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اندازه گیری نقشه دو بعدی تغییر شکل در اجسام با استفاده از چیدمان بهبود یافته برش نگاری پیسه اپتیکی

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در این مقاله یک چیدمان بهبود یافته برش نگاری پیسه اپتیکی برای اندازه گیری نقشه دو بعدی تغییر شکل های کوچک و تنش در اجسام معرفی میشود. این چیدمان بر پایه برش نگاری تداخل سنجی پیسه با استفاده از تداخل سنج مایکلسون بوده، اما در آن باریکه لیزر واگرا و یک سامانه جدید اپتیکی برای تصویر سازی و گسترش میدان دید به کار گرفته شده است. این چیدمان نسبت به چیدمان های مشابه قطعات اپتیکی کمتری داشته، نسبت به ارتعاشات نا خواسته پایدارتر است و فرآیند همخط سازی در آن ساده تر انجام میگیرد. برای نمایش کارآمدی این چیدمان نقشه دو بعدی مولفه خارج از صفحه تنش در یک صفحه آزمون فلزی تحت بار دینامیکی با کمک چیدمان پیشنهادی اندازه گیری و ارائه شده است.

کلید واژه- اندازه گیری تغییر شکل، برش نگاری، تداخل سنجی، تنش

Two dimensional deformation map measurement using an improved optical speckle shearography setup

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Abstract- In this paper a new optical speckle shearography setup to measure the two dimensional strain map in materials is introduced. This setup is based on the speckle shearography using a Michelson interferometer, but uses a divergent coherent laser beam and an innovated optical arrangement to expand the field of view and form the speckle images. Compared to other similar setups, our setup requires fewer optical components, is more robust against unwanted vibrations, and is easier to be aligned. To demonstrate the capabilities of our setup, two dimensional map of the out of plane component of the strain field in a metallic sample plate under dynamic load has been measured and presented.

Keywords: Deformation measurement, shearography, interferometry, strain

1. Introduction

Digital shearography is an efficient non-contact, whole field and non-destructive testing and optical measurement method for detection of very small deformations and strain map in materials [1-3]. In this technique the deformation gradient is measured by detecting the phase difference in the speckle interference pattern recorded before and after the deformation. The sensitivity of the measurement is improved by the phase shifting technique [4-5]. Digital shearography can be implemented by two methods: temporal, that is considered for static measurements, and spatial which is more suitable for dynamic measurements, such as online testing and biomedical applications [6]. In this paper, we introduce a modified shearography setup using a Michelson interferometer to measure out of plane deformation gradient in a metal sample. Our proposed setup uses fewer optical components, is simpler to align and more robust than other conventional shearography systems. The experimental results are presented and discussed.

2. Theory

Consider a Michelson interferometer in which the reference mirror (M1) is perpendicular to the optical axis, but the other one (M2) is tilted by some angle, θ as shown in fig. 1. The input wave is divided into two waves along the two orthogonal arms of the interferometer by the beam splitter B.S., and combine again after reflecting off the two mirrors. We call them the reference wave, u_1 and the tilted wave, u_2, respectively:

$$u_1(x,y) = |u_1(x,y)|\, exp[i\varphi(x,y)], \qquad (1a)$$

$$u_2(x,y) = |u_2(x,y)| \exp\{i\varphi(x+\Delta x, y) + 2\pi i f_0 . x\}. \qquad (1b)$$

The irradiance at a detector plane in the output is therefore proportional to:

$$I = (u_1 + u_2)(u_1^* + u_2^*) = u_1 u_1^* + u_2 u_2^* + u_1 u_2^* + u_2 u_1^*. \qquad (2)$$

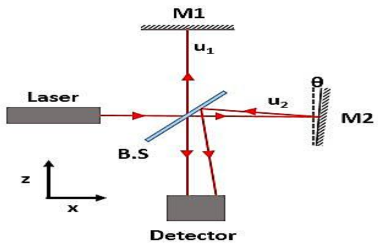


Fig. 1. Schematic of Michelson interferometer.

The Fourier transform of equation (2) is:

$$\mathrm{FT}(I) = U_1(f_x, f_y) \otimes U_1^*(f_x, f_y) + U_2(f_x + f_0, f_y) \otimes U_2^*(f_x + f_0, f_y) + U_1(f_x, f_y) \otimes U_2^*(f_x + f_0, f_y) + U_2(f_x + f_0, f_y) \otimes U_1^*(f_x, f_y). \qquad (3)$$

There are three spectral terms in the Fourier domain that are shown in fig. 3 by three separated bands. In view of equation (3) one realizes that $U_1 \otimes U_1^*$ and $U_2 \otimes U_2^*$ terms are located at the center of the frequency domain but the other two terms, $U_1 \otimes U_2^*$ and $U_2 \otimes U_1^*$ that carry the phase information are shifted by $\pm f_0$ to the left and right sides of the central bands, as seen in fig. 3 (b). By applying a Windowed Inverse Fourier Transform (WIFT) on the rectangle area centered at (f_0,0), the phase distribution can be calculated as:

$$[\theta + 2\pi x f_0] = arctan\frac{Im[u_2 u_1^*]}{Re[u_2 u_1^*]}. \qquad (4)$$

In this equation, θ is the phase difference between u_1 and u_2. Suppose that the test objects undergoes a deformation. The phase difference after the deformation will be denoted by:

$$[\theta' + 2\pi x f_0] = arctan\frac{Im[u_2' u'^*_1]}{Re[u_2' u'^*_1]}. \qquad (5)$$

The relative phase difference due to the deformation can be obtained as:

$$\Delta\theta = \theta - \theta'. \qquad (6)$$

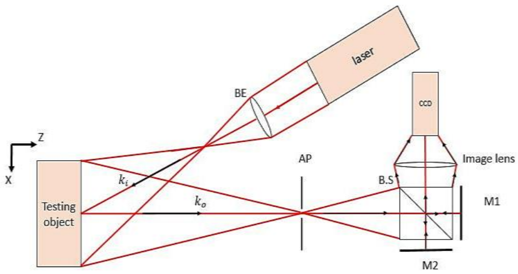
Since this phase difference is caused by the extra optical path difference induced by the out of plane deformation, we can write:

$$\Delta\theta = \frac{2\pi\cdot\Delta x}{\lambda}\, d \cdot s. \qquad (7)$$

Where λ is the laser wavelength, Δx is the shearing amount in the x direction, and **d** denotes the x component of the gradient of the deformation vector, $d = (\frac{\partial u}{\partial x}, \frac{\partial v}{\partial x}, \frac{\partial w}{\partial x})$. u, v, w represent the displacement components. The sensitivity vector **s** is defined as $k_i - k_o$, where k_i and k_o are the incident and scattered wave vectors. Therefore, by analyzing the phase difference, the out-of-plane deformation gradient of the test object can be evaluated.

3. Experiment and Results

Figure 2 shows the schematic of the shearography setup we used. A He-Ne laser with a wavelength of 632.8 nm is utilized as the light source and a beam expander (BE), located after the laser, is used to expand the light beam to illuminate the sample. The test object was an 80×80 mm^2 Aluminum plate with a thickness of 1 mm. A Deformable Plate Assembly (DPA) was built to firmly hold the test plate and apply the out of plane deformation by means of a micrometer screw pushing against the center of it from the back. The light scattered from the plate passes through a narrow slit S (to provide spatial coherency and control the size of speckles), and enters the Michelson interferometer. In the typical shearography setups parallel beam is used to illuminate the sample. Also an imaging lens after the slit S provides an initial image of the sample with sufficient Field Of View (FOV). Then, a 4f imaging system is used to transfer the initial image onto the detector [7]. In our setup, to reduce the number of optical components, improve the robustness of the setup against vibrations, and facilitate the alignment process, we used a divergent beam, and a single imaging lens right in front of the detector (Basler acA640 Digital CCD camera) that is adjusted to image the sample onto the detector through the slit S and, at the same time, provide the desired FOV.



(a)

(b)

Fig. 2. (a) Schematic of proposed shearography setup: beam expander (BE), slit (S), beam splitter (BS), reference mirror (M1), tilt mirror (M2). (b) Realization of the setup.

We record speckle patterns formed by the light scattered from the sample before and after a slight deformation is applied to the plate by our DPA. The desired spatial frequency shift, f_0 can be introduced into the shearograms via the tilt screws behind the mirror M2 (not shown). A sample speckle pattern interferogram recorded in our measurements is shown in fig. 3 (a). Shearing also shifts the spatial spectra as expressed by eq. (3) in the Fourier domain that is demonstrated in fig. 3 (b). According to equation (4), by applying the WIFT on the rectangle area, one of the side bands shown in fig. 3 (b), the phase distribution before and after the deformation can be calculated as shown in fig. 4 (a) and (b), respectively.

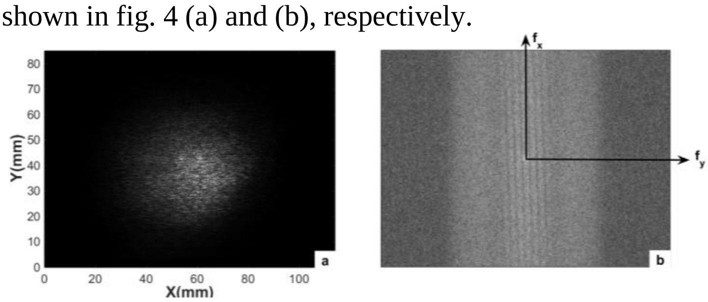


Fig. 3. (a) The two sheared images generate a speckle pattern, (b) Fourier Transform of a speckle pattern.

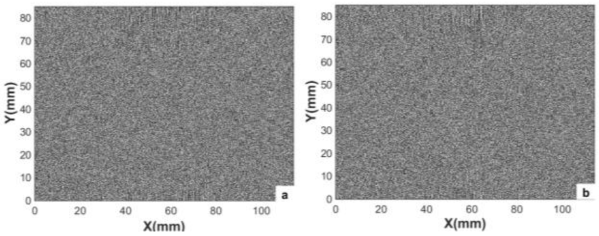


Fig. 4. Phase distribution: (a) before, and (b) after the deformation.

As expressed in eq. (6), the relative phase difference due to the deformation can be obtained by subtracting these two phase maps. The resulting map is shown in fig. 5 (a).

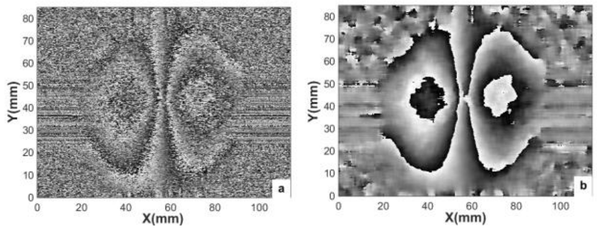


Fig. 5. (a) The wrapped phase map of the shearogram, (b) Resultant map filtered by a sine filter.

Phase maps created in Electronic Speckle Pattern Interferometry (ESPI), are inherently subject to speckle noise, which requires that noise reduction processes to be carried out to suppress the high-level noise in data. We applied standard sine filters [8] to the obtained phase maps to reduce the noise level to a tolerable level. The result is shown in fig. 5 (b) for comparison. Phase maps calculated using eq. (6) are wrapped between –pi and pi. In order to obtain continuous phase map, they have to be unwrapped using one of the standard phase unwrapping algorithms [9]. We used the MATLAB's *unwrap* function to do that. Figure 6 (a) shows the unwrapped phase map obtained. The final step in analyzing the data is to use eq. (7) to convert the measured phase map to the gradient of the out of plane deformation. This is shown in fig. 6 (b).

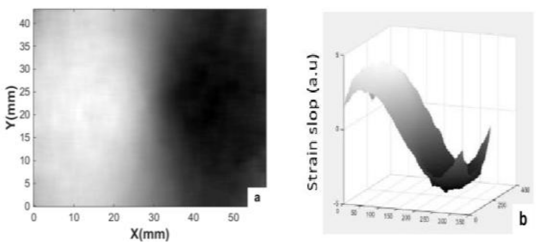


Fig. 6. (a) 2D plot of the unwrapped phase map. (b) 3D plot of the out-of-plane deformation gradient.

4. Conclusion

A new spatial phase shifting digital shearography system has been developed to measure the gradient of out of plane deformation in objects. The advantages of this systems are: simpler structure with fewer optical components, better stability and robustness against unwanted vibrations, large and easily adjustable field of view, and easier alignment process. To demonstrate our proposed setup we measured the gradient of the out of plane deformation in a metal test plate under dynamic load. The technique presented in this work can be realized with affordable components and used as an efficient tool for measuring the strain fields and deformations of objects where applicable.

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