_y}\sum_{x=u}^{u+N_x-1}\sum_{y=v}^{v+N_y-1} R(x,y) \tag{3}$$

The value of the maximum NCC coefficient $\gamma_{\max}$ is equivalent to the pixel location (u, v), where the target window is optimally matched to the ROI window. In $R(x-u,\ y-v)$, pixel $(x-u,\ y-v)$ has a gray level ranging from 0 to M_x-1 and M_y-1, and R is a set of pixels of the same size as the target window in the ROI window. Similarly, in $TW(x,y)$, pixel (x,y) has a gray level ranging from 0 to N_x-1 and N_y-1. $\overline{R}_{u,v}$.is the mean value of the gray level of the

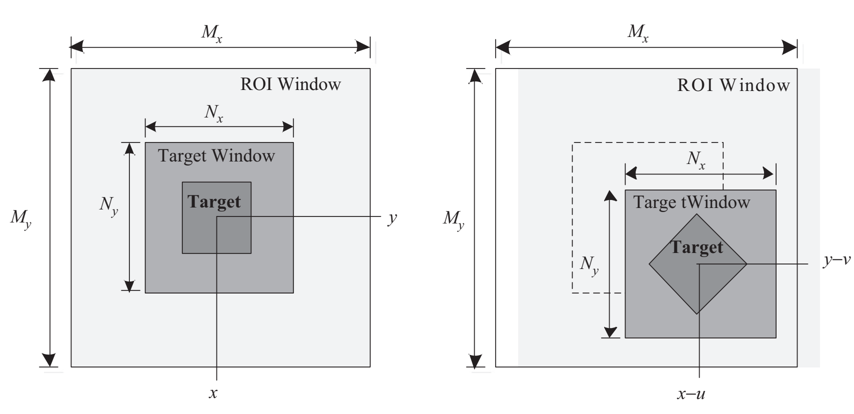

Fig. 1. Pixel coordinates of image before and after deformation.