Bridge Deflection Measurement Using Digital Image Correlation with Camera Movement Correction

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When displacement measurement by digital image correlation is performed in outside for the inspection of real structures, the position and the direction of a camera are often changed slightly because of wind, oscillations and the lack of stability of ground. In order to realize the bridge deflection measurement by digital image correlation, a method for correcting the effect of camera movement is proposed in this study. The relationship between images before and after the camera movement is described by an equation of perspective transformation. The unknown coefficients of the equation are determined from undeformed regions of the images. Then, the effect of the camera movement is eliminated by using the perspective transformation. The effectiveness is validated by applying the proposed method to the rigid body rotation and translation measurement of a planar specimen, the deflection measurement of a wide-flange beam, and the bridge deflection measurement. Results show that the effect of the camera movement can be corrected by the proposed method. It is emphasized that noncontact displacement measurement is possible by simple and easy procedure with digital image correlation for the structural evaluation of infrastructures.


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1. Introduction

For the structural evaluation of bridges, various tests are usually performed to investigate the structural properties such as natural frequencies, dynamic responses, and strains. One of these properties is vertical deflection of bridge girders. Several different types of transducers and sensors can be used to measure the deflection. However, most of these sensors require the access to measurement location under bridges. Therefore, it would be required to interrupt traffic under bridges for the setup of these transducers. In addition, the installation of these transducers is time-consuming. Therefore, various techniques for the noncontact measurement of bridge deflection have been studied. On the other hand, noncontact measurement of bridge deflection by a digital image correlation technique is possible as demonstrated by one author previously. Digital image correlation can obtain the surface deformation by comparing digital images of undeformed and deformed configurations. Since digital image correlation technique does not need a complicated optical system, the measurement can be performed simply and easily. Thus, a lot of applications of this method to various problems can be found in the field of experimental solid mechanics.

In digital image correlation, the camera position must not be changed during the measurement because this technique extracts displacements from digital images directly. When the measurement is performed in outside for the inspection of real structures, however, the position and the direction of a camera are often changed slightly because of wind, oscillations and the lack of stability of ground. In this case, the displacement cannot be measured because the effect of the camera movement is included in the measured displacement.

In order to realize the bridge deflection measurement by digital image correlation, a method for correcting the effect of camera movement is proposed in this study. The relationship between images before and after the camera movement is described by an equation of perspective transformation. The unknown coefficients of the equation are determined from undeformed regions of the images. Then, the effect of the camera movement is eliminated by using the perspective transformation. The effectiveness is validated by applying the proposed method to the rigid body rotation and translation measurement of a planar specimen, the deflection measurement of a wide-flange beam, and the bridge deflection measurement. Results show that the effect of the camera movement can be corrected by the proposed method. It is emphasized that noncontact displacement measurement is possible by simple and easy procedure with digital image correlation for the structural evaluation of infrastructures.

2. Method for Correcting the Effect of Camera Movement

Figure 1 shows the outline of the proposed method. An undeformed image (reference image) of an object such as bridge is recorded as shown in Fig. 1(a). The object is deformed by a load as shown in Fig. 1(b). When the camera is moved before acquiring an image of the deformed object, the image includes information of not only the deformation but also the camera movement, as shown in Fig. 1(d). In the proposed method, the camera movement shown in Fig. 1(c) is detected from the undeformed regions such as piers. Then, the deflection of the measured region such as a girder is obtained by eliminating the effect of the camera movement.

Figure 2 shows the geometric relationship between image planes of a camera before and after the camera movement. In this figure, a point P positioned at \((x, y, z)\) on an object is projected at \(P_1\) on an image plane. The point \(P_1\) is located at \((u, v)\) on the image plane. The same point \(P\) on the object is imaged at the point \(P_2\) at \((u', v')\) after the camera movement. In this case, the relationship between the coordinates \((u, v)\) of the point \(P_1\), and \((u', v')\) of the point \(P_2\) is expressed by perspective transformation as\(^{17}\)
where \( a_1 \sim a_8 \) are the coefficients that express the camera movement. Therefore, the coordinate \((u', v')\) on the image after the camera movement can be corrected to the coordinate \((u, v)\) before the camera movement provided that the coefficients of the equation are known. The coefficients are determined from fixed reference points that can be considered to be not deformed. Applying digital image correlation technique to the fixed region, the data sets of the coordinates \((u, v)\) and \((u', v')\) before and after the camera movement are obtained. Then, the coefficients in eq. (1) are determined using the method of linear least-squares. The coordinates of the deformed region such as a girder after the camera movement are then corrected using eq. (1). After that, the actual displacements can be determined.

3. Rigid Body Rotation and Translation Measurement

In order to validate the method described in previous section, rigid body rotation and translation are measured with and without the camera movement. The experimental setup is shown in Fig. 3. A planar specimen, 120 mm in height and 120 mm in width, is mounted on a rotation and translation stage. The resolution of the stage is \(4.0 \times 10^{-3}\) degrees for rotation and \(1.0 \times 10^{-3}\) mm for translation. Two additional planar objects are placed at the either side of the specimen. These planar objects are used as fixed reference regions for determining the coefficients in eq. (1). The surfaces both of the specimen and the fixed regions are sprayed by black and white paint to create random pattern. Then, the specimen surface and the fixed regions are observed by a monochromatic CCD camera (1280 x 1024 pixels and 8 bits). The specimen is moved 1 mm to left side and rotated 2 degrees in counterclockwise direction. The images of the specimen before and after the movement of the specimen are acquired to obtain the displacement without the camera movement. Next, the camera is moved 8 mm to right side and rotated about 0.6 degrees to observe the same region of the specimen surface and the fixed object surface as shown in Fig. 3. Then, the displacements with and without camera movement, and the corrected displacement by the proposed method are obtained.

Figure 4 shows the images obtained in this experiment. The random pattern created by spray painting for obtaining the correlation between two images is observed on both the measured and the fixed regions. The \(x\)-directional component \(u_1\) of the displacement obtained by digital image correlation is plotted in Fig. 5. In this figure, the displacement without the camera movement, that is, the actual displacement is also shown. The displacement distribution obtained when the camera is moved is different from the actual displacement by the effect of the camera movement. Figure 6 shows the difference \(u_1 - u_1^{\text{act}}\) between the displacements with and without camera movement. The difference, that is, the error
introduced by the camera movement is about 0.6 mm. Applying the proposed method, the displacement obtained with the camera movement is corrected. The difference \( u_x^{\text{corr}} - u_x^{\text{act}} \) between the corrected displacement and the actual displacement is also shown in this figure. As shown in this figure, the difference about 0.6 mm is corrected to zero.

The camera is moved again and the measurement is repeated as shown in Fig. 7. The average value of the difference of the actual and the corrected displacements with respect to the angle \( \theta \) of the camera are shown in Fig. 8. As shown in this figure, the difference is less than 0.1 mm even if the angle of the camera is large as 30 degrees. The difference of 0.1 mm corresponds to the small value of about 0.6 pixels. The results of the rigid body rotation and translation test show that the effect of the camera movement is corrected by the proposed method.

4. Measurement of the Deflection of a Wide-Flange Beam

Experimental tests have been performed to evaluate the applicability of the proposed method to the deflection measurement of bridges. The results show that the method effectively corrects the effect of camera movement on the measurement of deflection.

Fig. 4 Images obtained for rigid body rotation and translation test: (a) reference image; (b) image after rotation and translation.

Fig. 5 x-directional displacement distributions obtained with and without camera movement.

Fig. 6 Differences between the displacements with and without camera movement correction and the actual displacement.

Fig. 7 Setup for additional rigid body rotation and translation test.

Fig. 8 Difference between the corrected displacement and the actual displacement, and its standard deviation.
measurement of large structures. The deflection measurement of a beam under three-point bending is adopted in this experiment as shown in Figs. 9 and 10. A wide flange beam made of SS400 steel, 5000 mm in long, 200 mm in width and 8 mm in thickness, is placed on two supports. The modulus of elasticity and the moment of inertia of the cross-sectional area of the beam are estimated as 210 GPa and $1.60 \times 10^7$ mm$^4$, respectively. Various loads are applied at the middle point of the beam by a weight that is hung by a crane from the ceiling. The load is measured by a load cell placed between the weight and the beam. White colored random pattern is painted on the surface of the beam. Fixed areas with random pattern are placed on both sides and below the beam to apply the proposed method of the camera movement correction. The images of the beam before and after deformation are recorded by a single-reflex type digital camera (3504 × 2336 pixels × 24 bits). Here, after the undeformed image is recorded, the camera is removed and then placed at almost same position. Therefore, the amount of the camera movement is unknown. The deflections of the beam are also measured at the position of $1/4$, $1/2$ and $3/4$ of the length by displacement transducers of the resolution of 0.005 mm.
Applying digital image correlation to these images, the deflection distributions are determined. Figure 11 shows the deflection curve obtained by digital image correlation. Different values of the deflection at both supports are obtained. The deflection curves in Fig. 11 are corrected by the proposed method. Figure 12 shows the deflection curves after the camera movement correction. In this figure, the deflections corrected by the proposed method agree well with those obtained by the displacement transducers. The results of the beam deflection measurement also show that the effect of the camera movement is corrected by the proposed method.

5. Bridge Deflection Measurement

The field study of bridge deflection measurement is carried out for a concrete girder bridge. The length of the bridge is measured as about 20 m. Unlike the bridge load test reported in previous study, the deflection under usual load by traffic is measured. The image before deformation is recorded when there is no traffic on the bridge. The image after deformation is acquired at an instant when a bus passes on the bridge. The deflection without camera movement is obtained from these two images. Then, the camera position is moved slightly to demonstrate the proposed method. After that, the image after deformation with camera movement is obtained when another bus passes on the bridge. A single-reflex type digital camera (3008 × 2000 pixels × 24 bits) is used for measurements.

The photographs of the bridge before and after load are shown in Fig. 13. The fixed reference regions are both sides of the bridge as shown in this figure. The measured and corrected deflection distributions of the bridge girder are shown in Fig. 14. The abscissa shows the position that is measured from the left edge of the bridge. Because there is a barrier, the deflection at the left side is not obtained. In this figure, the deflection without the camera movement is also shown for comparison. The reasonable deflection distribution is obtained by correcting the camera movement. In addition, the values of the corrected deflection agree well with the values obtained without the camera movement. The results of the field study show that the bridge deflection can be measured by digital image correlation even if the position of the camera is moved.
The results shown in this paper indicate that digital image correlation can be used in place of displacement transducers. That is, easy and simple but effective measurement of structures can be realized using digital image correlation.

6. Conclusions

A method for correcting the effect of the camera movement is proposed for field application of two-dimensional digital image correlation. The validity of the proposed method is demonstrated by measuring the rigid body displacements, the deflection of the beam, and the deflection of the bridge. Results show that the effect of the camera movement can be corrected by the proposed method. It is emphasized that noncontact displacement measurement is possible by simple and easy procedure with digital image correlation for the structural evaluation of infrastructures.

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