Vision-Based Measurement System for Structural Vibration Monitoring and Damage Detection

Jianfeng Zhong and Shuncong Zhong

Abstract A vision-based measurement system for vibration monitoring was proposed by using a non-projection fringe pattern. The designed artificial fringe pattern was similar to the interferogram of 2D-OCVT system, which was named as quasi-interferogram fringe pattern (QIFP) and pasted on the surface of a vibrating structure. A high-speed CMOS camera worked as a detector was used to capture the image sequence of the fringe pattern during the structural vibration. The period density of the imaged QIFP changes due to the structural vibration, from which the vibration information of the structure could be obtained. The change of the dynamics parameters of a cracked structure was analyzed by Finite Element Method (FEM), traditional accelerometer-based method and the proposed method using a roving auxiliary mass, from which the frequency shift curves can be obtained. The crack position information can be achieved confidently from the discontinuity of the frequency shift curves owing to the auxiliary mass effect when the mass was located at the crack position. The results demonstrated that the proposed method was an effective and accurate technique to measure structural vibration without introducing extra mass on the tested structure. Significant advantages of the proposed method making the measurement system suitable for vibration monitoring of engineering structures and damage detection of beam structures.

Keywords Vision-based · Vibration measurement · Damage detection · Auxiliary mass · Frequency shift curve

J. Zhong · S. Zhong (✉)
Laboratory of Optics, Terahertz and Non-Destructive Testing,
School of Mechanical Engineering and Automation, Fuzhou University,
Fuzhou 350108, People's Republic of China
e-mail: zhongshuncong@hotmail.com

S. Zhong
Shanghai University, Shanghai, P. R. China

L. Yao et al. (eds.), *Advanced Mechanical Science and Technology for the Industrial Revolution 4.0*, https://doi.org/10.1007/978-981-10-4109-9_22

1 Introduction

One or more of the dynamic properties will change when a structure suffers from damages. Conversely, the damage could be identified using the changes in the structural dynamic response characteristics. Reviews on these issues have been presented by Salawu [1] and Jassim et al. [2]. The most useful damage detection and localization methods are probably those using changes in natural frequencies because frequency measurements can be conveniently conducted, less contaminated by experimental noise and often reliable. Zhong et al. [3–5] proposed an approach based on auxiliary mass spatial probing to provide a method for crack detection in beam-like structure. The key of the method is the precise positioning of the auxiliary mass and accurate identification of the natural frequencies of the test structures from the vibration signals.

Techniques available for vibration measurement can be generally classified as contact and noncontact types. Contact-type sensors usually have limitations in practical applications, such as the physically connection to the structure and extra mass loading on the structure. In recent years, there were many vision-based techniques for non-contact measurement of dynamic deformation or vibration in different industrial areas, in which various physical quantities need to be measured based on two-dimensional sensors like CCD or CMOS camera. Projected-fringe measurement method is a vision-based non-contact whole field optical methodology allowing measurement of surface contour or low-frequency vibration [6, 7]. Since it is based on several phase-shift images to determine the magnitude and phase of the vibrating object, it is suitable for very low-frequency vibration measurement. Motion detection systems [8, 9] based on a COMS image sensor (CIS) were introduced by many researchers, where all or part pixels of the successive images were used for comparison using a complex algorithm.

Recently, the authors proposed 1D- and 2D-optical coherence vibration tomography (OCVT) systems [10–12] offering the possibility of performing high resolution and non-intrusive vibration measurements. The vibration information was obtained from the interferogram that vary with the change of the distance between the surface of a reference mirror and the tested object in the 2D-OCVT system [11]. A non-projection QIFP vibration measurement method similar to the principle of OCVT was proposed in this study, which can realize vibration measurements and damage detection by using QIFP as a sensor and a high-speed CMOS image sensor (CIS) camera as a detector.

2 Theoretical Background

2.1 Principle of the Proposed Method

Figure 1a is an interferogram from the 2D-OCVT system, from which the displacement of the object at the sample arm can be obtained from the change of the fringe density. Taking the concept from the 2D-OCVT system, a quasi-interferogram fringe pattern (QIFP) that looks similar to the real interferogram had been designed, as shown in Fig. 1b. The artificial QIFP was printed by a normal printer. As can be seen from the photograph of experimental device shown in Fig. 1c, the printed QIFP was attached to the surface of the vibrating structure.

Figure 1b is the schematic layout of imaging principle for the QIFP. The high-speed camera was used to record the image sequence of the QIFP during the structure vibrating. Note that the QIFP was imaged in the middle of the sensor and only the fringe scope marked by the blue box was recorded to decrease the image size and save the memory. Subsequently, the video images of the QIFP were digitized in 8-bit grey scales and were streamed into the computer for further processing. The width of the imaged QIFP varies with the change of the object distance between the QIFP and the lens. Consequently, different vibration amplitudes bring about different period densities of the imaged QIFP. The fringe intensities in the middle line of each imaged QIFP were used for the calculation of

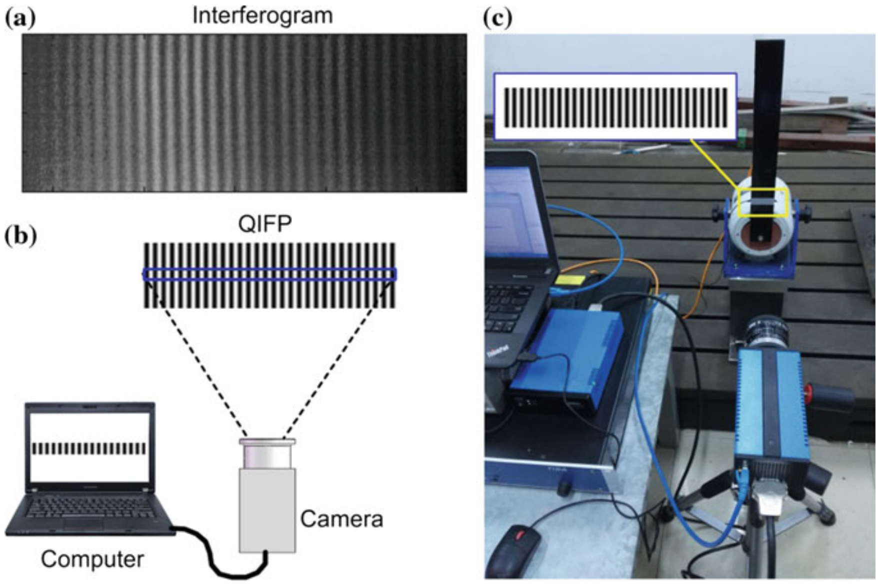

Fig. 1 **a** An interferogram from a 2D-OCVT system; **b** schematic diagram of the vision- and QIFP-based vibration measurement system; and **c** the photograph of the proposed system for dynamic measurement of a beam

the dynamic displacement by applying Fast Fourier Transform (FFT) to them. Subsequently, the real-time displacement can be obtained by combing the main peak of each QIFP-FFT waveform. It should be noted here that the calculation of the period density of the imaged QIFP was corrected using a spectral center correction method (SCCM) [3] to decrease the signal leakage effect of the Fast Fourier Transform (FFT).

According to the imaging principle shown in Fig. 1c, the displacement in time domain can be expressed as

$$\Delta Z(t) = f(1 + L/C_0)[d(t) - d_0]/d_0 \tag{1.1}$$

where f is the focal length of the lens, L is the physical length of the QIFP, C_0 is the length of imaged QIFP as reference that could be calculated from $C_0 = aN_{i,}$ a is the width of the pixel, whilst N_i is the pixels number covered by the QIFP. d_0 and $d(t)$ are the calculated fringe period density of the reference imaged QIFP and the QIFP at time t. Note that the detectable displacement should be smaller than the depth of field of the lens to prevent blurry images.

2.2 *Performance Evaluation of the Vision-Based Quasi-OCVT System*

In the vision-based Quasi-OCVT, the resolution of the camera CMOS image sensor (CIS) is 1024 × 1280 pixels and the pixel size is 12 × 12 μm. During the acquisition, the random distribution of dark current, temporal noise and fixed pattern noise of CIS are the major troublesome issues that will introduce noise on the obtained fringe intensity images and these noise sources will be affected by the illumination condition and the exposure time. The exposure time of the CIS will introduce different level of noise on the imaged fringe intensity, which has significant impact on the performance of the proposed system. In order to estimate the influence of the noise sources on the performance of the Quasi-OCVT and to characterize the measurement accuracy of the proposed system, some simulations were carried out. Normally, the noise of the CIS increases with the decrease of the exposure time. In the simulation, therefore, different levels of noise were added into the fringe intensities of the simulated QIFP series to simulate the noise under different exposure time. Two QIFPs with fringe period density of 10 period/cm (Fig. 2a) and 20 period/cm (Fig. 2b) were considered. The simulated movement was a 20 Hz sine vibration with amplitude of 50 μm. The pixel number for sampling the intensity was 800.

As shown in Fig. 2, the displacements can be correctly obtained if the intensity of the two QIFPs without noise. However, the displacements in Fig. 2a have more noise than that in Fig. 2b when the signal-to-noise ratios of the intensities of the QIFP were 20 and 30 dB. Therefore, the increase of the fringe period density of the QIFP can improve the measurement accuracy when the noise level of the CIS was

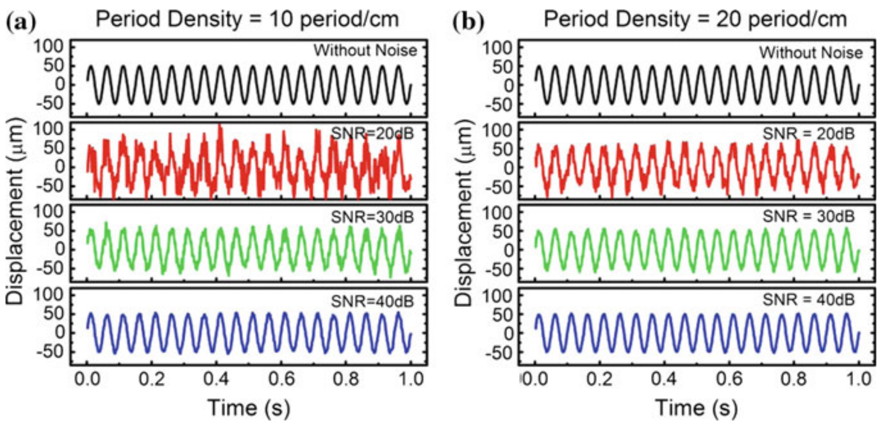

Fig. 2 The displacements obtained from two kinds of QIFP with different fringe period densities under different level of noise

high. That is, we can use a QIFP with higher fringe period density when the exposure time of the CIS is short or the illumination condition is bad for the performance improvement of the method. Because the increase of the fringe period density increased the signal-to-noise ratio of the imaged QIFP intensity on the condition that the noise energy is constant, which will improve the correction accuracy of the SCCM. However, the noise of the CIS decreased significantly if the exposure time was long enough, and the fringe period density had a decreasing effect on the measurement accuracy, which could be seen from the displacements in Fig. 2a, b when the SNR of the intensities were equal to 40 dB.

In addition, the resolution of the image sensor also influences the measurement accuracy. The measurement accuracy increases with the increasing of the sampling point of the QIFP. The sampling point has relationship with the object distance and the physical size of the pixel. Generally, the pixel size is constant for a camera. Therefore, there are two methods that can improve the measurement accuracy by increasing the sampling points for a QIFP with constant size and period density: one is shortening the object distance for more pixels involved to sample the QIFP; the other one is using the camera image sensor with smaller pixel size.

2.3 Damage Detection for a Cantilevered Beam

When the cantilevered beam is subjected to a crack, the dynamic behavior of the structure will be changed. This change could be amplified by an auxiliary concentrated mass. Therefore, in the damage detection experiment, an auxiliary mass was employed since it can influence the natural frequency of the beam structure. During the detection process, the auxiliary mass traversed from one end to the other end with a constant spatial distance. At each position, the proposed vision-based vibration system was used to measure the dynamic signals to characterize each order of frequency of the cantilevered beam. Noted that the QIFP was pasted on the free end of the beam to avoid interfere the movement of the auxiliary mass. The frequency shift curves could be obtained by the combination of the same order of natural frequencies. The frequency shift curves will be smooth for an intact beam when the auxiliary mass moves along the length direction from one end to the other end with a fixed spatial interval. However, a discontinuous point or sharp variation point occurs in the FSC when the mass located close to the crack position [4] because the presence of a crack causes the local stiffness of the beam to decrease.

3 Experiments and Discussion

In the experiment, two kinds of cantilevered bean were employed to verify the performance of the vision-based Quasi-OCVT system. One is a plastic cantilevered beam excited by an exciter to verify the performance of the system in dynamic monitoring with a large amplitude vibration; the other one is a cracked steel cantilevered beam excited by a hammer to test the performance of the system in dynamic parameters characterization for damage detection and crack localization.

3.1 Vision-Based Quasi-OCVT Technique for Dynamic Monitoring of a Plastic Beam

In the experiment, a plastic beam-like structure and a QIFP with a period density of 20 period/cm were used. The QIFP was pasted on the surface of the beam at a distance of 190 mm from the fixed end. The cantilever beam ($420 \times 50 \times 4$ mm) was excited by the exciter. The excitation signal was generated by a function generator and was amplified by a power amplifier. Initially, the camera was placed perpendicular to the beam surface and the QIFP pasted on the beam surface was imaged in the middle of the CIS. The optical lens of the high-speed camera can be manually tuned for better imaging quality. Then the swept exciting signal with frequency from 0–400 Hz during a period of 8 s was inputted and the structure vibrated and deformed with the excitation. The camera sampling frequency was set to 1869 Hz. Figure 3 shows the obtained displacement of the plastic beam and its FFT result, from which we can know that the structural vibration amplitudes became larger when the frequency of the exciting signal close to the natural frequencies. The calculated first six natural frequencies are 5.25, 33.90, 95.73, 176.53, 198.92, and 318.61 Hz respectively, which can be obtained from the inset figure s5. For clarity, the displacement curves in the red boxes are shown in the inset figures named s1, s2, s3, and s4, respectively. The results obtained by the proposed

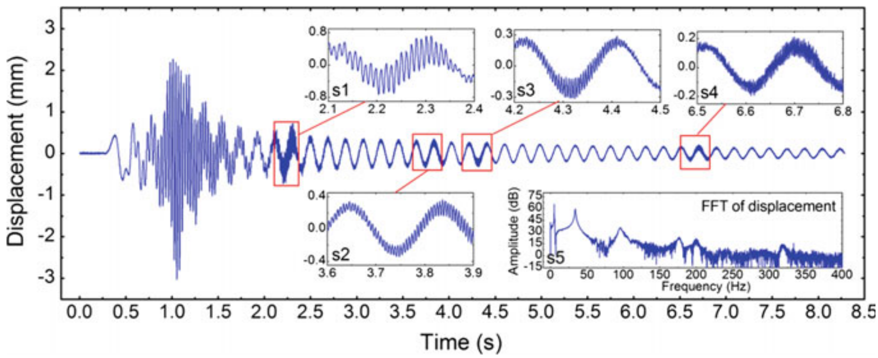

Fig. 3 The obtained displacement and its FFT of a plastic cantilever beam under a swept excitation

quasi-OCVT method demonstrated its high precision and stability for the dynamic monitoring for a vibration with amplitude up to 3 mm.

3.2 Vision-Based Quasi-OCVT Technique for Damage Detection of a Steel Cantilevered Beam

A cantilevered beam with a transverse crack was used to further illustrate the performance of the quasi-OCVT technique for damage detection. The size of the steel beam was 700 × 40 × 4 mm. One transverse saw cut with depth of 2 mm and width of 1.5 mm was located at 430 mm from the fixed end of the beam. Both the precise positioning of the auxiliary mass and the exact determination of the natural frequencies were the key points for the success of the frequency shift curve based damage detection method [3]. Grids were drawn on the surface of the cantilevered beam to accurately positioning the auxiliary mass. During the experiment, a magnet with weight of 80 g as the auxiliary mass was traversed along the beam from the fixed end to the free end. The spatial probing distance was 10 mm, which results in a total number of 69 measuring points.

Cantilevered beam model with same dimension, defect and auxiliary mass was also studied using Finite Element Method (FEM). In the simulation, the steel beam model have the following material properties: Young's modulus of elasticity $E = 2.1 \times 10^{11} \mathrm{N/m^2}$, mass-density $\rho = 7860 \mathrm{kg/m^3}$, Poisson ratio $\nu = 0.3$. Sixty-nine cases were simulated when the magnetic auxiliary mass located at different positions. After each simulation, the first five natural frequencies of bending mode shapes were extracted and plotted against the axial location of the auxiliary mass to generate the frequency shift curves. Traditional accelerometer-based vibration measurement system was also employed to obtain the frequency shift curves for further comparison.

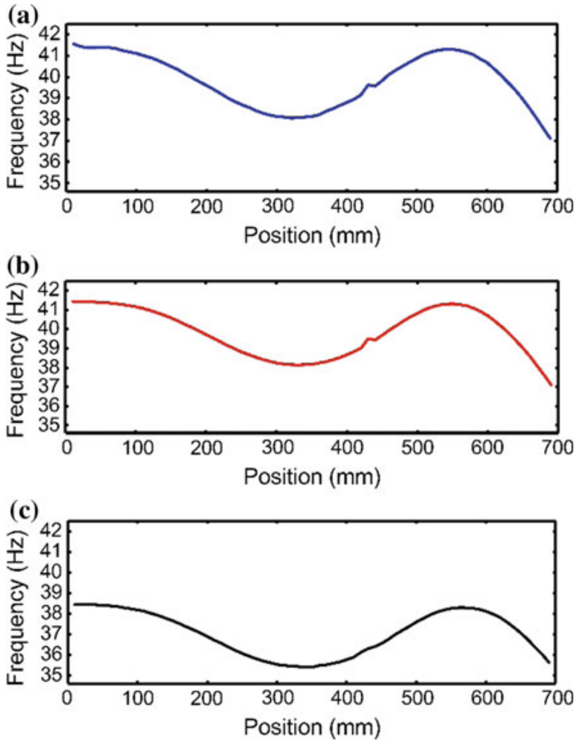

Fig. 4 The 2nd frequency shift curves obtained by Quasi-OCVT technique (**a**), simulation (**b**) accelerometer-based method (**c**)

The obtained experimental and simulated frequency shift curves are shown in Fig. 4. The blue solid line (a), the red solid line (b) and the black solid line (c) are corresponding to the result obtained by quasi-OCVT technique, simulation and traditional accelerometer-based method, respectively. From the blue and red solid lines, a step change or discontinuity in the curves occur when the auxiliary mass was exactly at the crack location. Hence, it can directly detect the crack in the beam from these curves. The good agreement of the Quasi-OCVT based result and numerical result illustrates the validity, efficiency and accuracy of the proposed method. However, the frequency shift curve extracted from the acceleration data is smaller than both the simulation and quasi-OCVT-based results owning to the mass effect of the accelerometer, as shown by the black solid line in Fig. 4c.

4 Conclusions

This paper proposes a vision-based vibration measurement approach using an artificial QIFP and a high-speed camera. Both the systemic factors that have influence on the measurement accuracy and the performance of the system were discussed and illustrated by simulation. The good agreement of the results between the simulation and Quasi-OCVT laboratory tests verify the efficiency, practicability and high accuracy of the proposed Quasi-OCVT method. In addition, the proposed vision-based vibration measurement system is simple and non-contact in nature. Compared with the traditional contact methods, complicated setup is not needed and mass-effect is not introduced, making it attractive for the application in the characterization of structural modal parameters and damage detection of light structures.

Acknowledgements This work is supported by the Fujian Provincial Excellent Young Scientist Fund (2014J07007), the National Natural Science Foundation of China (51675103), the Training Program of Fujian Excellent Talents in Universities, the Specialized Research Fund for the Doctoral Program of Higher Education, the Ministry of Education, P. R. China (20133514110008) and the Ministry of Health, P.R. China (WKJ-FJ-27).

References

1. O.S. Salawu, Detection of structural damage through changes in frequency: a review. Eng. Struct. **19**(9), 718–723 (1997)
2. Z.A. Jassim et al., A review on the vibration analysis for a damage occurrence of a cantilever beam. Eng. Fail. Anal. **31**, 442–461 (2013)
3. S. Zhong, S.O. Oyadiji, K. Ding, Response-only method for damage detection of beam-like structures using high accuracy frequencies with auxiliary mass spatial probing. J. Sound Vib. **311**(3–5), 1075–1099 (2008)
4. S. Zhong, S.O. Oyadiji, Identification of cracks in beams with auxiliary mass spatial probing by stationary wavelet transform. J. Vib. Acoust. **130**(4), 041001 (2008)
5. S. Zhong, S.O. Oyadiji, Analytical predictions of natural frequencies of cracked simply supported beams with a stationary roving mass. J. Sound Vib. **311**(1–2), 328–352 (2008)
6. Y. Fu, Low-frequency vibration measurement by temporal analysis of projected fringe patterns. Opt. Lasers Eng. **48**(2), 226–234 (2010)
7. M.H. Ortiz, E.A. Patterson, Location and shape measurement using a portable fringe projection system. Exp. Mech. **45**(3), 197–204 (2005)
8. Y. Fukuda et al., Vision-based displacement sensor for monitoring dynamic response using robust object search algorithm. Sens. J., IEEE **13**(12), 4725–4732 (2013)
9. D. Ribeiro et al., Non-contact measurement of the dynamic displacement of railway bridges using an advanced video-based system. Eng. Struct. **75**, 164–180 (2014)
10. J. Zhong, S. Zhong, Q. Zhang, Two-dimensional optical coherence vibration tomography for low-frequency vibration measurement and response-only modal analysis. Mech. Syst. Signal Process. **79**, 65–71 (2016)
11. J. Zhong et al., Two-dimensional optical coherence tomography for real-time structural dynamical characterization. Opt. Lasers Eng. **66**, 74–79 (2015)
12. S. Zhong, H. Shen, Y. Shen, Real-time monitoring of structural vibration using spectral-domain optical coherence tomography. Opt. Lasers Eng. **49**(1), 127–131 (2011)