Exploring of PST-TBPM in Monitoring Bridge Dynamic Deflection in Vibration

Guojian Zhang¹, Shengzhen Liu², Tonglong Zhao³ and Chengxin Yu⁴

¹School of Environmental Science and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China
²The first geodetic surveying team of the national geographic information bureau, Xi’an 710054, China
³College of Surveying and geo-informatics, Shandong Jianzhu University, Jinan 250101, China
⁴Business School, Shandong Jianzhu University, Jinan 250101, China

*Corresponding author e-mail: g_j_zhang@cumt.edu.cn

Abstract. This study adopts digital photography to monitor bridge dynamic deflection in vibration. Digital photography used in this study is based on PST-TBPM (photographing scale transformation-time baseline parallax method). Firstly, a digital camera is used to monitor the bridge in static as a zero image. Then, the digital camera is used to monitor the bridge in vibration every three seconds as the successive images. Based on the reference system, PST-TBPM is used to calculate the images to obtain the bridge dynamic deflection in vibration. Results show that the average measurement accuracies are 0.615 pixels and 0.79 pixels in X and Z direction. The maximal deflection of the bridge is 7.14 pixels. PST-TBPM is valid in solving the problem-the photographing direction not perpendicular to the bridge. Digital photography used in this study can assess the bridge health through monitoring the bridge dynamic deflection in vibration. The deformation trend curves depicted over time also can warn the possible dangers.

1. Introduction
Deformation monitoring is an important content to assess bridge health, especially the deflection [1]. The increase of the bridge flexibility makes it more important. Although the fatigue and injury is a long-term process, the bridge safety accident happens in one moment. It therefore is more important to monitor the dynamic deflection of a bridge [2]. The traditional surveying methods [3] cannot monitor the dynamic deflection of a bridge. Physical sensors cannot monitor bridge global deflection [4]. GPS (Global Positioning System) monitors the dynamic deflection of a bridge with low accuracy [5, 6]. The three-dimensional laser scanning [7] is limited to monitor the dynamic deflection of a bridge due to its relative-long scanning cycle.

However, digital photography [8-10] can monitor the dynamic deflection of a bridge as it monitors a bridge by a digital camera, which can capture the instantaneous deformation in 1‰ second and can monitor a bridge seven times in one second. Although digital photography has not been as popular in bridge structures as in other fields, many pioneering applications in this field have illustrated the
potential for growth [11]. Researchers in the City University of London adopted digital photography to monitor a military steel bridge [12]. Forno et al. [13] adopted digital photography to monitor a decommissioned masonry arch bridge and a full-scale laboratory model of the bridge. These examples suggest that digital photography has a unique advantage in monitoring the bridge deflection.

The aims of this study are to explore PST-TBPM in monitoring the dynamic deflection of a bridge in vibration and to assess the bridge health based on these dynamic deflection data and its trend curves.

2. Digital photography

2.1. Distortion correcting of a digital camera

This study adopts a grid method [14] to eliminate the distortion of a digital camera to improve measurement accuracy. Figure 1 illustrates the distortion resulting in one same point from Position A to Position A’. ΔX and ΔY are the corresponding horizontal and vertical deformation, respectively.

![Figure 1. Influence of distortion error](image)

Table 1. Accuracy verification for deformation points U0 and U1

| Name | Actual coordinates/m | Calculated coordinates/m | Differences/mm |
|------|-----------------------|--------------------------|----------------|
| U0-X | 108.825               | 108.826                  | 1              |
| U0-Y | 95.887                | 95.888                   | 1              |
| U0-Z | 99.441                | 99.440                   | 1              |
| U1-X | 109.067               | 109.065                  | 2              |
| U1-Y | 96.935                | 96.934                   | 1              |
| U1-Z | 99.394                | 99.394                   | 0              |

Table 1 shows that the maximum and minimum error is 2mm and 0mm, respectively. The average error is 1mm. This suggests that the camera used in this study can meet the accuracy requirements of deformation observation.

2.2. Photographing scale transformation-time baseline parallax method

The time baseline parallax method is commonly used to solve digital camera data [15]. But it consists of the parallax caused by the camera vibrating [16]. For improving the measurement accuracy, the PST-TBPM (Figure 2) was used to correct errors caused by the change of intrinsic and extrinsic parameters of digital cameras. And the photographing direction is perpendicular to the reference plane. The reference plane does not coincide with the object plane.
Reference plane in Figure 2 consists of six reference points labeled as C0-C5. It is used to match images and eliminate the parallax.

Thus, we obtained the deformations based on the photographing scale M:

\[
\begin{align*}
\Delta X'_R &= \frac{SA}{Sa}\Delta P'_x = M\Delta P'_x \\
\Delta Z'_R &= \frac{SA}{Sa}\Delta P'_z = M\Delta P'_z
\end{align*}
\]

(1)

Where M is the photographing scale on the reference plane, SA and Sa are the photographic distance and the focus respectively, \((\Delta P'_x, \Delta P'_z)\) are the corrected displacements of the deformation point on the image plane. \(\Delta X'_R\) and \(\Delta Z'_R\) are the corrected horizontal and vertical deformation of deformation point on the reference plane.

Then, the actual deformations are obtained by the coefficient of the photographic scale transformation:

\[
\begin{align*}
\Delta X' &= \Delta is \cdot \Delta X'_R \\
\Delta Z' &= \Delta is \cdot \Delta Z'_R
\end{align*}
\]

(2)

Where \(\Delta is\) is the coefficient of the photographing scale transformation, \((\Delta X', \Delta Z')\) are the corrected actual deformations of the deformation point on the object plane.

3. Bridge test

Figure 3 shows Caiyuan road bridge which is a footbridge. It is 102.52 meters in length, 17.8 meters in width. Its span is 92.04 meters.

Before the test, the digital camera was set on the north of Xiaoqing river and the deformation points labeled as U0-U7 was lay on its deck uniformly to study the dynamic deflection trend of the bridge in vibration. In addition, the reference system formed by the reference points labeled as C0 to C7 was set near the camera, which was used to calculate the baseline data and to match the successive images.
with the zero image, respectively. The photographing direction is perpendicular to the reference system.

Figure 3. Test field of the bridge

The test process is as follows:
(1) The digital camera was used to monitor the bridge in static as a zero image.
(2) The digital camera was used to monitor the bridge every three seconds as the successive images when the crane was operating resulting in the vibration of the bridge.

4. Data analysis
Due to the calculation, the average measurement accuracies are 0.615 pixels and 0.79 pixels in X and Z direction. In order to assess the bridge health, the deflection trend curves (Figure 4) are depicted based on these dynamic deflection data.

Table 2. Measurement accuracy/pixel

|       | C6 | C7 |
|-------|----|----|
| X     | 0.77 | 0.46 |
| Z     | 0.74 | 0.84 |

Figure 4. Deformation trend curves of deformation points in vibration
Table 3. Relative deflection/pixel

| Test | U0   | U1   | U2   | U3   | U4   | U5   | U6   | U7   |
|------|------|------|------|------|------|------|------|------|
| 1    | -0.61| -0.49| -0.31| -0.09| -0.77| -1.47| -2.07| -1.56|
| 2    | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3    | -1.12| -1.01| -0.86| -0.68| -0.41| -2.16| -1.82| -1.38|
| 4    | -2.17| -1.25| -1.36| -1.48| -1.67| -1.84| -2.07| -1.27|
| 5    | -6.32| -4.80| -4.03| -3.13| -1.78| -1.55| 1.13 | 3.05 |
| 6    | -5.06| -5.06| -4.06| -4.05| -4.03| -4.01| -3.98| -3.77|
| 7    | -1.57| -1.39| -1.13| 0.18 | 0.64 | 0.05 | 0.62 | 2.25 |
| 8    | 2.99 | 2.31 | 1.32 | 1.17 | -0.57| -2.12| -4.27| -5.58|
| 9    | -4.18| -4.45| -4.85| -4.30| -4.98| -5.58| -6.61| -7.08|
| 10   | 1.54 | 1.07 | 1.37 | 0.56 | -0.66| -2.76| -3.27| -3.88|
| 11   | 1.37 | 0.82 | 0.01 | 0.08 | -1.34| -3.60| -5.34| -7.14|
| 12   | 0.38 | 0.82 | 0.01 | -0.92| -2.33| -3.60| -5.34| -6.14|
| 13   | -1.18| -0.25| -0.36| -0.49| -0.67| -0.84| -2.07| -1.26|
| 14   | -1.00| -1.00| 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 |
| 15   | -1.18| -0.26| -0.37| -0.49| -0.67| -1.84| -2.06| -2.26|
| 16   | -1.85| -0.72| -0.53| -0.30| -0.97| -1.66| -1.24| -0.71|
| 17   | -0.34| 0.46 | 1.16 | 0.81 | 0.28 | -1.19| -0.84| -1.55|
| 18   | -1.35| -1.50| -1.73| -0.98| -2.36| -3.69| -3.16| -3.56|
| 19   | -0.86| -0.99| -1.18| -1.40| -2.72| -3.01| -4.40| -4.72|
| 20   | -2.58| -2.27| -1.82| -1.30| -1.51| -0.80| -0.81| -0.66|
| 21   | -2.99| -1.61| -1.06| -1.42| -0.45| -0.58| 0.61 | 1.94 |
| 22   | 2.17 | 1.95 | 1.62 | 1.23 | 0.65 | -0.87| -1.58| -2.37|

Table 4 shows the relative deformation values of deformation points labeled as U0 to U7. The negative and positive in Table 4 represent the deformation point moving down and up. The maximal deflection of the bridge is 7.14 pixels.

Figure 4 shows that the deformation trend of one deformation point on bridge deck conforms to the others in Z direction. This suggests a good rigidity of the bridge. Caiyuan road bridge therefore is safety.

5. Conclusion

This study use digital photography based on PST-TBPM to monitor the dynamic deflection of the bridge in vibration. Deformation trend curves of the bridge are depicted over time based on these dynamic deflection data to assess the bridge health. Through analyzing test results, the following conclusions are obtained:

1) The measurement accuracy of PST-TBPM reaches the sub-pixel. The average measurement accuracies are 0.615 pixels and 0.79 pixels in X and Z direction.

2) The maximal deflection of the bridge is 7.14 pixels.

3) The deflection trend of one deformation point on bridge deck conforms to the others, which suggests a good rigidity of the bridge.

4) The deformation trend curves depicted over time can warn the possible dangers.

It is proved that digital photography based on PST-TBPM can solve the problem-the photographing direction not perpendicular to the bridge. But it requires the photographing direction perpendicular to the reference system. Digital photography can monitor the dynamic deflection of a bridge. Digital photography used in this study provides data support for the site decisions to the bridge structure safety. And it will be popular in monitoring bridge dynamic deflection in the future.
Acknowledgments
The corresponding author is Guojian Zhang. This study was supported by the Science and Technology project of Shandong province, China (Grant No. 2010GZX20125). It was also supported by PhD research fund project of Shandong jianzhu university, 2016 (Grant No. XNBS1635) and Housing and urban-rural construction hall science and technology project of Shandong province (Grant No.2017-K2-001).

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