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Vibration analysis based on Electronic stroboscopic speckle--shearing pattern interferometry[1]

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ABSTRACT

In this paper, an electronic speckle-shearing pattern interferometer with pulsed laser and pulse frequency controller is fabricated. The principle of measuring the vibration in the object using electronic stroboscopic speckle--shearing pattern interferometer is analyzed. Using a metal plate, the edge of which is clamped, as an experimental specimen, the shear interferogram are obtained under two experimental frequencies, 100 Hz and 200 Hz. At the same time, the vibration of this metal plate under the same experimental conditions is measured using the time-average method in order to test the performance of this electronic stroboscopic speckle-shearing pattern interferometer. The result indicated that the fringe of shear interferogram become dense with the experimental frequency increasing. Compared the fringe pattern obtained by the stroboscopic method with the fringe obtained by the time-average method, the shearing interferogram of stroboscopic method is clearer than the time-average method. In addition, both the time-average method and stroboscopic method are suited for qualitative analysis for the vibration of the object. More over, the stroboscopic method is well adapted to quantitative vibration analysis.

Key words: Electronic stroboscopic speckle--shearing pattern interferometry, time-average method, vibration, stroboscopic method and shearing interferogram.

1 INTRODUCTION

Electronic speckle-pattern interferometry (ESPI) is a technology of non-destructive testing that can be used to measure the difference in out of plane displacement, flaw in the surface, and surface strain in the field of medical and industry [1]. Its advantages are of real-time observation, high measurement sensitivity, the elimination of chemical development, the independent measurement of orthogonal displacement components [2] and tolerance to environment disturbances [3]. There are many techniques for measuring the vibration of the object, such as laser stroboscopic[4] , Laser-Doppler vibrometry [5], the simulation technique[6] and ESPI. Electronic speckle--shearing pattern interferometry (ESSPI) is developed from the ESPI. Compared with other interferometries, ESSPI is robust against stability problems caused by turbulent effects in the light trajectory and also against problems that are due to reduced coherence of the illuminating source [7]. Because of mentioned-above advantages, ESSPI is widely used in

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industrial field. Since the ESSPI sensitivity depends on the amount of shearing, the measurement range of ESSPI can be adjusted according to the requirement, that is to say, the measurement range is correspondingly expanded [8]. Because of the complexity of motion, the stroboscopic system with pulsed laser is introduced into the ESSPI in order to study the vibration process of object in micro system [9].

In this paper, a system using ESSPI is constructed. The shearing interferometric technique and stroboscopic illumination technique are integrated in this system. The system can be used to measure out-of-plane displacements and in-plane displacements under either a static or a dynamic loading. During the measurements of vibration, the time-averaged method should be used for qualitative vibration analysis and observe the zero-order fringe of interferogram in the first step. But to quantify the out-of-plane displacement displacement, the stroboscopic method is adopted. During the test, a rectangle plate, the edge of which is fixed, is placed in the field of interferometer so that the speckle pattern is formed. Finally the experimental results of vibration of specimen are present and the fringe pattern gotten using the time-average method and stroboscopic method under the same experimental condition is analyzed so that we can discuss the resolution of both measuring vibration methods.

2 PRINCIPLE OF DETECTING VIBRATION

Generally, there are two basic techniques that are used to measure the vibration of object in ESSPI: the time-averaged method and stroboscopic method. Compared with the stroboscopic method, the experimental set up of time-averaged method is low-cost and easy to establish, so the time-averaged method is widely used for the vibration measurement [2]. But it is difficult to quantitatively evaluate the fringe pattern, so the stroboscopic illumination technique is introduce into the ESSPI in order to get the phase map of the fringe pattern [9].

When continuous illumination is used for the light source in the ESSPI, since the vibration periods of object is shorter than the shutter opening time of charge-coupled device (CCD) camera, the intensity integrated by the CCD camera is time-averaged intensity within the sampling time of CCD. To complete the time-averaged measurement, a two-step sequence is performed. The first step is that a shearing interferogram of the specimen under test is obtained by the CCD camera, while the specimen is in a static position. The intensity detected by the CCD camera can be written as [10]:

$$I_1(x,y)=2a^2\{1+\cos[\phi(x,y)]\} \quad (1)$$

where a is the light amplitude which is assumed equal for the two neighboring points, $\phi(x,y)$ is the phase difference between the two neighboring points, represents a random phase angle.

The second step is that the specimen is excited at a frequency according to the experimental requirement, while the intensity distribution of speckle pattern in the CCD camera is changeable. If the frequency the excited specimen is more than or equal to five times of image acquisition frequency of the CCD, the image obtained by the CCD camera is considered as the integral of intensity in a period, so the time-averaged intensity in this CCD is expressed by

$$I(x,y)_{ave}=\frac{1}{T_f}\int_0^{T_f} 2a^2\{1+\cos[\phi(x,y)+\Delta(x,y,t)]\}dt \quad (2)$$

where T_f is the period of image acquisition, $\Delta(x, y, t)$ is a relative variable of phase due to relative displacement between the two neighboring points.

When the specimen under testis illuminated by the coherent light source, we assumed the image-shearing action is in the x-direction, $\Delta(x, y, t)$ is written as [11]

$$\Delta(x, y, t) = \delta x \frac{4\pi}{\lambda} \frac{\partial w}{\partial x} \cos \omega t \tag{3}$$

where λ is the wavelength of the light source, δx is the amount of image-shearing along the reference x-axis, w is the out-of –plate displacement due to the vibration, and frequency ωis circular frequency of vibration.

Combining equation (2) and (3) and subtracting from equation (1), the intensity of time-averaged shearing interferogram is expressed by

$$I(x, y) = I_1(x, y) - I(x, y)_{ave} = 2a^2 \cos\phi(x, y)\left[1 - J_0\left(\delta x \frac{4\pi}{\lambda} \frac{\partial w}{\partial x}\right)\right] \tag{4}$$

here J_0 is the zeroth order Bessel function of the first kind.

From the equation (4), we can see that the final shearing interferogram is modulated by $1 - J_0\left(\delta x \frac{4\pi}{\lambda} \frac{\partial w}{\partial x}\right)$ to produce the bright and dark fringe pattern. The shear calculating time in ESSPI should be less than the acquisition time of a CCD camera so that the motion of the specimen under test is real-time displayed.

The stroboscopic illumination technique and Electronic speckle pattern interferometry is integrated in the stroboscopic method. The specimen under test is illuminated by a pulsed laser, the width of which is shorter than the period of vibration cycle. In this way, the CCD camera samples discrete points on the vibration cycle, rather than averaging over a period [9]. The shearing interferogram is similar to be frozen at a certain state of displacement for each point. Therefore the phase-extracting algorithms and phase-unwrapping algorithms are applied for calculating the phase map of the specimen surface under the test.

3 STRUCTURE OF THE ELECTRONIC SPECKLE-SHEARING PATTERN INTERFEROMETER

The Michelson type of Electronic stroboscopic speckle--shearing pattern interferometer is shown in Fig.1and the view of the ESSPI is depicted in Fig.2. The interferometer is made up of two light sources, Michelson interferometer, objective lens, CCD camera, Driver, high-performance

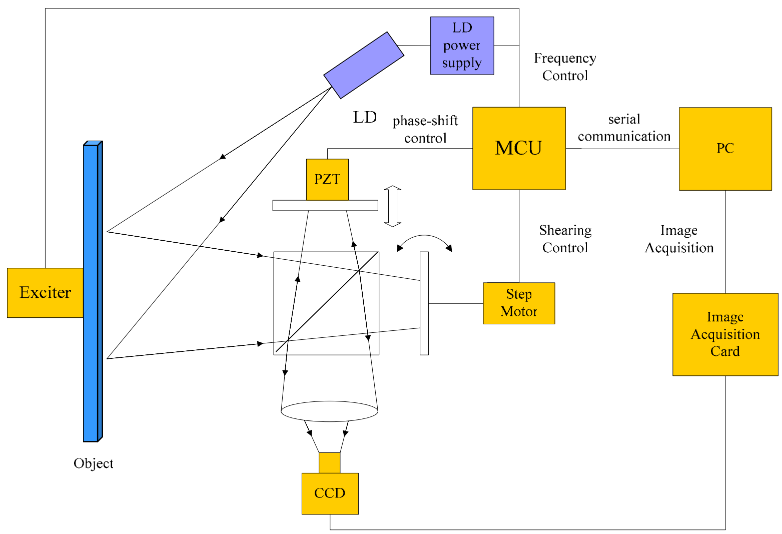


Fig.1 the schematic layout of an electronic stroboscopic speckle--shearing pattern interferometer

piezoelectric translator (PZT) and personal computer. The two light sources are a laser diode (LD)with wavelength $\lambda = 532$nm, power= 60mw and a LD with wavelength $\lambda = 650$nm, power= 40mw , respectively. The two light sources can generate both the continuous illumination and a stroboscopic illumination by a controller. The advantages of using two light sources are of improvement of the measurement precision and expanding the range of measurement. The coherent light is collimated onto the surface of the specimen under the test. The test specimen is a square metal plate of 220 mm×165 mm with all edges clamped onto a heavy base. It was excited in the center by a loudspeaker, which should be in contact with the back surface of the specimen. The coherent light is reflected by the surface of the specimen and inters the Michelson interferometer. A 50/50 beam splitter is used to divide the entering light into two beams that transmits in different interfereometric arms. The reflected beam with two mirrors is imaged by the MTV-23F1 CCD camera via an objective lens. As ESSPI is used in the subtraction mode, one of mirrors needs to tilt a little angle; witch is driven by a step motor. In this way, two adjacent point images in the specimen surface can project onto the same point of the CCD.

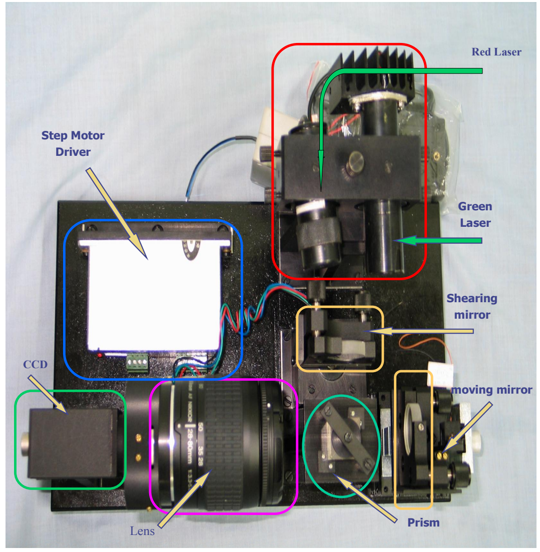


Fig.2 the photo of an electronic stroboscopic speckle--shearing pattern interferometer

Both the digital image processing system and the test device Driver, microprocessor control unit (MCU) are controlled by a computer that contain a image acquisition card that collect the interferometic fringe obtained by the CCD camera. In addition, the real-time shearing pattern of intererogram is displayed via the computer in order to observe the process of vibration object, the fringe patterns are processed using the image processing algorithm to remove the speckle noise content and the phase maps are calculated by use of the phase step algorithm in this computer. At the same time, the MCU is used to control the pulse frequency of the LD, PZT to realize the phase step and the step motor to shear the interforgram.

When the specimen is illuminated by the laser pulse, the controller of the LD accepts a trigger input to synchronize laser pulse. In order to capture the motion of vibration object, the stroboscopic illumination should be synchronized with the excitation signal. The pulse width should be as short as possible to keep the out-of-plane displacement due to the vibration unchangeable. A timing diagram of the synchronization scheme used in this ESSPI is shown in Fig.3. So we can observe the specimen under test at many different phases of its vibration cycle from these fringe patterns of shearing interferogram. Because the phase map is obtained by using the phase stepping techniques to quantitative analysis of the stroboscopic shear interferogram, the PZT is mounted on the arm of Michelson interferometer to change the optical difference.

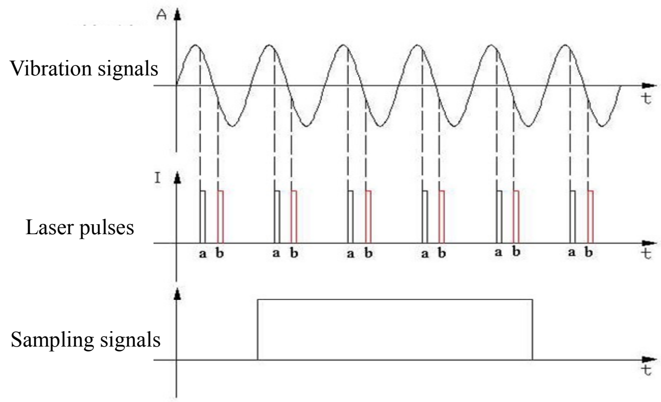
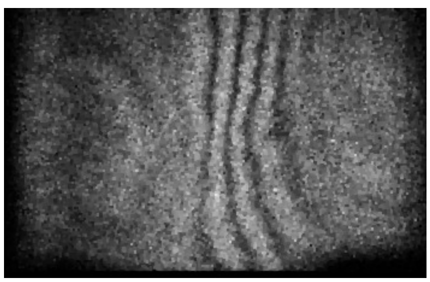


Fig.3 relationship among vibration signals, laser pulses and sampling signals of the CCD camera

4 EXPERIMENTAL RESULTS AND DISCUSS

The experimental results of an ESSPI that use continuous illumination of variable frequency are shown in Fig. 4. Fig. 4 (a) is the fringe pattern of vibration object at the frequency of 100Hz and Fig. 4 (b) is the fringe pattern of vibration



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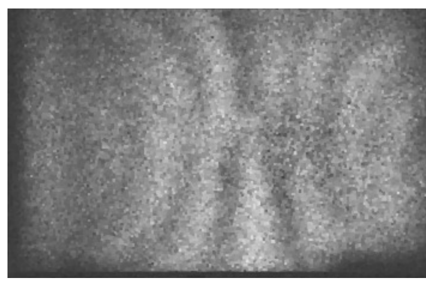

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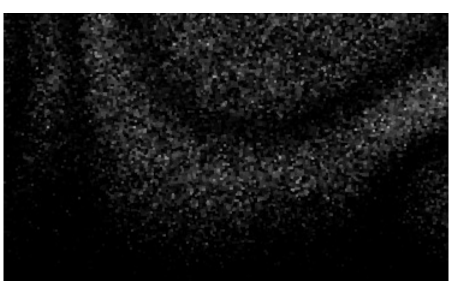
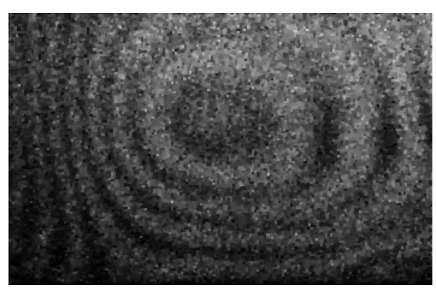
(a) (b)

Fig.4 time-averaged shearing interferogram at two different frequencies

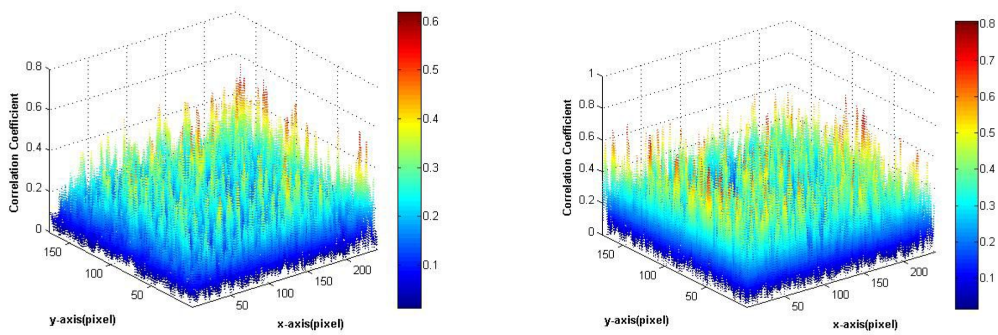
object at the frequency of 200Hz. To improve the contrast of shearing interferogram, a self-adaptive filter algorithm is used to process the interferogram of vibration object. At the same experimental conditions, the fringe pattern of vibration object is obtained using the stroboscopic illumination. The Fig.5 shows the shearing interferogram at the frequency of 100 Hz and 200 Hz (Fig.5 (a) is 100Hz; Fig.5 (b) is 200Hz). Due to the limitation of experimental





(a) (b)

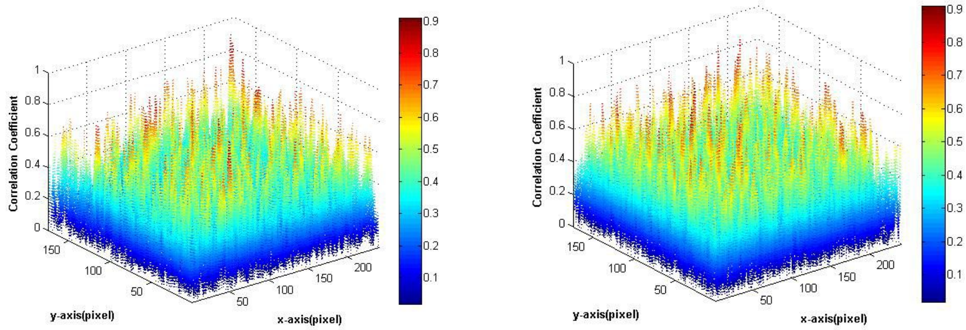
Fig.5 stroboscopic illumination shearing interferogram at two different frequencies conditions, the phase stepping process can employed to calculate the phase map of interferogram. So we have to qualitatively analyze these shearing interforgrams. To compare the two vibration measurement methods mention above a correlation algorithm is adopted to analyze the quality of fringe pattern. When the images are processed using the algorithm, the correlation coefficient is subtracted from 1to indicate the change of fringe pattern at the different frequency. Fig.6 shows the correlation coefficient between the fringe pattern before and after vibration at the frequency of 100Hz and 200Hz using the time-averaged method, respectively. It can be seen that the correlation coefficient of the specimen under test increases with the excitation frequency increasing and the variation range of the correlation coefficient at the frequency of 100Hz is smaller than at the frequency of 200Hz. The results indicate that out-of-plane displacement of the specimen increases with the excitation frequency increasing and the variation range of the out-of-plane displacement at the frequency of 200Hz is almost all field and larger than at the frequency of 100Hz.



(a) (b)

Fig.6 the correlation coefficient between the fringe pattern before and after vibration at the frequency of 100Hz and 200Hz using the time-averaged method, respectively: (a) vibration at the frequency of 100Hz, (b) vibration at the frequency of 200Hz

Fig.7 shows a similar set of results for the fringe pattern of vibration object using the stroboscopic method at the frequency of 100Hz and 200Hz. We can see that the correlation coefficient of the vibration object at the frequency of 100Hz and 200Hz is almost same. It also indicates that the variation range of out-of-plane displacement of the specimen at the frequency of 100Hz is similar to that of at the frequency of 200Hz and the out-of-plane displacement at the frequency of 200Hz is as same as at the frequency of 100Hz.



(a) (b)

Fig.7 the correlation coefficient between the fringe pattern before and after vibration at the frequency of 100Hz and 200Hz using the stroboscopic method, respectively: (a) vibration at the frequency of 100Hz, (b) vibration at the frequency of 200Hz

To analyze the performance of vibration at the high frequency, the further correlation coefficient is calculated between the fringe pattern at the frequency of 100Hz and the fringe pattern at the frequency of 200Hz. The Fig.8 is calculation result of two fringe pattern obtained by the time-averaged method. The correlation coefficient distribution of two fringe pattern obtained by the stroboscopic method is shown in the Fig.9. The results indicated that the variation of the out-of-plane displacement between 100Hz and 200Hz using continuous illumination is larger than the variation using the stroboscopic illumination. The main reasons causing this phenomenon are that the intensity received by the CCD camera corresponding to the time-averaged method is integrated over a period of vibration, but the CCD camera samples discrete points on the vibration cycle or only receives a small part of the laser power due to the stroboscopic effect. So the fringe pattern of interferogram due to the time-averaged method is different (see Fig.6), while the fringe pattern due to the stroboscopic method is almost same (see Fig.7).

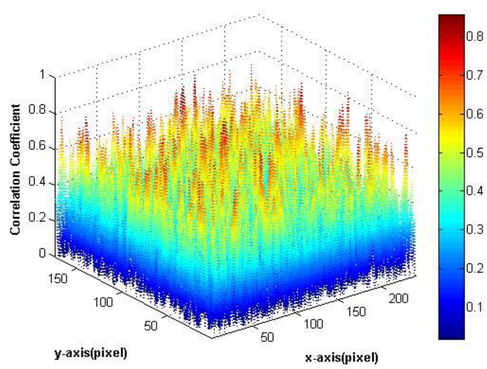


Fig.8 the correlation coefficient between the fringe pattern at the frequency of 100Hz and the fringe pattern at the frequency of 200Hz applying the time-averaged method

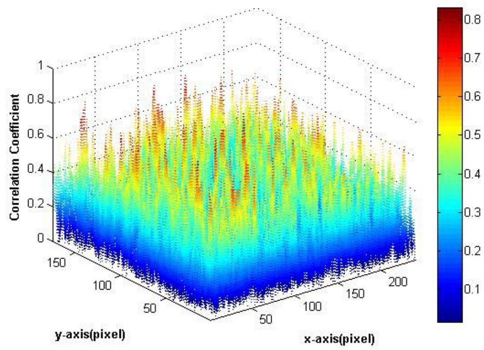


Fig.9 the correlation coefficient between the fringe pattern at the frequency of 100Hz and the fringe pattern at the frequency of 200Hz applying the stroboscopic method

5 CONCLUSIONS

The ESSPI is a powerful technique for measuring the out-of-plane and in-plane displacement of object at the different frequency. As described in this paper, the Michelson type of Electronic speckle--shearing pattern interferometer is designed with the integration of the shearing interferometric technique and stroboscopic illumination technique. At the same time, the fringe patterns of shearing interferogram are obtained by using the time-averaged method and stroboscopic method based on the principle analysis. The image processing algorithm is employed to remove the noise content of the interferogram. The results indicated that bath the stroboscopic method and time-averaged method are suited for full-field qualitative measurement of vibration. As the phase-stepping process is not used to extract the phase map of the shearing interferogram duo to the limitation of experimental conditions, we can not calculate the out-of-plane displacement of the specimen under test. In other words, we can not get advantages of stroboscopic method over the time-averaged method. To make up the shortcoming of this experiment, the correlation algorithm is used for data analysis. The calculating results show that the stroboscopic method is used to accurately measure the position of vibration cycle.

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