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Multi-point displacement monitoring of bridges using a vision-based approach

X.W. Ye[*1], Ting-Hua Yi[2a], C.Z. Dong[1b], T. Liu[1c] and H. Bai[3d]

[1]*Department of Civil Engineering, Zhejiang University, Hangzhou 310058, China*
[2]*School of Civil Engineering, Dalian University of Technology, Dalian 116023, China*
[3]*Tangram Electronic Engineering Co. Ltd., Beijing 100088, China*

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Abstract. To overcome the drawbacks of the traditional contact-type sensor for structural displacement measurement, the vision-based technology with the aid of the digital image processing algorithm has received increasing concerns from the community of structural health monitoring (SHM). The advanced vision-based system has been widely used to measure the structural displacement of civil engineering structures due to its overwhelming merits of non-contact, long-distance, and high-resolution. However, seldom currently-available vision-based systems are capable of realizing the synchronous structural displacement measurement for multiple points on the investigated structure. In this paper, the method for vision-based multi-point structural displacement measurement is presented. A series of moving loading experiments on a scale arch bridge model are carried out to validate the accuracy and reliability of the vision-based system for multi-point structural displacement measurement. The structural displacements of five points on the bridge deck are measured by the vision-based system and compared with those obtained by the linear variable differential transformer (LVDT). The comparative study demonstrates that the vision-based system is deemed to be an effective and reliable means for multi-point structural displacement measurement.

Keywords: structural health monitoring; dynamic displacement; vision-based system; digital image processing technique; pattern matching algorithm

1. Introduction

Long-span bridges are prone to be damaged due to structural vibration caused by operational vehicle loadings and stochastic wind excitations (Li *et al*. 2006). It will bring significant negative effects to structural safety and user comfortability if excessive vibration-induced structural deformations occur (Li *et al*. 2013a, b). In the last three decades, the technology of structural health monitoring (SHM) has been broadly employed to on-line track the structural behaviors (e.g.,

*Corresponding author, Associate Professor, E-mail: cexwye@zju.edu.cn
[a] Professor
[b] MSc Student
[c] MSc Student
[d] Engineer

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acceleration, strain, displacement, etc.) in a continuous and real-time manner and to ensure that the engineering structures are operated in the specified tolerance and safe range (Ni *et al*. 2010, Yi *et al*. 2011, Ni *et al*. 2012, Ye *et al*. 2012, Yi *et al*. 2012, Ye *et al*. 2014). In general, the structural displacement of bridges can be measured by use of contact or non-contact methods. For the contact measurement methods, the structural displacement is usually directly measured by use of the linear variable differential transformer (LVDT), and alternatively is calculated by double integration of recorded acceleration data with appropriate filter selection and baseline correction or by derivation from the strain-deflection relationship based on measured strain time histories. On the other hand, the non-contact measurement methods mainly include the global positioning system (GPS) and the laser Doppler vibrometer (LDV). Relevant investigations on structural displacement measurement by contact or non-contact methods can be found in Nakamura (2000), Kaito *et al*. (2005), Meng *et al*. (2007), Moschas and Stiros (2011), Im *et al*. (2013), Yi *et al*. (2013), Cho *et al*. (2014), Payo and Feliu (2014).

In the past decade, the vision-based technology has gained rapid developments and multitudinous achievements in structural performance and behavior monitoring/measurement (Koch *et al*. 2014). Gales *et al*. (2012) evaluated, validated and used a novel digital image correlation technique to measure the tendon deformation during the high-temperature testing. German *et al*. (2013) proposed a novel vision-enhanced framework for postearthquake inspection. Jeon *et al*. (2014) proposed a vision-based displacement measurement system with a uniquely designed marker to monitor the 6-DOF structural displacement. Kohut *et al*. (2013) presented a comparative study of two noncontact measurement methods, i.e., the vision-based method and the radar interferometer dedicated to the examination of the structural state of civil engineering. Lee *et al*. (2012) introduced an advanced vision-based system for real-time dynamic displacement measurement of high-rise buildings by use of a partitioning method. Li *et al*. (2007) proposed a novel vision-based method to measure the vibration amplitude based on the image motion blur. Liu *et al*. (2014) proposed a complete procedure for automated crack assessment based on the adaptive digital image processing. Mazzoleni and Zappa (2012) presented a vision-based measurement technique for the vertical load estimation in cased of jumping and bobbing crowd. Park *et al*. (2010) proposed a novel vision-based displacement measurement technique by employing a partitioning approach. Poudel *et al*. (2005) presented the method of structural vibration measurement using high-resolution images based on sub-pixel edge identification. Wang and Cuitino (2002) presented the ability of a digital image correlation technique to capture the heterogeneous deformation fields appearing during compression of ultra-light open-cell foams. Wu *et al*. (2014) implemented a vision-based system to monitor the 2D plane vibration of a reduced scale frame mounted on a shaking table.

In the context of bridge engineering, a considerable number of investigations on structural monitoring and condition assessment by use of the vision-based system have been carried out (Winkler *et al*. 2014). Ye *et al*. (2013) developed a vision-based dynamic displacement measurement system by use of the digital image processing technology which is feature by its distinctive characteristics in non-contact, long-distance, and high-precision structural displacement measurement. Santos *et al*. (2012) introduced a vision-based measurement system suitable for structural monitoring of long-span bridges. Adhikari *et al*. (2014) proposed a method for automating the condition rating prediction of bridges by analyzing the digital images. Zaurin and Catbas (2010) addressed a method by integrating video images with sensor data for safety monitoring of bridges. Busca *et al*. (2014) proposed a vision-based technique to measure both the static and dynamic responses of bridges due to the train pass-by. Jauregui *et al*. (2003) conducted an investigation of vertical deflection measurement of bridges using the digital close-range terrestrial photogrammetry. Ho *et al*. (2013) developed an efficient image-based damage detection system for automatically identifying the damage to the cable surface of the cable-stayed bridge using the image processing technique and pattern recognition. Ribeiro *et al*. (2014) described the development of a non-contact dynamic displacement measurement system for railway bridges based on the video technology. Lee and Shinozuka (2006) proposed a vision-based system for remotely measuring the dynamic displacement of bridges in real-time by use of the digital image processing technique. This paper presents a methodology for multi-point structural displacement measurement with the vision-based system, and the effectiveness of the proposed method is validated through experimental study of vision-based multi-point displacement measurement for a scale arch bridge model.

2. Vision-based method for displacement measurement of multiple points

2.1 Multi-point pattern matching and localization procedure

The methodology of digital image processing is the core theoretical basis of the vision-based structural displacement measurement. As an effective means for digital image processing, the pattern matching algorithm is capable of effectively locating the target in an image that matches a predefined pattern. In the process of multi-point structural displacement calculation with a pattern matching algorithm, the patterns with identifiable targets in an original image are established which will be employed to match the subsequent images captured by the digital camera, and the scores on the basis of the pattern matching algorithm will be calculated. When these scores reach the maximum values, it indicates that the patterns best correspond with the targets in the original image and meanwhile the target positions are identified (Gonzalez and Woods 2008). Fig. 1 illustrates the flowchart of multi-point structural displacement measurement by use of the pattern matching algorithm. Firstly, the initial image containing the targets on the structure is captured by the digital camera, and the patterns with the initial pixel coordinates are obtained from the acquired image. Then, the process of pattern matching is continuously performed between the predefined patterns and the succeeding images captured by the digital camera. Based on the correlation computation (Ye *et al*. 2013), the normalized correlation coefficients are calculated during the movement of the patterns within the image areas. The pixel coordinates of the target positions are achieved when the normalized correlation coefficients attain the maximum values, indicating that the patterns best match the images at the designated locations. Subsequently, the offsets of the targets in the pixel coordinate system are acquired by subtracting the pixel coordinates at the identified locations with the initial pixel coordinates. Finally, the structural displacements of multiple points are derived by the obtained coordinate offsets and the scale ratios between the actual sizes of the patterns and the pixels of the patterns in the images.

2.2 Description of vision-based displacement measurement system

In this study, a commercialized vision-based system (ISM-VG4-PRO) developed by Imetrum Limited, UK is used for measurement of multi-point structural displacements (McCormick *et al*. 2014). As shown in Fig. 2, this system mainly consists of a digital camera with the resolution of

1024 pixels (horizontal) × 768 pixels (vertical), a lens with the focal length of 25 mm, a data acquisition device, and a computer installed with the customized software. In the process of structural displacement measurement, the image data continuously acquired by the digital camera are transmitted through the Gigabit Ethernet standard LAN wire from the digital camera to the computer via the data acquisition device, and promptly analyzed and managed by the customized software incorporated with the advanced digital image processing algorithms.

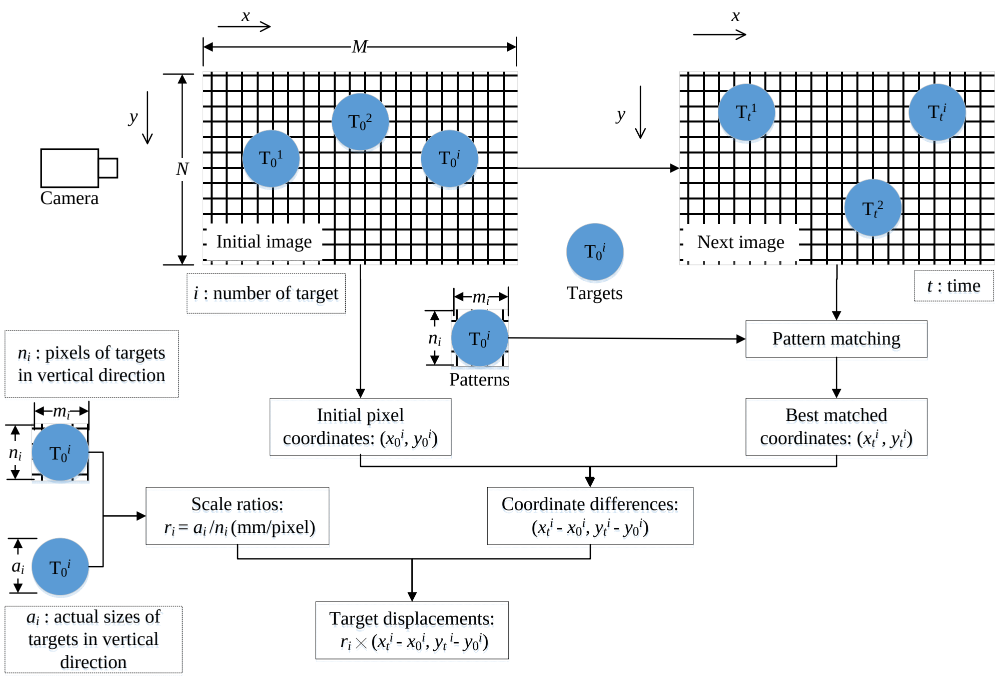


Fig. 1 Flowchart of vision-based multi-point displacement measurement

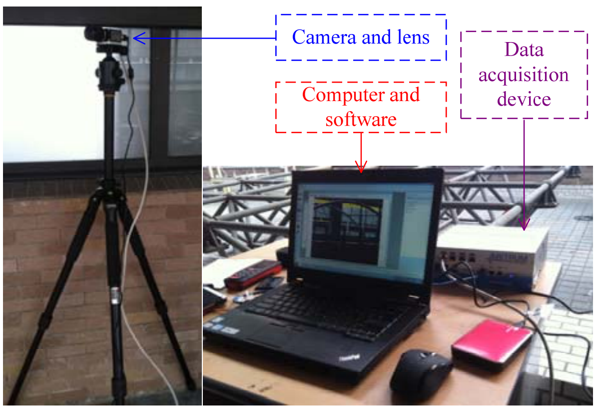
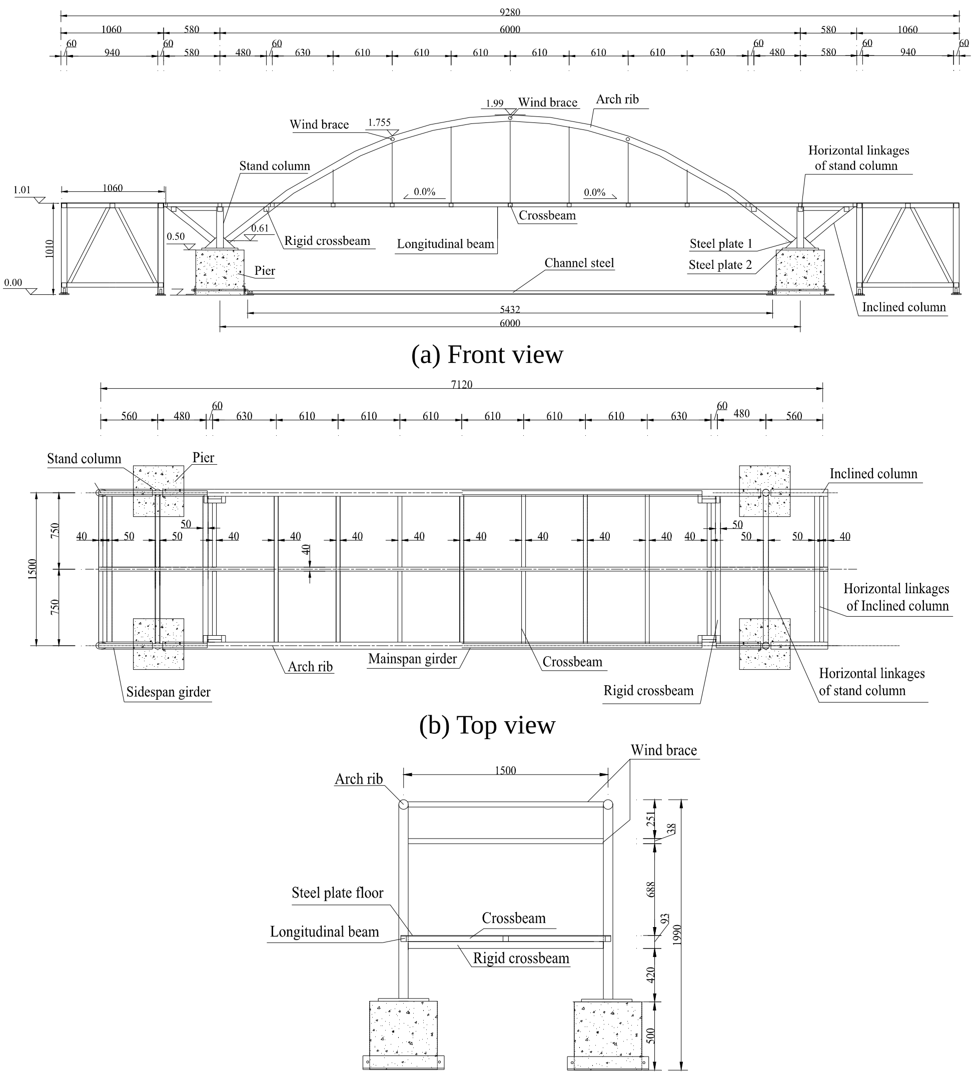


Fig. 2 Vision-based system for multi-point displacement measurement

3. Design and implementation of scale arch bridge model

An experimental education platform of bridge health monitoring has been implemented in the Department of Civil Engineering, Zhejiang University, China. This teaching demonstration platform aims at cultivating the creativity and practical capability of the undergraduate and postgraduate students majored in bridge engineering and promoting the SHM technology to the students being interested. To this goal, a half-through steel-tube arch bridge with a main span of 6 m and a deck width of 1.5 m has been designed and fabricated as a scale model testbed. The technical drawings of the scale arch bridge model are illustrated in Fig. 3.



(a) Front view

(b) Top view

(c) Side view

Fig. 3 Technical drawings of scale arch bridge model (Unit: mm)

Fig. 4 Photos of scale arch bridge model

For this scale arch bridge model, two main arch ribs with a rise-to-span ratio of 4.21 are made by seamless circular tubes with a diameter of 70 mm and a wall thickness of 5 mm. The longitudinal beams and crossbeams of the bridge deck system are assembled by rectangular steel tubes. There are three longitudinal beams installed in the bridge deck system, and two side ones are supported at the junction of the arch ribs by the rigid crossbeams whose ends are welded on the arch ribs. The length of the crossbeam in the longitudinal direction is 610 mm, and the distance between the rigid crossbeam on the arch ribs and the adjacent crossbeam is 692 mm. The bridge deck is overhanged by suspenders which are made of steel wire ropes with a diameter of 3 mm. 7 pairs of suspenders whose ends are anchored to the arch ribs and the side longitudinal beams are installed symmetrically with respect to the midspan. For convenience of disassembility and installation, three transverse wind braces are installed at the vault and quarter points to ensure the lateral stability and stiffness of the scale arch bridge model, which are made of seamless steel tubes with a diameter of 38 mm and a wall thickness of 4 mm. Two stand columns and two inclined columns bracings which are connected by the rectangular steel tubes with a side length of 40 mm and a wall thickness of 4 mm are installed at the arch foot as the transition between the deck system and the platform. The material of all the steel tubes is grade Q345. Fig. 4 shows the photos of the established scale arch bridge model.

4. Experimental study of vision-based multi-point displacement measurement

4.1 Instrumentation and loading conditions

Two rail tracks are set on the deck surface of the scale arch bridge and a self-made test bogie is fabricated and used to simulate the moving loadings alike the highway traffic on the real bridge. Apart from the self-weight of the test bogie (5 kg), the steel blocks with a known mass can be imposed on the test bogie to be as the additional weight during the moving loading experiments, and also the velocity of the test bogie can be adjusted. Table 1 lists the loading conditions for the moving loading experiments with different loading masses and velocities of the bogie. During the moving loading experiments, the bogie moves through the deck of the scale arch bridge from the west side to the east side.

Table 1 Loading conditions for moving loading experiments

Loading scenario	Loading mass (kg)	Bogie’s velocity (m/s)
Case 1	105	0.24
Case 2	105	0.48
Case 3	205	0.24
Case 4	205	0.48

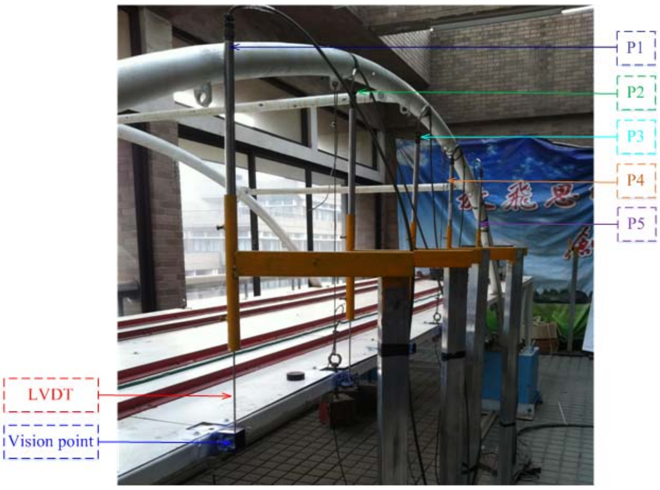


Fig. 5 Deployment of vision points and LVDTs

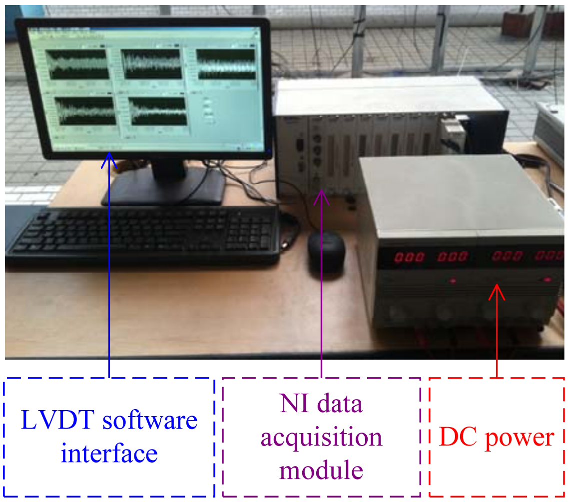


Fig. 6 Data acquisition system for LVDT

In this study, five points on the scale arch bridge are chosen for quasi-distributed structural displacement measurement. To verify the accuracy and effectiveness of the vision-based displacement measurement system, the multi-point structural displacements of the bridge deck are simultaneously measured by the vision-based displacement measurement system and the conventional contact-type electrical displacement sensor, i.e., LVDT with the same sample rate being 100 Hz. Fig. 5 illustrates the deployment of the vision points for the vision-based displacement measurement system and the LVDTs. Fig. 6 shows the data acquisition system for the LVDT.

4.2 Statistical analysis of test results

Figs. 7-10 illustrate the measured displacement time histories by the vision-based system and the LVDT for cases 1~4. It is seen from Figs. 7-10 that the structural displacements measured by the vision-based system are matched well with those measured by the LVDT for all the cases. The amplitudes of the measured structural displacements are changed with different loading masses and velocities of the bogie, while all of the gained curves are smooth with similar shapes. It should be noted that the bogie moves through the deck of the scale arch bridge from the west side to the east side for all the moving loading experiments. In this connection, the sequence of the structural displacement reaching the maximum value is appearing from P5 to P1 for all the cases, and the structural displacement of the measurement point increases when the bogie is approaching and decreases when it is departing.

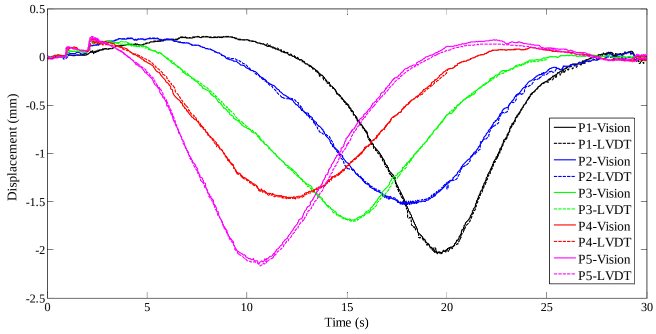


Fig. 7 Measured displacement time histories by vision-based system and LVDT (Case 1)

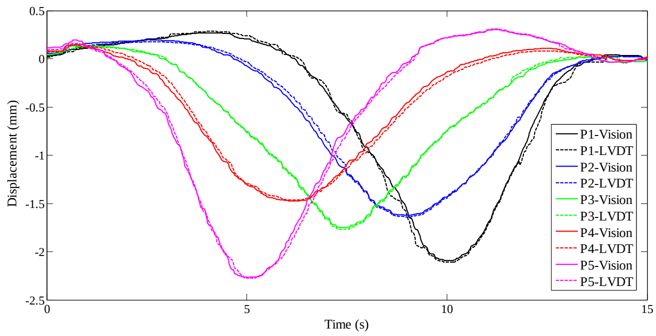


Fig. 8 Measured displacement time histories by vision-based system and LVDT (Case 2)

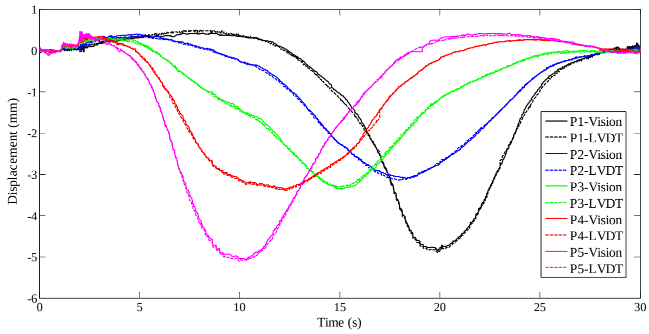


Fig. 9 Measured displacement time histories by vision-based system and LVDT (Case 3)

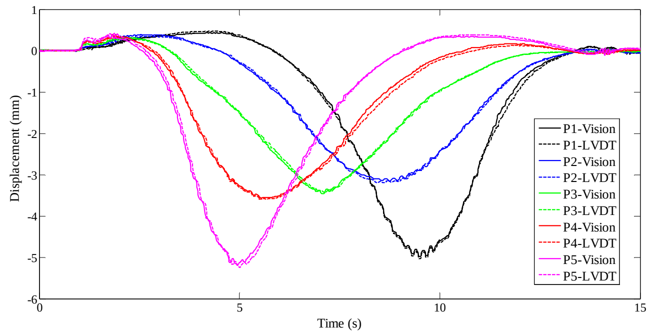


Fig. 10 Measured displacement time histories by vision-based system and LVDT (Case 4)

Table 2 Statistical analysis of measured displacement results (Unit: mm)

Case	Point	V_{max}	L_{max}	$D_{max\text{-}pct}$	d_{max}	$\overline{d}$	RMSE
1	P1	2.0379	2.0401	0.11%	0.0881	0.0116	0.0116
	P2	1.5338	1.5185	1.01%	0.0649	0.0154	0.0148
	P3	1.6915	1.7023	0.63%	0.0795	0.0118	0.0119
	P4	1.4626	1.4772	0.99%	0.0892	0.0130	0.0133
	P5	2.1410	2.1681	1.25%	0.0955	0.0270	0.0180
2	P1	2.0903	2.1112	0.99%	0.1685	0.0270	0.0306
	P2	1.6215	1.6377	0.99%	0.1037	0.0219	0.0200
	P3	1.7495	1.7670	0.99%	0.0621	0.0113	0.0096
	P4	1.4747	1.4642	0.72%	0.0941	0.0291	0.0194
	P5	2.2666	2.2764	0.43%	0.1226	0.0254	0.0269
3	P1	4.8497	4.8982	0.99%	0.1588	0.0461	0.0316
	P2	3.0960	3.1423	1.47%	0.1007	0.0257	0.0190
	P3	3.3648	3.3147	1.51%	0.1015	0.0285	0.0217
	P4	3.3653	3.3990	0.99%	0.1983	0.0246	0.0280
	P5	5.0718	5.1098	0.74%	0.1495	0.0327	0.0255
4	P1	4.9859	5.0358	0.99%	0.2954	0.0387	0.0394
	P2	3.1514	3.1961	1.40%	0.1387	0.0281	0.0228
	P3	3.4544	3.4201	1.00%	0.1469	0.0247	0.0242
	P4	3.5605	3.5961	0.99%	0.2138	0.0472	0.0409
	P5	5.1760	5.2438	1.29%	0.3103	0.0551	0.0500

Table 2 gives the obtained results through the statistical analysis of the structural displacement measured by the vision-based displacement measurement system in reference to the LVDT. The maximum displacement obtained by the vision-based system and the LVDT are represented by V_{max} and L_{max}, respectively. The percentage of the difference of the maximum displacement, $D_{max\text{-}pct}$, the maximum displacement difference, d_{max}, the average displacement difference, $\bar{d}$, and the root-mean-square error (RMSE) of the displacement are calculated by

$$V_{\max} = \max\left(\left|V_i\right|\right) \tag{1}$$

$$L_{\max} = \max\left(\left|L_i\right|\right) \tag{2}$$

$$D_{\max\text{-pct}} = \left|V_{\max} - L_{\max}\right| / L_{\max} \tag{3}$$

$$d_{\max} = \max\left(\left|d_i\right|\right) = \max\left(\left|V_i - L_i\right|\right) \tag{4}$$

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n}\left|d_i\right| = \frac{1}{n}\left[\left|V_1 - L_1\right| + \left|V_2 - L_2\right| + \cdots + \left|V_n - L_n\right|\right] \tag{5}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(V_i - L_i\right)^2}{n}} \tag{6}$$

where V_i is the structural displacement measured by the vision-based system, and L_i is the structural displacement measured by the LVDT.

5. Conclusions

In this study, the methodology for multi-point structural displacement measurement by use of the vision-based technology was introduced. Laboratory experiments were conducted to investigate the accuracy and effectiveness of the vision-based system in measuring multi-point structural displacements. A scale arch bridge model was designed and fabricated to be a testbed and five points on the bridge deck were selected to deploy the vision points. The moving loading experiments were carried out under different loading masses and velocities of the bogie. The structural displacement results measured by the vision-based system were compared with those obtained by the LVDT, and the comparative study reveals that the vision-based system is deemed to be a reliable and robust means for multi-point structural displacement measurement. In the further study on this issue, the effect of the difference of the operation condition for the vision-based system on the measurement accuracy and reliability will be comprehensively examined such as the working distance between the vision-based system and the target structure, the day and the night, sunny weather and foggy day, etc. Furthermore, for the field measurement of the structural displacement using the vision-based system, it should take into account the inclination between the digital camera and the target point, the settlement of the ground supporting the camera tripod, and the jiggle of the digital camera due to the ambient vibration.

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