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Monitoring of structural dynamic behaviors by vision-based system

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ABSTRACT

In this study, a vision-based method for monitoring of structural dynamic behaviors is presented. With the aid of digital image processing technique and multi-point pattern matching algorithm, an integrated system for monitoring of structural dynamic behaviors is developed. A comparative study of vibration monitoring and dynamic characteristics identification is conducted with the vision-based displacement measurement system and the acceleration measurement system synchronously. The experimental results demonstrate that the structural dynamic indicators analyzed by the proposed vision-based system and the acceleration measurement system are quite consistent, which validates the feasibility of the proposed method for monitoring of structural dynamic behaviors by vision-based system.

1. INTRODUCTION

Civil engineering structures are prone to vibrate under the external stochastic loadings (e.g., wind, earthquake, and traffic), which will result in fatigue damage and cracking in critical structural components. Monitoring of the structural dynamic behaviors is very useful to update the structural model, build the damage identification method, and establish the vibration control strategy. Structural vibration monitoring and dynamic characteristics identification have been one of the most important tasks within the field of structural health monitoring (SHM).

For the traditional structural dynamic monitoring, the accelerometers are usually fixed on the structures to acquire the vibration signals under the artificial or ambient excitations. With the acceleration time history signals, the structural dynamic characteristics can be obtained. Chen et al. (2009) proposed a wavelet-based method for identification of damping ratios and natural frequencies of structures with accelerometers. Ubertini et al. (2014) identified the natural frequencies of a reinforced concrete beam using carbon nanotube cement-based sensors. Cho et al. (2015) presented a wireless-based decentralized system identification procedure by stochastic

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subspace identification. However, the traditional dynamic monitoring methods need to fix sensors on the target structure which will cause the issues of data transmission, power supply, traffic jam, etc.

In recent years, vision-based structural vibration monitoring techniques have been rapidly developed with the development of digital image processing technique and computer science (Fukuda et al. 2010, Ye et al. 2013, Wu et al. 2014, Ye et al. 2015). In this study, a vision-based multi-point structural dynamic displacement measurement method is proposed for structural vibration monitoring and dynamic characteristics identification. Comparative experiments are conducted between the vision-based measurement system and the traditional acceleration measurement system. The results validate the feasibility of the proposed vision-based system in the application of monitoring of structural dynamic behaviors.

2. METHODOLOGY STATEMENT

2.1 Vision-based Measurement of Multi-point Structural Displacements

The multi-point pattern matching algorithm is the kernel theory of the method of vision-based structural dynamic displacement measurement. The actions of pattern matching will quickly locate the concern regions in a grayscale image through matching the known reference patterns, also referred as models or templates, which are created to represent the measurement targets. Patterns with targets are predefined and then they will be selected to match the subsequent images captured by the digital camera. Scores on the basis of multi-point pattern matching algorithm will be calculated. When scores of the matching tasks 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).

As illustrated in Fig. 1, the sub-images which are chosen to be the patterns $f_k(x, y)$ with the sizes of $m_k \times n_k$ within an image $g^t(x, y)$ with an size of $M \times N$, where k is the number of the patterns and t is the time at which the image is captured. The initial coordinate of the center point of $f_k(x, y)$ is $(x^0{}_k, y^0{}_k)$. The correlation between $f_k(x, y)$ and $g^t(x, y)$ at the point $(i^0{}_k, j^0{}_k)$ is given by

$$c_k(i, j) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f_k(x, y) g^t(x + i, y + j) \tag{1}$$

where $i = 0, 1, ..., M\text{-}1$ and $j = 0, 1, \ldots, N$. The summation is taken over the region in the image where $f_k(x, y)$ and $g^t(x, y)$ are overlapped. Assuming that the origin of the image $g^t(x, y)$ is at the top left corner, the correlation is the process of moving the templates or sub-images $f_k(x, y)$ around the image area and computing the values $c_k(i, j)$. This involves multiplying each pixel in the templates by the overlapped image pixels and then summing the results over the pixels of the templates. The maximum value of $c_k(i, j)$ indicates the position where $f_k(x, y)$ best matches $g^t(x, y)$, and the coordinate of the center point of the overlap part is $(x^t{}_k, y^t{}_k)$.

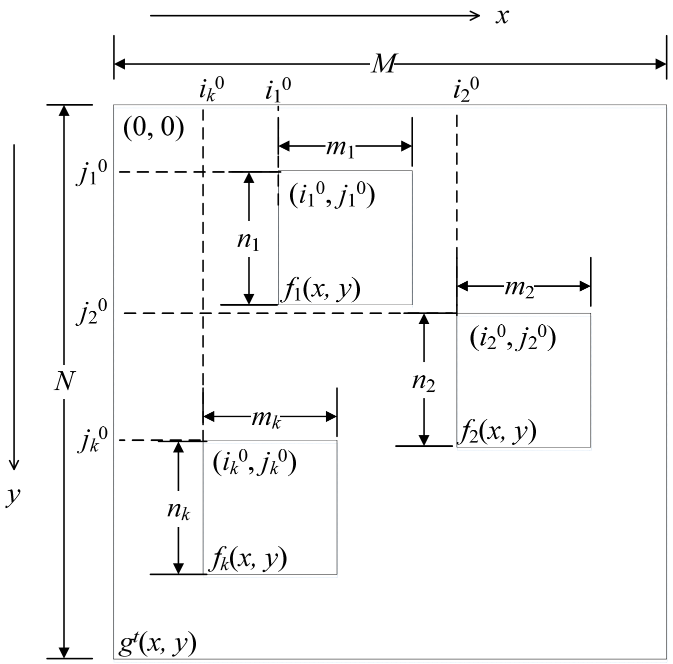


Fig. 1 Correlation between patterns and captured images

If there are h pixels in the vertical direction of the target in the image and the actual size of the target in the vertical direction is H, the scale ratio, r, will be calculated by

$$r = \frac{H}{h} \tag{2}$$

With the initial coordinate of the center point of the pattern, $(x^0{}_k, y^0{}_k)$, and the coordinate of the center point of the overlapped part $(x^t{}_k, y^t{}_k)$, when the pattern is best matched with the image captured at the time of t, the horizontal displacement, $x_k(t)$, and the vertical displacement $y_k(t)$, of the kth target can be derived by

$$\begin{bmatrix} x_k(t) \\ y_k(t) \end{bmatrix} = r \begin{bmatrix} x_k^t & x_k^0 \\ y_k^t & y_k^0 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ -1 & -1 \end{bmatrix} \tag{3}$$

2.2 Displacement-based Identification of Structural Dynamic Characteristics

In the process of structural dynamic characteristics identification based on displacement time history signals, it needs to set vision points as the measurement targets in advance. Then a random transient excitation is imposed on the structural component and the data acquisition device records the displacements of the vision targets during the whole vibration process of the structural component. When the vibration stops, the displacement time history of the kth measurement point is obtained which is denoted as $x_k(t)$.

To minimizing the leakage caused by transformation from the time domain to the frequency domain, the weighting function (windowing) is used to process the displacement time history. The Fourier spectrum, $Y_i(f)$, the amplitude spectrum, $|Y_i(f)|$, and the imaginary part spectrum, $\mathrm{Im}[Y_i(f)]$ are obtained after fast Fourier transform (FFT), where f is the frequency.The peak values in the amplitude spectrum are consistent with the order of the modes. The lth peak denotes the lth order mode of the structure. The horizontal coordinate of the peak represents the frequency of the lth order mode. The vertical coordinate of the peak dominates the vertical coordinate of the modal shape. The sign of the amplitude of each measurement point is determined by the imaginary part spectrum. For the lth order modal shape, the horizontal coordinate of the kth measurement point, $S_k(f_l)$ will be derived, which is defined as

$$S_k(f_l) = \begin{cases} |X_k(f_l)|, \ \mathrm{Im}[X_k(f_l)] > 0 \\ 0, \ \mathrm{Im}X_k(f_l) = 0 \\ -|X_k(f_l)|, \ \mathrm{Im}[X_k(f_l)] < 0 \end{cases} \tag{4}$$

Then, the lth order modal coordinate of the kth measurement point, $(y_k, S_k(f_l))$ can be obtained, where y_k is the location of the kth measurement point. In addition, at the supporting point, the vertical coordinate of the modal shape is zero. The lth modal shape is formed with the lth modal coordinates of all the measurement points and the supporting points.

3. EXPERIMENTAL VERIFICATION

3.1 Vision-based Measurement System and Experimental Setup

As illustrated in Fig. 2, the vision-based structural dynamic displacement measurement system consists of a high-resolution industrial charge-coupled-device (CCD) digital camera, an extended-range zoom lens, a Gigabit Ethernet standard local area network (LAN) wire, a computer and a suite of software. The system measurement accuracy is dependent on the resolution of the CCD digital camera and the distance between the digital camera and the target on the structure. In this study, the CCD camera is Prosilica GE1050 manufactured by the Allied Vision Technologies Company in Germany. Its resolution is 1024 × 1024 pixels and the maximum frame rate is 59 FPS.

A vertical steel bar simulating the bridge tower is fabricated as shown in Fig. 2. The height of the steel bar is 1.5 m with the cross section size of 4 mm × 30 mm. The density of the steel bar is 7800 kg/m^3 and the Young's modulus is 195 GPa. In this study, a comparative study of vibration monitoring and dynamic characteristics identification is conducted with the vision-based measurement system and the acceleration measurement system. Three measurement points (P1, P2 and P3) are set on the steel bar. An LED lamp and an accelerometer are fixed on each measurement point for synchronously recording vibration signals of the steel bar.

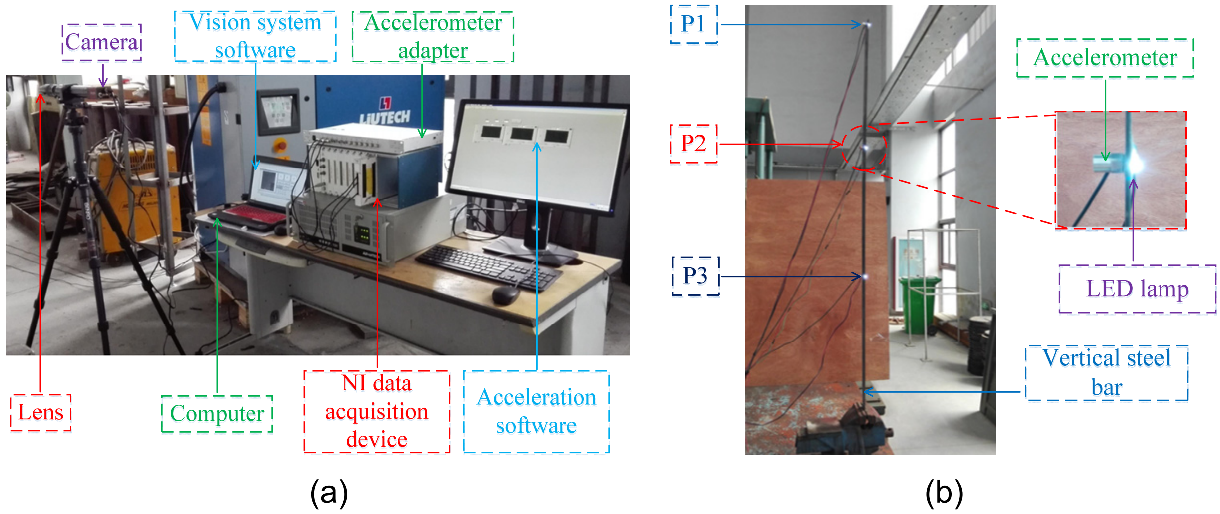


Fig. 2 Layout of experimental setup: (a) vision-based system and acceleration system; (b) vertical steel bar and sensor deployment points

3.2 Analysis of Experimental Results

A random transient excitation is imposed on the vertical steel bar. Two kinds of data acquisition systems (vision-based system and accelerometer system) record the signals along with the attenuation of vibration of the steel bar. Figs. 3~5 and Figs. 6~8 show the measurement and analysis results of the three measurement points obtained by the vision-based system and the acceleration system, respectively.

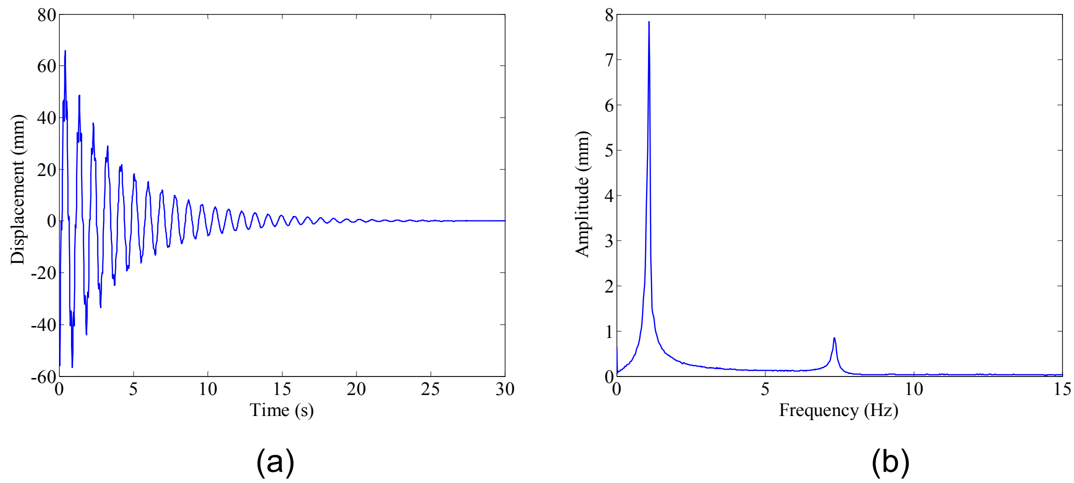
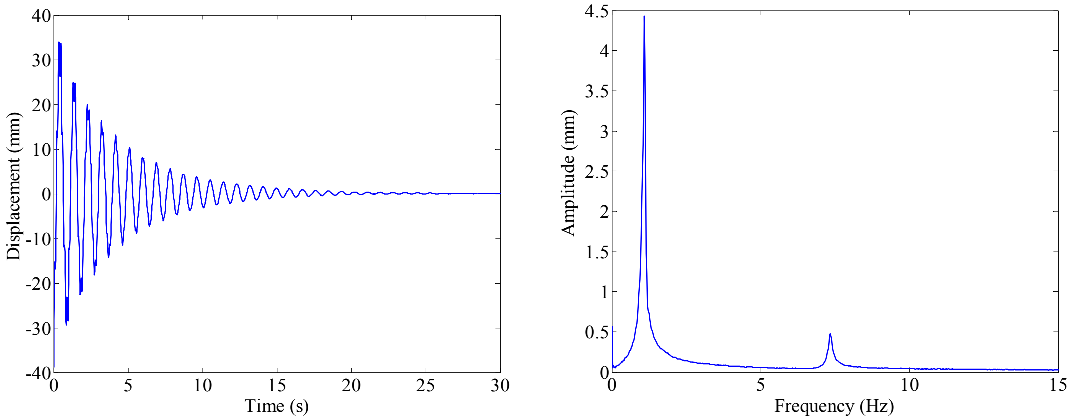
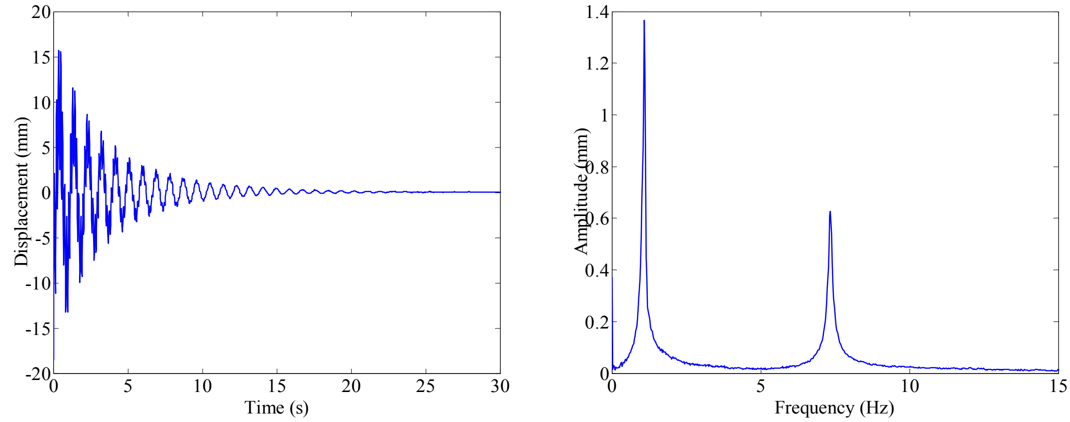


Fig. 3 Results of P1 obtained by vision-based system: (a) displacement time history; (b) FFT spectrum



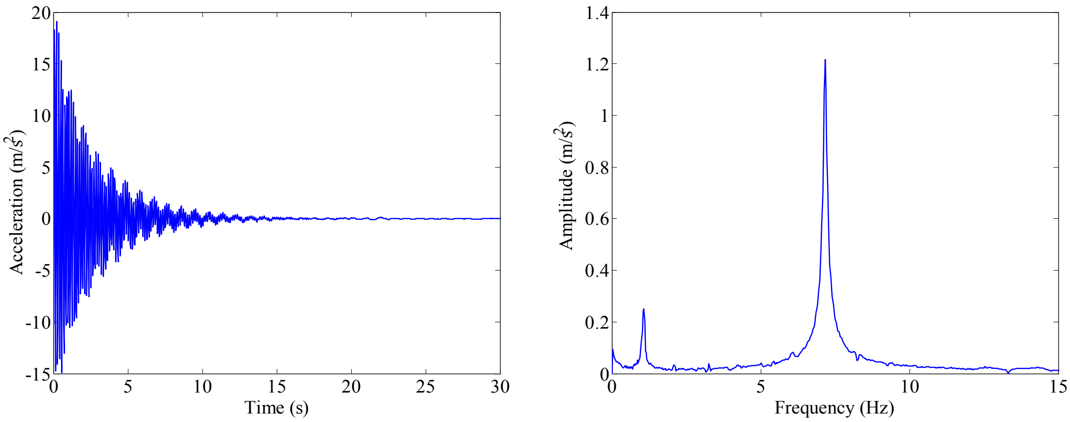
(a) (b)

Fig. 4 Results of P2 obtained by vision-based system: (a) displacement time history; (b) FFT spectrum



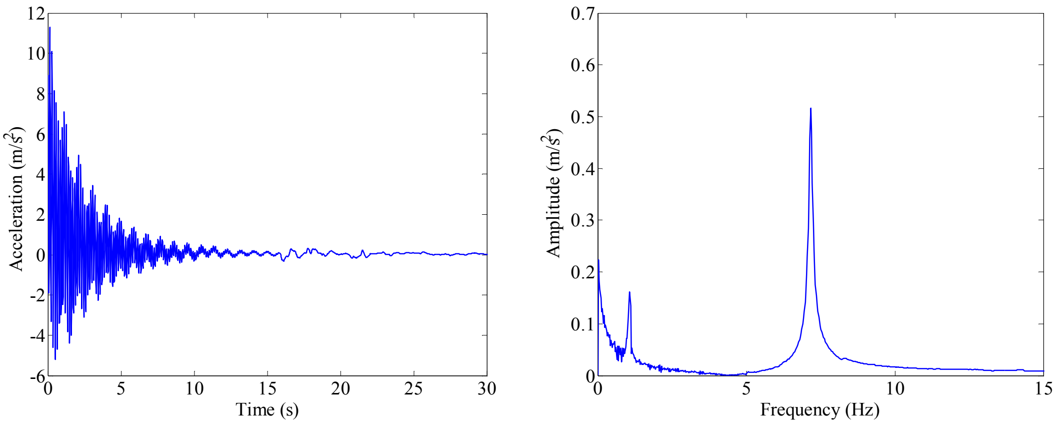
(a) (b)

Fig. 5 Results of P3 obtained by vision-based system: (a) displacement time history; (b) FFT spectrum



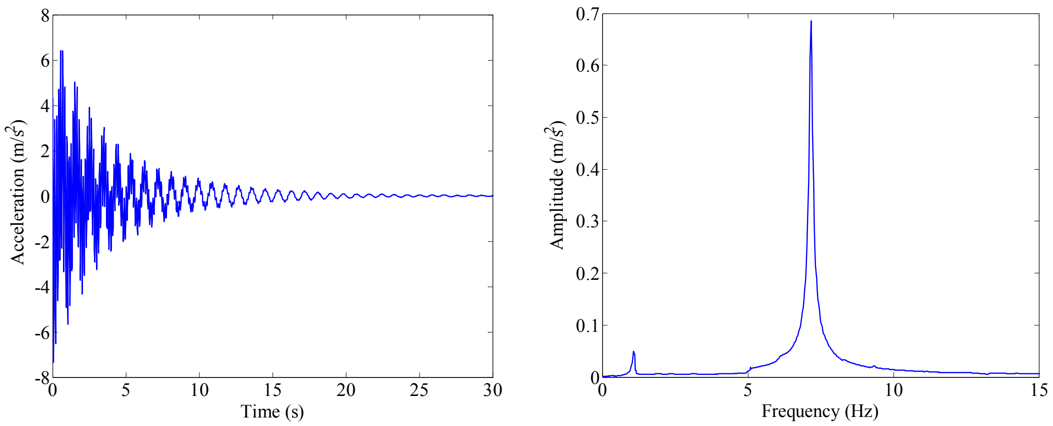
(a) (b)

Fig. 6 Results of P1 obtained by acceleration system: (a) acceleration time history; (b) FFT spectrum



(a) (b)

Fig. 7 Results of P2 obtained by acceleration system: (a) acceleration time history; (b) FFT spectrum



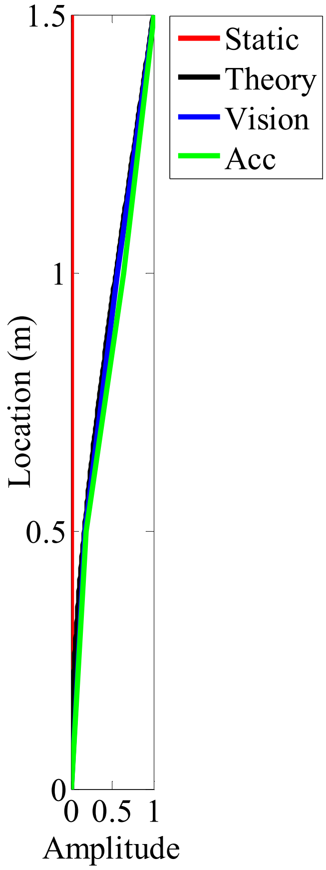
(a) (b)

Fig. 8 Results of P3 obtained by acceleration system: (a) acceleration time history; (b) FFT spectrum

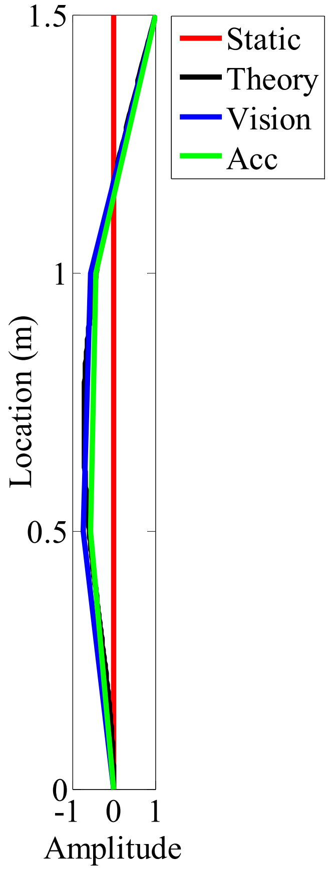
Tab. 1 illustrates the first two modal frequencies of the vertical steel bar analyzed by the vision-based system, the acceleration system, and the theory solution. The modal shapes are obtained by picking the peaks of the FFT spectrum and using the phase relationship among the modes. Fig. 9 illustrates the first two modal shapes obtained by the vision-based system (blue line), the acceleration system (green line), and the theory solution (black line) (Clough and Penzien 2003). The modal shapes analyzed by the vision-based system are consistent with those by the acceleration system and the theory solution, indicating that the vision-based system is feasible in the application of structural dynamic characteristics identification.

Table 1 Comparative study of modal frequency

Modal frequency	Theory solution (Hz)	Vision-based system (Hz)	Acceleration system (Hz)
1st order	1.414	1.095	1.078
2nd order	8.200	7.351	7.170



(a)



(b)

Fig. 9 Comparative analysis of modal shapes: (a) first mode; (b) second mode

4. CONCLUSIONS

In this paper, a vision-based structural dynamic displacement measurement method is proposed. A vertical steel bar is fabricated for monitoring of the structural dynamic behaviors by the vision-based system and the traditional acceleration system. Results of the comparative study show that the vision-based system can monitor the dynamic displacement of multiple points in a noncontact manner. It is also demonstrated that the dynamic characteristics (frequency and modal shape) analyzed by the vision-based system and the acceleration system are consistent quite well. In the near future, additional field experiments will be carried out for research of the effect of the environmental factors on the system performance.

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