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ORIGINAL PAPER

Real-Time Displacement Measurement of a Flexible Bridge Using Digital Image Processing Techniques

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Abstract In this study, real-time displacement measurement of bridges was carried out by means of digital image processing techniques. This is innovative, highly cost-effective and easy to implement, and yet maintains the advantages of dynamic measurement and high resolution. First, the measurement point is marked with a target panel of known geometry. A commercial digital video camera with a telescopic lens is installed on a fixed point away from the bridge (e.g., on the coast) or on a pier (abutment), which can be regarded as a fixed point. Then, the video camera takes a motion picture of the target. Meanwhile, the motion of the target is calculated using image processing techniques, which require a texture recognition algorithm, projection of the captured image, and calculation of the actual displacement using target geometry and the number of pixels moved. Field tests were carried out for the verification of the present method. The test results gave sufficient dynamic resolution in amplitude as well as the frequency. Use of this technology for a large suspension bridge is discussed considering the characteristics of such bridges having low natural frequencies within 3 Hz and the maximum displacement of several centimeters.

Keywords Displacement measurement · Digital image processing · Real-time · Bridge structures

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Introduction

Bridge structures are exposed to various external loads such as traffic, earthquakes, gusts, and wave loads during their lifetime. The structures may get deteriorated along with time in unexpected ways, which may lead to structural damage causing costly repair and/or heavy loss of human lives. Consequently, structural health monitoring has become an important research topic for continuous assessment and evaluation of structural safety. In this respect, monitoring the structural responses can give valuable information to assess the structural integrity. Displacement under a certain loading condition is fundamental and crucial information to be obtained. However, measuring the displacement of flexible bridges is very difficult, since most bridges overpass the sea or the river. Installation of the conventional devices for displacement measurement is almost impossible, or extremely costly, if not impossible.

Traditional structural displacement sensors, such as linear variable differential transformers (LVDTs) and dial gauges, perform measurement at a certain point of a structure. They are flexible for measuring displacement in any direction and meeting the resolution requirement for structural testing. However, these sensors require stationary platform as the measurement reference and to which the sensors are to be fastened. The platform usually has to be close to the structure because the sensor size is relatively small compared to the size of the structure in which case wire-connection devices must be used at a possible loss of accuracy. Indeed, this has been a typical problem for field testing when access to the structure is costly, and establishment of the required platform is difficult.

There have been numerous studies related to the technical feasibility of using Global Positioning System (GPS) technology to measure displacement of bridge structures. The dynamic characteristics of the Humen Bridge in China were identified using the wind-induced vibration responses measured by a real-time kinematic (RTK) global position system (GPS) [1]. The RTK-GPS system has a resolution of ±5 mm horizontally and ±10 mm in height. Meo et al. (2005) employed RTK-GPS system to measure the low-frequency vibration of the Nottingham Wilford suspension footbridge [2]. The GPS receivers and antennas were capable of acquiring the real-time absolute three-dimensional positions at 2 mm positioning accuracy at a rate of 10 Hz. Use of GPS system to measure displacement of flexible civil infra-structures has advantages in many ways such as positioning accuracy of millimeter-level, dynamic measurement up to 10 Hz, real-time monitoring, and remote measurement without access to the bridge site. However, there remain problems to be resolved such as high electro-magnetic noise, usage limitation due to weather and limitation to the measurement period and duration due to satellite cycling, since GPS system requires communications between the GPS receivers and a satellite. And the cost of high-accuracy and high sampling rate GPS-based tracking is significantly more than the proposed vision-based approach.

Nassif et al. [3] compared the results from dynamic live load tests using the non-contact laser Doppler vibrometer (LDV) system with those from contact sensors [3]. The use of the laser Doppler vibrometer system as a non-contact, non-destructive means of measuring bridge vibration and deflection provided accurate displacement results compared with LVDT-cable system that is directly mounted onto the bridge girder. The LDV system also provided accurate girder velocity measurements when compared with the mounted geophone sensor. A microwave interferometer with imaging capability was utilized to measure the displacement of a real-scale building [4]. The images were obtained by a synthetic-aperture interferometric radar, and the phase information of the synthesized microwave images was exploited for detecting displacements of the illuminated structure. However, these devices are very expensive and difficult to be implemented.

Estimation of bridge displacement using measured acceleration has been carried out by several researchers [5, 6]. While in principle, one can determine the time history of the displacement by double-integrating the corresponding accelerations which can be conveniently measured by conventional accelerometers, there are some major pitfalls in various digital signal processing approaches that can cause significant distortion in the extracted time histories of the estimated displacement. Kim and Cho [7] developed a method to estimate the bridge deflection using fiber optic Bragg-grating strain sensors [7]. By applying classical beam theory, a formula is rearranged to estimate the continuously deflected profile by using strains measured directly from several points. The regression analysis was performed to obtain a strain function from the measured strain data, and the deflection curve was estimated by applying the strain function to the formula. However, this approach has some limitations; it should be applied to beam-type structures. Strain data is very sensitive to noise, and should be measured at many points to accurately estimate the deflection profile of a bridge.

On the other hand, optical devices have offered effective alternatives to displacement measurement. With rapid advancement in electronics and computer technology, these optical devices have become affordable, and they are expected to be more so in the future. Stephen et al. (1992) suggested a visual tracking system to measure deck displacement of the Humber Bridge in the UK. For the real-time processing, the transputer-based parallel processing techniques were employed to track the motion of multiple, independent objects at video frame rate. For object tracking, templates of the user-selected object features are extracted from the initial frame and a template matching operation using the minimum least squares error scheme is applied repeatedly. This system was successfully utilized to measure the very low frequency movement of the Humber Bridge [8]. Olaszek [8] developed a method for the investigation of the dynamic characteristic of bridges based on the photo-gram-metric principle using additional reference system [9]. The reference point concurrently measured with a target point is used to exclude the effect of translational movement at image capturing camera. However, this correction-by-reference scheme is not applicable to the case of rotational movement. Moreover, a specially-manufactured optical device should be employed to concurrently capture two distant points (reference and target points) using one image capturing device. Whabeh et al. [10] deployed the high-fidelity video camera with a resolution of 520 lines and a capability of 450 digital zoom, and the targets consisted of black steel sheets 28 inches high by 32 inches wide, on which two high-resolution red lights (LED) were mounted, to measure displacement of the Vincent Thomas Bridge located in San Pedro, California [10]. Sophisticated signal processing techniques, including optical data reduction and a nonlinear Gaussian regression curve fit to determine the center of the high-intensity red spot, were applied to the entire optically recorded data of 30 minutes in off-line manner due to computational time.

This paper focuses on the measurement of dynamic displacement of flexible bridges using digital image processing techniques. This technique is highly cost-effective and easy to implement, but still maintains the advantages of measuring dynamic displacement with good resolution. Basic technical backgrounds on real-time displacement measurement by image processing techniques are described in the following section. For the verification of the presented method, two field tests were carried out on a bridge with steel plate girders and a bridge with open-box girders. Finally, the use of this technology for a large suspension bridge is briefly discussed.

Real-Time Displacement Measurement Using Image Processing Techniques

Figure 1 shows the schematics of real-time displacement measurement system using digital image processing techniques. At first, the measurement point is marked with a target panel of known geometry. A commercial digital video camera with a telescopic lens is installed on a fixed point beyond the bridge (e.g., on the coast) or on a pier (abutment), which can be regarded as a fixed point. Then, the video camera takes a motion picture of the target placed at the measurement point. Meanwhile, the displacement of the target is calculated using the image processing techniques, which require the texture recognition algorithms, projection of the captured image, and calculation of the actual displacement using target geometry and number of pixels moved. The image processing software was developed using image acquisition toolbox in MATLAB 7.0.

A displacement measurement system using digital image processing techniques is composed of (1) hardware including a target object, a telescopic lens, a digital camcorder, a IEEE1394 port, and a laptop computer and (2) software including continuous image capturing, a target recognition algorithm, calculation of a trigonometric transformation matrix from pre-captured images, and the actual displacement calculation from on-line image data. In this study, we deployed a commercial digital camcorder with 30× optical zooming capability, a resolution of 720 by 480 pixels, and the frame rate of 30 frames a second. A telescopic lens with 8× optical zooming capability was installed on the camcorder to trace the target more far away from the camcorder. A laptop computer with Pentium M 1.6 GHz processor and 512 MB RAM was used to process the real-time data. The total cost of these systems is less than \$2000, which is very economical while pursuing real-time displacement measurement of bridges.

Figure 2 shows a target object which has four white spots with known geometry and black background. The horizontal (L_x) and vertical length (L_y) should be determined considering the expected maximum displacement to be measured and the performance of hardware including a digital video camcorder and a telescopic lens. A light source can be utilized to brighten white spots on the target. To recognize the white spots on the target, a threshold for the black and white image is calculated based on the brightness of background and target region as

$$\theta = median\,[\mu_B + 3\sigma_B, \mu_T - 3\sigma_T] \quad (1)$$

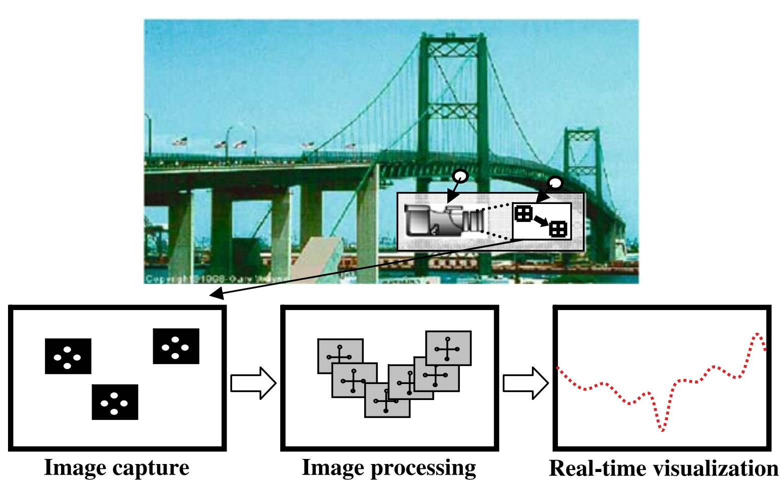
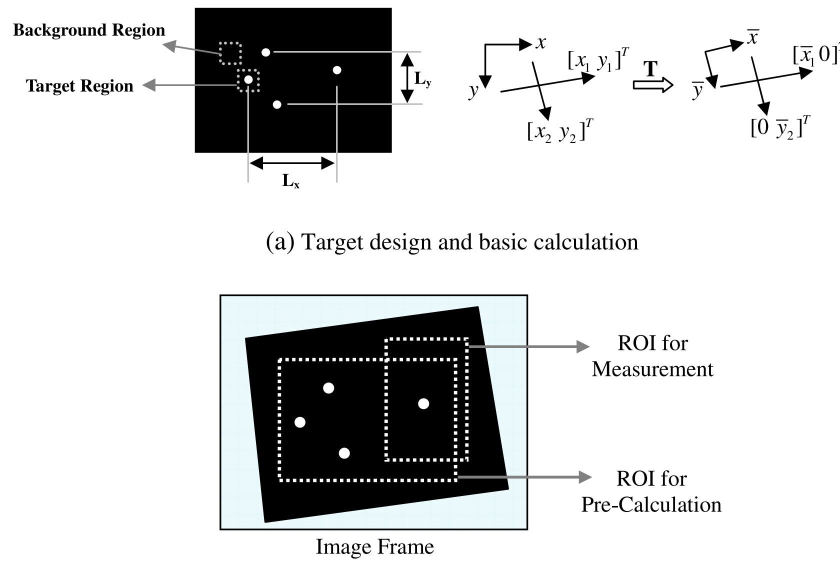


Fig. 1. Real-time displacement measurement system using digital image processing techniques

Fig. 2. Target object for image processing



(a) Target design and basic calculation

(b) Region of Interests (ROIs)

where, μ_B and σ_B are average and standard deviation of brightness in background region, and μ_T and σ_T are average and standard deviation of brightness in target region.

The centers of four white spots can be located from the black and white image. Then the direction vectors ($[x_1 y_1]^T$, $[x_2 y_2]^T$) corresponding to the actual horizontal and vertical direction are decided in pixel-coordinate (x, y). The trigonometric transformation matrix (**T**) to transform the directions of an image frame (x, y) to the actual directions in a bridge (x, y), and the scaling factors (SF_x, SF_y) to correlate the number of pixels in an image frame to the actual target length are calculated as

$$\mathbf{T} = \begin{bmatrix} X_1 & X_2 \\ Y_1 & Y_2 \end{bmatrix}^{-1}, \quad SF_x = L_x \Big/ \sqrt{x_1^2 + y_1^2}, \qquad SF_Y = L_Y \Big/ \sqrt{x_2^2 + y_2^2} \tag{2}$$

where, $[X_1 Y_1]^T = [x_1 y_1]^T \Big/ \sqrt{x_1^2 + y_1^2}$ and $[X_2 Y_2]^T = [x_2 y_2]^T \Big/ \sqrt{x_2^2 + y_2^2}$. Actual displacement ($[d_x d_y]^T$) is calculated based on the number of pixels of target movement ($[xy]^T$), and transformation matrix and scaling factors as

$$[d_x d_y]^T = \begin{bmatrix} SF_x & 0 \\ 0 & SF_y \end{bmatrix} \mathbf{T}[xy]^T \tag{3}$$

The accuracy of the current system depends on the hardware performance and the distance to target. Using a commercial video camcorder with 30× optical zoom and a telescopic lens with 8× optical zoom, it is possible to take a picture of the target with 1 cm in length in the whole range of a frame at a distance of 10 m. The number of pixel is 480 in vertical direction. Therefore, the resolution is about 0.021 mm/pixcel. When the distance to target becomes double, the resolution becomes also double. Considering the expected maximum displacement of a common bridge, which should be several millimeter, the camera can be placed at a distance of several tens of meters. For the case of a long-span bridge, such as a suspension bridge, the camera should be placed much far from the target, possibly a couple of hundreds meters. But, the expected maximum displacement is several (tens of) centimeters.

For the purpose of real-time measurement, image processing should be carried out within 1/30 second, since most commercial video camcorders support the frame rate of 30 frames a second. While capturing image frames, the displacement of the target is calculated using image processing techniques, which include target recognition, calculation of the number of pixel movement, calculation of the actual displacement using transformation matrix and scaling factors, and display and storage of the calculated displacement. The quantity of information depends on the number of pixels per frame and the number of frames per second. Region of interest (ROI) for the pre-calculation of transformation matrix and scaling factors should cover four white spots region. Pre-calculation is carried out using several frames, possibly 30 frames, and the average of calculated results are utilized to construct the transformation matrix and scaling factors more

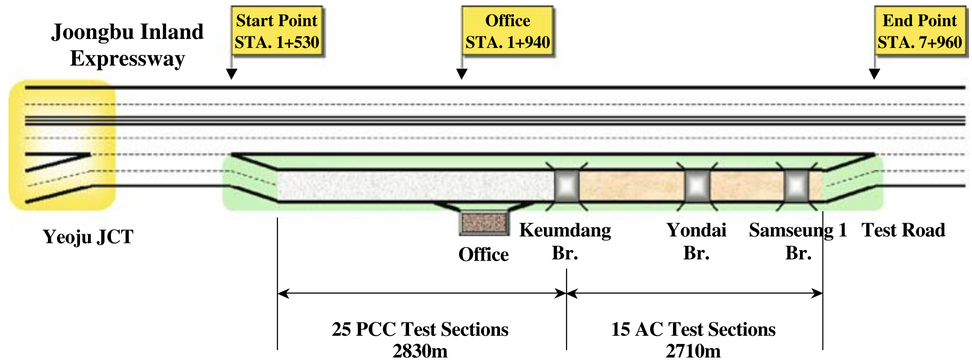


Fig. 3. KHC Test Road

robustly under vibrating condition of a structure. However, ROI for target recognition at the measurement stage does not need to cover four white spots and can be reduced more. It is needed to trace only one spot to reduce the quantity of information to be processed in real-time manner as in Fig. 2b.

Verification Through Field Tests

Korea highway corporation (KHC) built a test road to verify and enhance the pavement design guides based on the measured data from the real traffic and environmental conditions. The rest road is an ordinary two lane expressway of 7.7 km long constructed along the Joongbu Inland Expressway in Korea, as shown in Fig. 3. There are 3 test bridges along the test road. Field applications of the present method were made on a steel plate girder bridge and a steel box girder bridge with precasted bridge deck using truck loading tests.

Application to a Steel-Plate Girder Bridge

A field test was performed on the Samseung Bridge with a simple span and five steel plate girders. The span length is 40 m. Vehicle running tests were performed using three dump trucks with the load of 15, 30 and 40 tons. The vibrations due to vehicle running at the speed of 3 and 50 km/hr are measured at the center of the span by three different sensors: a contact-type displacement transducer based on wire connection with the sampling rate of 1000 Hz (the OU displacement transducer, Tokyo Sokki Kenkyujo Co. Ltd.), a laser vibrometer with the sampling rate of 100 Hz (OFV-505 Standard Optic Sensor Head and OFV-5000 Modular Controller, Polytec, Inc.), and a digital camcorder with 30 frames a second. Figure 4 shows the experimental setups. The conventional displacement transducer and a laser vibromter were installed on the ground below the measurement point and the camcorder was placed at the ground near an abutment. Figure 5 shows the comparison results. In the case of the running speed of 3 km/hr, the maximum displacements were about 1, 2, and 2.5 mm for 15, 30 and 40 tons, respectively. The displacement measured by digital image processing techniques showed close results to the laser vibrometer with low noise level. But the conventional contact-type displacement transducer with wire-connection showed large measurement noise. The measurement error, which is the difference between the displacements measured by a laser vibrometer and by image processing techniques, in-

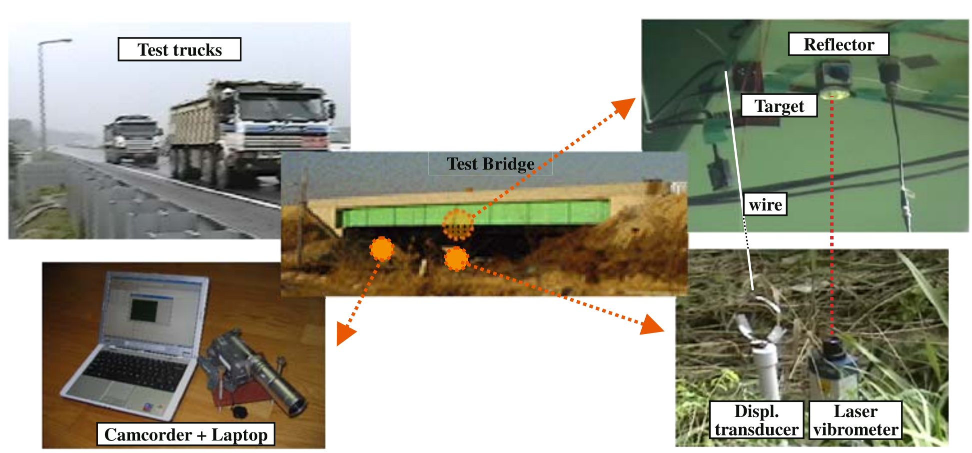


Fig. 4. A field test on a steel-plate girder bridge

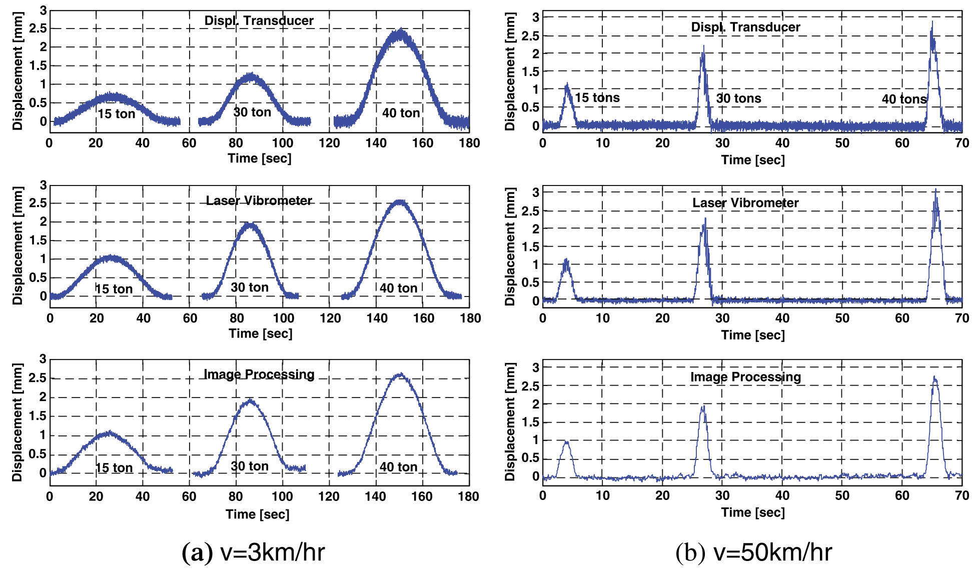


Fig. 5. Test results on a steel-plate girder bridge

creased a little bit in the case of the running speed of 50 km/hr, since the sampling rate of 30 Hz in the digital camcorder is not sufficient to trace the higher frequency dynamic motion of the test bridge, of which the first natural frequency is found to be 4.2 Hz. However, it has been found to be still reasonable. The accuracy of this system, of course, is limited by the dynamic characteristics of monitored structures and the frequency content of applied loads. Nevertheless, it is expected that the proposed system can be successfully applied to measure the vibration of bridges, probably with less than 10% error, since the first natural frequency of a common bridge lies between 2 to 5 Hz, and the lower modes below 15 Hz will contribute to more than 90% of the total displacement of the bridge.

Application to a Steel-Box Girder Bridge

Another field test was performed on the Yeondae Bridge with four continuous spans and two open-box steel girders. Vehicle running tests were performed using two dump trucks with the load of 30 and 40 tons and the running speed of 20 and 40 km/hr. The dynamic displacement are measured at the center of the first span by a laser vibrometer with the sampling rate of 1 kHz (LB-1000, KEYENCE Co.), and digital image processing techniques. Figure 6 shows the test bridge and Fig. 7 shows the comparison results in time and frequency domain, respectively. The displacement measured by digital image processing techniques showed close results to the laser vibrometer and small measurement noise. The present vision-based system was able to trace the dynamic response of the bridge very well, since the frequency contents of measured response were within less than 3 Hz.

Applicability to a Large Suspension Bridge

A vision-based real-time displacement measurement of long span bridges such as suspension bridges has drawn lots of interests these days, since most long span

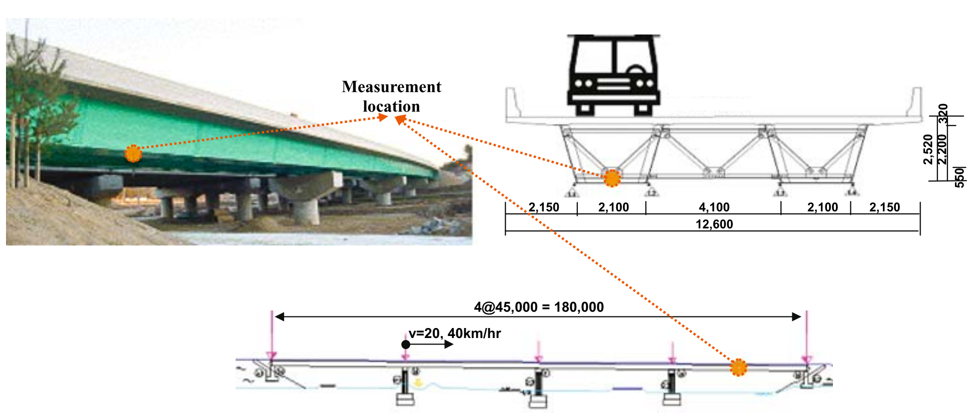
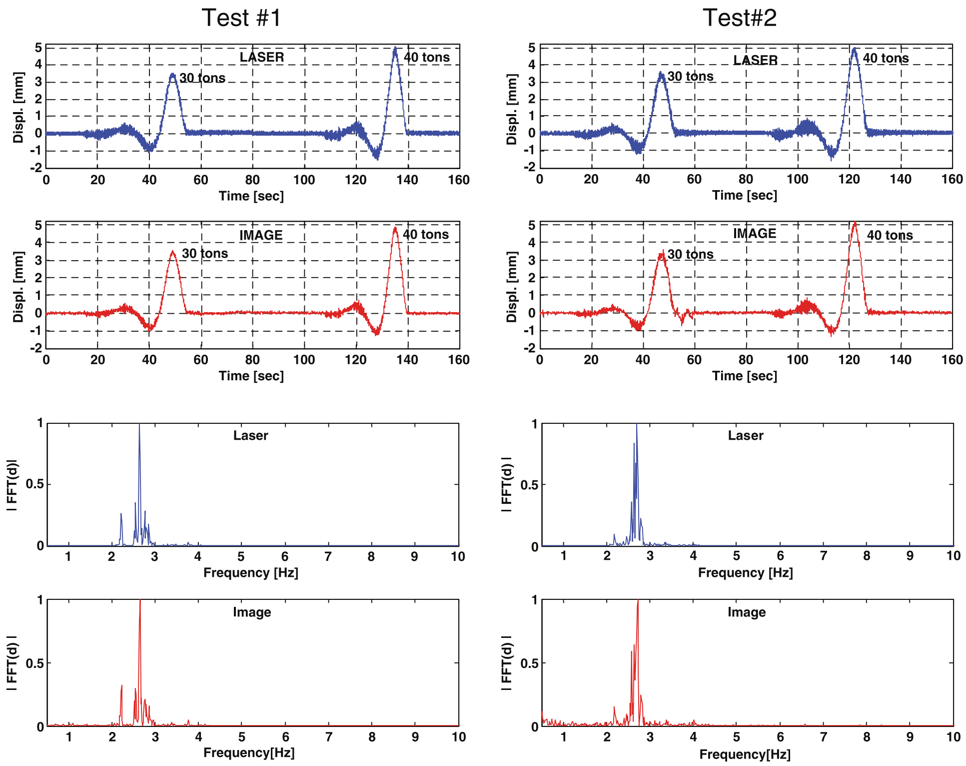
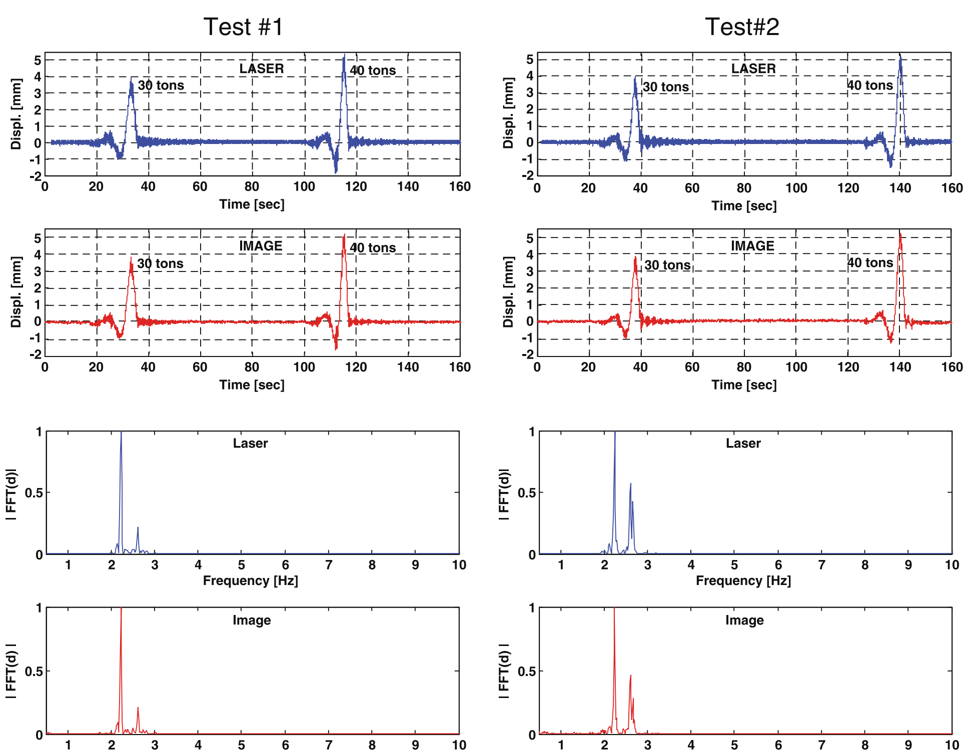


Fig. 6. A field test on a steel-box girder bridge



(a) v=20km/hr



(b) v=40km/hr

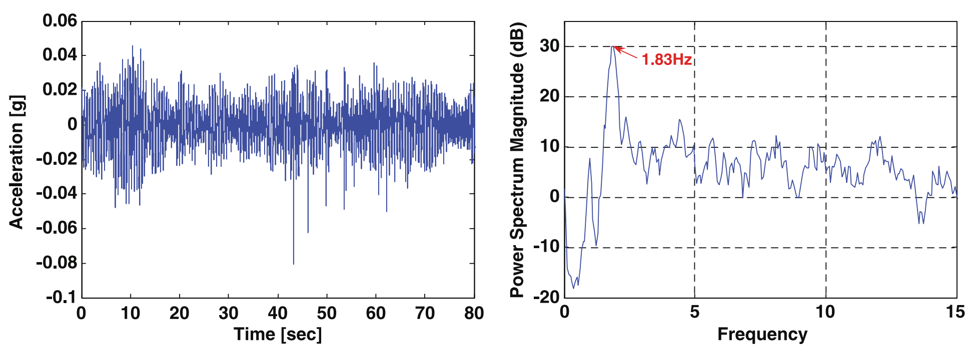
Fig. 7. Comparison results for displacement measurement

Fig. 8. A pedestrian suspension bridge

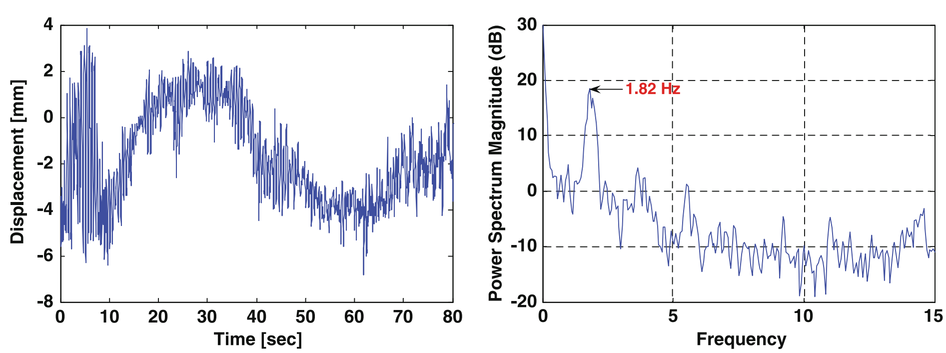
bridges overpass the sea or the river and the installation of the conventional devices for displacement measurement is almost impossible, or extremely costly, if not impossible. Whabeh et al. [10] reported the results of an analytical and experimental study to develop, calibrate, implement and evaluate the feasibility of a vision-based approach to measure displacement of the Vincent Thomas Bridge located in San Pedro, California [9]. However, there remain some drawback to be improved; (1) digital zoom can be replaced by optical zoom, (2) Sophisticated signal processing to determine the center of the target should be replaced by simple algorithms to be implemented in real-time manner, and (3) the angular orientation of the camera with respect to the target should be considered by coordinate transformation.

To check the applicability of the present method to a suspension bridge, a feasibility test was performed on a pedestrian suspension bridge with stiffened steel girders as shown in Fig. 8. The total length of the bridge is about 120 m. A target was placed at the center point of mid-span, and the camera was placed at the ground near an abutment. The distance from the camera to the target is about 70 m. Acceleration was also measured with the sampling rate of 500 Hz at the same location. Figure 9 shows the responses measured by an accelerometer and digital image processing techniques. The measured first natural frequency is 1.83 Hz based on acceleration and 1.82 Hz based on image processing techniques. The vibration is mainly due to pedestrians and wind loads. Large amplitude vibrations with a period of nearly 60 seconds are due

Fig. 9. Responses in time and frequency domain



(a) Accelerometer



(b) Image Processing

to the pedestrian crossing. Considering the Influence Line for the displacement at the center point, and assuming the walking speed of pedestrians is 3–4 km/hr, it takes about 108–144 seconds to cross the bridge. The vibration with a period of nearly 60 seconds corresponds to the 1/2–3/4 of the Influence Line. In principle, one can determine the time history of the displacement by double-integration of the corresponding accelerations. However, this double-integrating scheme was not applicable to this field test, since it was not easy to design high-pass filters so that low frequency component of the bridge response can be accurately constructed. In fact, the cutoff frequency in the high-pass filter caused the instability in the estimated displacement.

The accuracy of the system depends on the hardware performance and the distance to target. In the current system using a commercial video camcorder with 30× optical zoom and a telescopic lens with 8× optical zoom, it is possible to take a picture of the target with 1 cm in length in the whole range of a frame at a distance of 10 m. The number of pixel is 480 in vertical direction. Therefore, the resolution is 0.021 mm/pixcel. As for the pedestrian bridge, the distance from camera to target is about 70 m, and the resolution comes to 0.147 mm/pixcel. The measured data in the pedestrian bridge showed the displacement with several millimeters (up to 1 cm). The lateral and vertical deflection of the Humber Bridge [8] came to several tens of centimeters, and the displacement variation of the Vincent Thomas Bridge [10] in ambient vibration condition showed five centimeters. Considering the span length and the performance of the current system, it is expected that the present method can be successfully utilized to monitor the dynamic motion of a suspension bridge.

Concluding Remarks

In this study, dynamic displacement measurement system using digital image processing techniques is developed. The applicability and effectiveness of the present method were verified through two field applications on a bridge with steel plate girders and a bridge with steel box girders.

Vehicle running tests were performed using dump trucks with various loads and various running speeds in two field applications. The displacement measured by digital image processing techniques showed close results to the laser vibrometer with small measurement noise for all cases. The test results gave sufficient dynamic resolution in frequency as well as the amplitude. A feasibility test was made on a pedestrian suspension bridge with stiffened steel girders to check the applicability of the present method to a suspension bridge. The first natural frequency measured by image processing techniques showed a close value measured by acceleration. And the present method is expected to be successfully deployed to measure the displacement of a large suspension bridge.

From these results, it can be concluded that the present method can be successfully utilized to measure the displacement of a flexible bridge. Real-time displacement measurement system using digital image processing techniques is innovative, highly cost-effective and easy to implement, still maintains the advantages of dynamic measurements with high resolution. Hence, it is expected that this technology will provide the sensor and monitoring community with a powerful addition of an advanced sensor to the current list.

Measuring the whole deformation of bridge is very informative. However, it is very difficult to do so using the commercial digital video camcorder. To measure the displacements of multiple locations simultaneously, the synchronous measurement system based on the present system is under development. This system can be also applied to measure three-dimensional motion of a bridge using two current in-plane measurement systems, which are timely synchronized, and geometrically correlated. The results will be reported soon.

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