Calibration Method for Dynamic Deflection Measurement of Bridges by Photogrammetry

Huayang He, Yishu Zhou, Jinjin Cao and Jinning Zhang

Research Institute of Highway, Ministry of Transport, Beijing, China

ys.zhou@rioh.cn

Abstract. Heavy vehicular traffic and aggressive environmental conditions can cause unexpected bridge deterioration, thus, periodic inspections to identify and assess possible defects are required. One indicator is the amount of vertical deflection that occurs during loading. Some different types of transducers can be used to measure the deflection. One of them is the photogrammetry. It is a typical noncontact measurement method. Unfortunately, it is difficult to calibrate this type of instruments. The key point is the evaluation of the dynamic deflection measurement capability. A dynamic calibration system of bridge photogrammetric measurement system was composed of the motorized linear stage, LED target and computer. The Fré chet distance was used as a model to evaluate the dynamic deflection measurement capability of bridge deflection photogrammetry. The photogrammetric bridge deflection measuring instruments are products of BIOET, which are used to carry out the measurement experiment. The results show that this system can calibrate the dynamic deflection measurement error of photogrammetric bridge deflection measuring instruments. Fré chet distance can reflect the relationship between the curves. This evaluation method is more accurate than the current evaluation method based on the error of indication of maximum dynamic deflection.

1. Introduction

For the structural evaluation of bridges, different tests are usually performed to know the structural properties such as natural frequencies, dynamic responses, static deflections, dynamic deflections, stresses, and strains [1]. What is more, it is important to monitor the change of these properties as well as damages to evaluate the structural integrity of bridges. One of these properties is vertical deflection of bridge girders. Vertical deflection includes static deflection and dynamic deflection. Several different types of sensors can be used to measure the static deflection and dynamic deflection [2-3]. However, most of these sensors need to be installed under the bridges. Therefore, the tests would interrupt the traffic under the bridge for the setup of these sensors. Another approach to measure bridge static deflection and dynamic deflection is to use the noncontact measurement methods. Noncontact methods realize the measurement of the deflection of bridges without occupying space and interrupt the traffic under bridges. Thus, various methods such as Photogrammetry [1,4], Moiré [5-6], Laser Scanning [7-8], and Laser Doppler [9] have been proposed, utilized, and applied to measure real or model bridge static deflections and dynamic deflections. Close-range photogrammetry has been used to determine the three-dimensional geometry and deformation of bridges since the 1970s.

Close-range photogrammetry for bridge deformation measurement has many advantages. It can measure difficult-to-access bridges by taking pictures away from the bridge and record a large amount
of two-dimensional information in a short time. A basic bridge photogrammetric measurement system consists of a camera, accessories, LED targets, scale bars, and software for photogrammetric processing. However, calibrating this type of instruments is very difficult. The key point is the evaluation of the dynamic deflection measurement capability.

The camera photogrammetric calibration was in need of an automated system [10]. Calibrated devices consisting of the motorized linear stages can be used to calibrate static deflection, the error of indication is not more than 0.01mm [11]. However, it was difficult to calibrate the dynamic deflection measurement error. Dynamic Bayesian Network and Canonical Time Warping were used in motion retrieval to recognize the similarity of two motion curves [12]. The Fréchet distance was used by some researchers to measure the correlation between two polygonal curves [13]. And some used the Hausdorff distance metric to comparative analysis of dendritic architecture of identified neurons [14]. In the signature verification method, the distance threshold was got by training the Siamese Network [15].

According to the needs of transportation industry, standard and verification regulation of the bridge photogrammetric measurement system are being made. A displacement device was designed. The displacement device was used to simulate the bridge vibration. The operation of the displacement device was recorded by a digital camera. Hereafter, the deflection distribution was evaluated by model, which was based on Fréchet distance. The results show that the model can be used to evaluate the results obtained using digital image technique.

2. Devices and methods

2.1. Displacement device

The displacement device simulating the bridge vibration process was composed of the motorized linear stage, LED target and computer (Figure 1). The motorized linear stage is a positioning device providing high precision linear motion with minimized runout. This behaviour is critical to the success of simulation. The LED target is fixed on the stage.

![Figure 1. Displacement device](image)

2.2. Dynamic deflection curves

As dynamic load test was performed to measure the dynamic deflection of the bridge, which was a prestressed continuous small box girder bridge with the span of 20 meters, the dynamic response of
the structure under forced vibration was recorded. The load of moving vehicles would cause vibration, shock, and dynamic response.

A car drove through the bridge at a speed of 40 km/h without any obstacles. Arranging the strain measuring points in the control sections to measure the dynamic strain of the bridge structure under dynamic loads. The testing data about the strain collected automatically by strain gauges, data acquisition instrument and computers. Dynamic strain on the experimental process, the dynamic vertical deflection signal was recorded, sorted, and data was analysed to determine the dynamic vertical deflection of the bridge structure under traffic loads. One of the measured dynamic deflection curves is shown in Figure 2.

![Figure 2. dynamic deflection curve](image)

2.3. Dynamic Measurement Capability Assessment Model
The Fréchet distance is a popular and widespread distance measure for point sequences and for curves [16]. Suppose two-tuple \((S, d)\) is a metric space, and \(d\) is the metric function of \(S\). The mapping \(\gamma: [0,1] \rightarrow S\) in unit interval \([0, 1]\) is continuous mapping, then \(\gamma\) is continuous curve in \(S\). If \(\tau: [0,1] \rightarrow [0,1]\) subject to three conditions: (1) \(\tau\) is continuous. (2) \(\tau\) is non-descending. (3) \(\tau\) is surjection. This implies that \(\tau\) is the reparameterized function of unit interval \([0, 1]\), and \(\tau(0) = 0, \tau(1) = 1\).

During the calibration of the photogrammetric bridge deflection measurement system. The dynamic deflection curve measured by the laser interferometer is called the standard curve, and the dynamic deflection curve measured by the photogrammetric bridge deflection measurement system is called the detected curve. Suppose the standard curve \((sc)\) and the detected curve \((dc)\) are the continuous curves in \(S\). And \(SC: [0,1] \rightarrow S\), \(DC: [0,1] \rightarrow S\), then the Fréchet distance between standard curve and detected curve defined as \(F(sc, dc) = \inf_{\tau \in [0,1]} \max_{t \in [0,1]} \left\{ d\left( sc(SC(t)), dc(DC(t)) \right) \right\}\), \(d\) is the metric function of \(S\). It is shown in Figure 3.
3. Results and discussion

The photogrammetric bridge deflection measuring instruments were products of BIOET, which were used to carry out the measurement experiment (As is shown in Figure 4).

The error of indication of maximum dynamic deflection were calculated by $\frac{|SC_{\text{max}} - DC_{\text{max}}|}{SC_{\text{max}}} \times 100\%$, where $SC_{\text{max}}$ is the maximum dynamic deflection of the standard curve, $DC_{\text{max}}$ is the maximum dynamic deflection of the detected curve. In order to facilitate the analysis, the results of Fréchet distances was normalized.

The results presented in Figure 5 and Table 1 show that DC2 is more deviated from SC than DC1, the maximum dynamic deflection of DC4 appears at the end of the curve, and DC3 has the lowest similarity to SC. Fréchet distances accurately reflects the relationship between the curves. The Fréchet distance between DC1 and SC is smaller than the Fréchet distance between DC2 and SC. Fréchet distance between DC3 and SC is the maximum. However, the error of indication of DC2 is smaller than DC1. The error of indication between DC1 and SC is similar to the error of indication between DC4 and SC. This indicates that the error of indication cannot present the situation of the curves accurately.
Figure 5. The experiment results

Table 1. The experiment results

| Detected curve | Error of indication (maximum dynamic deflection) | Fréchet distance (normalization) |
|----------------|-----------------------------------------------|----------------------------------|
| DC1            | 0.624%                                         | 1                                |
| DC2            | 0.163%                                         | 1.69                             |
| DC3            | 0.976%                                         | 3.48                             |
| DC4            | 0.608%                                         | 2.70                             |

The Fréchet distance is a curve comparison method rather than the error of indication, which indicates point-to-point comparison. As the Fréchet distance was better suited for comparing results on their intrinsic structure, the Fréchet distance and its variants can be used to compare the results obtained by photogrammetry technique and displacement device.

4. Conclusion
A dynamic calibration system for photogrammetric measurement of bridges was designed based on the motorized linear stages. And this system can calibrate the dynamic deflection measurement ability of photogrammetric bridge deflection measurement system.

Fréchet distance can reflect the relationship between the curves more accurately than the error of indication of maximum dynamic deflection. Compared to the error of indication, Fréchet distance is of more practical significance. All the work have built a solid base for more dynamic deflection test.

5. Acknowledgements
This work is supported by the Standardization Project of MOT (No. 2016-04-37) and Central Public-interest Scientific Institution Basal Research Fund (No.2017-9061). We thank Hongbo Guo for help with experiments.

References
[1] Yoneyama S, Kitagawa A, Iwata S, et al. BRIDGE DEFLECTION MEASUREMENT USING DIGITAL IMAGE CORRELATION[J]. Experimental Techniques, 2007, 31(1):34–40.
[2] Nassif H H, Gindy M, Davis J. Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration [J]. Ndt & E International, 2005, 38(3): 213-218.
[3] Guan S, Rice J, Li C, et al. Bridge deflection monitoring using small, low-cost radar sensors[C]//Structures Congress 2014. 2014: 2853-2862.
[4] Jiang R, Jauregui D V. Development of a digital close-range photogrammetric bridge deflection measurement system [J]. Measurement, 2010, 43(10): 1431-1438.
[5] Chen X, Chang C C. In-plane motion measurement by using digital sampling moiré method[C]//Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2016. International Society for Optics and Photonics, 2016, 9803: 980311.

[6] Tomita D, Murata Y, Fujigaki M. 3D Displacement Distribution Measurement Using Sampling Moire Method with Multiple Cameras[C]//Emerging Challenges for Experimental Mechanics in Energy and Environmental Applications, Proceedings of the 5th International Symposium on Experimental Mechanics and 9th Symposium on Optics in Industry (ISEM-SOI), 2015. Springer International Publishing, 2017: 187-194.

[7] Sithole G, Vosselman G. Bridge detection in airborne laser scanner data [J]. ISPRS Journal of Photogrammetry and Remote Sensing, 2006, 61(1): 33-46.

[8] Truong-Hong L, Laefer D F. Using Terrestrial Laser Scanning for Dynamic Bridge Deflection Measurement[C]//IABSE Istanbul Bridge Conference, Istanbul, Turkey, 11-13 August 2014. 2014.

[9] Miyashita T, Ishii H, Fujino Y, et al. Clarification of the effect of high-speed train induced vibration on a railway steel box girder bridge by monitoring using laser Doppler vibrometer [C]//Proceedings of Third International Conference on Bridge Maintenance, Safety and Management. 2015: 265-267.

[10] De Villiers J. Design and application of an automated system for camera photogrammetric calibration[D]. University of Cape Town, 2015.

[11] ZHOU Zhi-Chun. Research on Automatic Calibration System for Bridge Deflection Instrument [J]. Quality and Technical Supervision Research, 2015(1):32-33.

[12] Xiao Q, Siqi L. Motion retrieval based on dynamic bayesian network and canonical time warping[J]. Soft Computing, 2017, 21(1): 267-280.

[13] Alt H, Godau M. Computing the Fréchet distance between two polygonal curves[J]. International Journal of Computational Geometry & Applications, 1995, 5(01n02): 75-91.

[14] Mizrahi A, Benner E, Katz M J, et al. Comparative analysis of dendritic architecture of identified neurons using the Hausdorff distance metric.[J]. Journal of Comparative Neurology, 2015, 422(3):415-428.

[15] Bromley J, Guyon I, LeCun Y, et al. Signature verification using a" siamese" time delay neural network[C]//Advances in Neural Information Processing Systems. 1994: 737-744.

[16] Bringmann K, Mulzer W. Approximability of the discrete Fréchet distance[J]. Journal of Computational Geometry, 2015, 7(2): 46-76.