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Phase Shift and Carrier Techniques of Shear Beam ESPI for Static and Dynamic In-Plane Displacement Measurement

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Abstract Novel phase shift and carrier techniques for measurement of in-place displacement field are proposed. In shear beam ESPI (Electronic Speckle Interferometry) the illumination beam is split into two wave fronts by a prism. Laterally movements of the prism introduce phase shifts. A small angle wedge is set behind the prism. A rotation of the wedge produces carrier fringes. The movement of the prism or the wedge can be controlled precisely be mechanical or electrical mechanism. Digital image processing algorithms, phase iteration and FTM (Fourier Transform Method), are used to extract defoemation information. Theories and thier experimental demonstrations are presented.

Key words phase shift, carrier, image processing, ESPI, shear beam.

1 Introduction

Optical metrology methods enjoy advantages of being fast response, non contacting, and generally full-field measurement. Digital image processing have promoted these methods to a new platform. ESPI has been used successfully in displacement measurement and vibration analysis[1, 2]. Leenderta developed a whole field measuring method in which the objects is illuminated by two coherent wave fronts[3]. The speckle patterns generated by these wave fronts at different instances are correlated to produce a fringe patterns indicating the movement of the object surface. The method is sensitive to one resolved component of the inplane displacement. Variations of this method have been applied to the measurements of displacement and strain[4, 5]. Sincs the pattern is formed by the interfernce of two widely separated beams, the coherent length of the source is crucial. The single beam speckle photography[6]

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enjoys the simplicity of its optical set up in recording a specklegram. In order to get Youn g's fringes or whole field fringe pattern, the specklegram has to be filtered in a second step. This additional step makes the real time pricessing difficult. Electronic shearography is excellent in both simplicity and real time performance[7, 8]. Shear beam ESPI[9] employs the idea of split beams by a prism in in-plane displacement measurement. Phase shift and carrier techniques are developed in this paper to quantitatively extract information form shear beam ESPI fringe pattern. Image processing is carried out by phase iteration[10] and FTM[11] algorithms.

2 Shear Beam ESPI[9]

As shown in Fig. 1(a). a specimen is illuminated by a coherent light source that goes through a prism. The prism splits the light source into two and shears them laterall, see the side view A in Fig. 1(b). A TV camera takes first exposure before the specimen is deformed

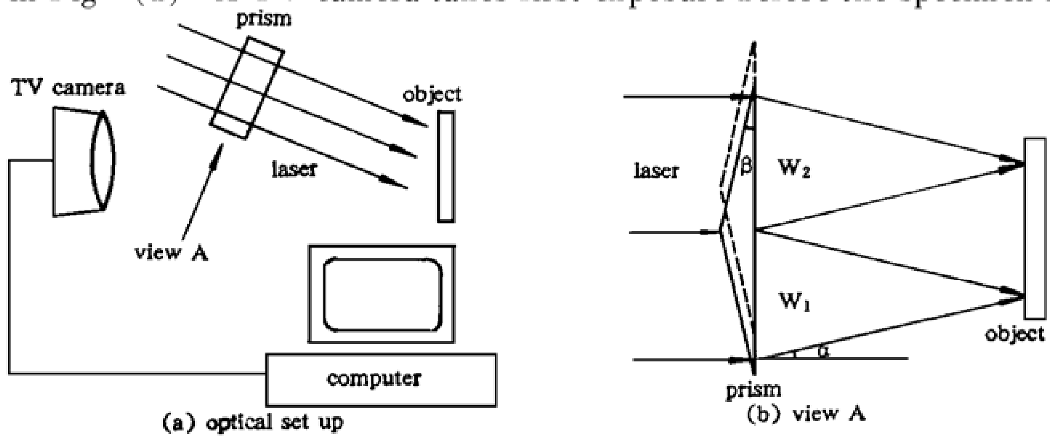


Fig. 1 Shear Beam ESPI set up (a) Optical set up, (b) View A

and second exposure after the specimen is deformaed. The computer does a subtraction from these two exposures to produce a fringe pattern, which has a light intensity of

$$I \propto \left| sin\ (\Phi + \frac{\delta}{2}) \right| \left| sin\ \frac{\delta}{2} \right| \qquad (1)$$

where Φ is the phase of the speckle field and therefor $|\sin(\Phi + \delta/2)|$ is a random background[7]. The import factor, $|\sin \delta/2|$, provides fringes in the pattern. The intensity valleys occur where $\delta = 2n\pi, \quad n = 0, 1, 2\cdots$ (2)

where δ is the phase due to in-plane displacement:

$$\delta = \frac{4\pi}{\lambda} V\ sin\ \alpha \qquad (3)$$

V is the vertical component of the in-plane displacement vector, α is an angle shown in Fig. 1 (b).

3 Phase shift technique for shear beam ESPI

A constant phase should be introduced between two exposures if a technique is to accomplish a phase shift. To do this the prism is moved in the direction perpendicular to the light path, see Fig. 1(b) and Fig. 2. As shown in Fig. 2, the optical path change between two exposure before and after the prism is moved can be deduced as:

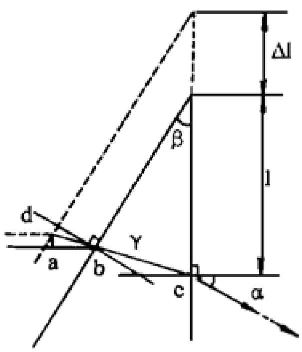


Fig. 2 Optical path change dueto a lateral movement

$$\overline{ab} + n_0 \overline{bc} - n_0 \overline{dc} = \Delta l \frac{\sin \beta}{\cos \gamma} [\cos(\beta - \gamma) - n_0] \tag{4}$$

where n_0 is the refraction index of the glass. So the phase change, Δp, introduced by move the prism is

$$\Delta p = \frac{2\pi}{\lambda} 2(\overline{ab} + n_0 \overline{bc} - n_0 \overline{dc}) = \text{const.} \tag{5}$$

where λ is the wave length of the light source. Δp is superimposed on the phase due to deformation. The factor that reveals fringes in eq. (1) is then

$$I_{\text{fringe}} = \left| \sin \frac{\delta + \Delta p}{2} \right| \tag{6}$$

There is no need to find Δp by eq. (5). The important conclusion from eq. (5) is that Δp is a constant. In practive the constant phase is found by calibration. So, by moving the prism and proper calibration, we can set the constant to 0°, 90°, 180°, 270° in order to get four phase shifted fringe patterns.

There are two ways to obtain the four phase shifted patterns. In the first way the sequence of operation is as follow. Take the first exposure before the specimen is deformaed, deform the specimen, take the second exposure, perform subtraction between the first and second exposures to get I_0, move the prism for 90° shift, take the third exposure, do subtraction between the first and third exposures to get I_{90}, move the prism for 180° shift, take the fourth exposure, do subtraction between the first and fourth exposures to get I_{180}, move the prism for 270° shift, take the fifth exposure, do subtraction between the first and fifth exposures to get I_{270}. This is a typical procedure for a static analysis. In the second way the sequence of operation goes as following. Do not deform the specimen, set the prism at the position for − 270° phase shift, take the first exposure, move the prism for − 180° shift, take the second exposure, move the prism for − 90° shift, take the third exposure, move the prism for a 0° shift, take the fourth exposure, deform the specimen, take the fifth exposure, do subtraction between the first and fifth exposure to get I_{270}, do subtraction between the second and fifth exposures to get I_{180}, do subtraction between the third and fifth exposure to get I_{90}, do subtractions between the fourth and fifth exposures to get I_0. The second way saves four phase shifted exposures from underformed specimen. The specimen is deform only to get the fifth exposure. We can deform the specimen under various loads and take more exposures. Subtraction between these later exposures and the first four exposures provide four phase shift pattens for each load status. The second way is useful in a transient analysis.

4 Carrier technique for shear beam ESPI

Carrier fringes are obtained if only a linear phase is introduced between two exposures. To achieve this for shear beam ESPI a small angle wedge behind the prism is rotated for a small angle, see Fig. 3. The optical path length before the wedge is rotated is, see Fig. 4:

$$\text{path}_{\text{before}} = L + T(n_0 - 1) \tag{7}$$

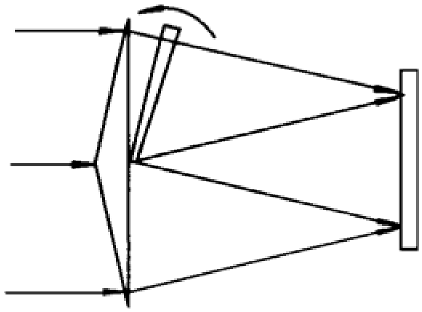


Fig. 3 Rotate a wedge to produce a carrier fringe pattern

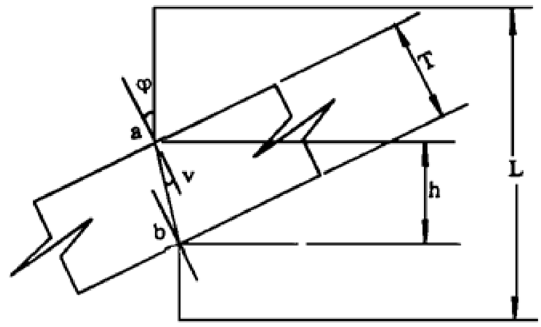


Fig. 4 Optical path change due to a tilt of the wedge

The optical path length after the wedge is rotated is:

$$\text{path}_{\text{after}} = L + T\frac{n_0 - \cos(\varphi - \theta)}{\cos\theta} \tag{8}$$

where φ is the incident angle and θ is the refraction angle. The phase change is then:

$$\Delta p = \frac{2\pi}{\lambda}(\text{path}_{\text{after}} - \text{path}_{\text{before}}) = kT \tag{9}$$

where k is a constant and T is the thickness of the wedge. For a small angle wedge, T is a linear function of the coordinate. So,

$$\Delta p = k_1 + k_2 y \tag{10}$$

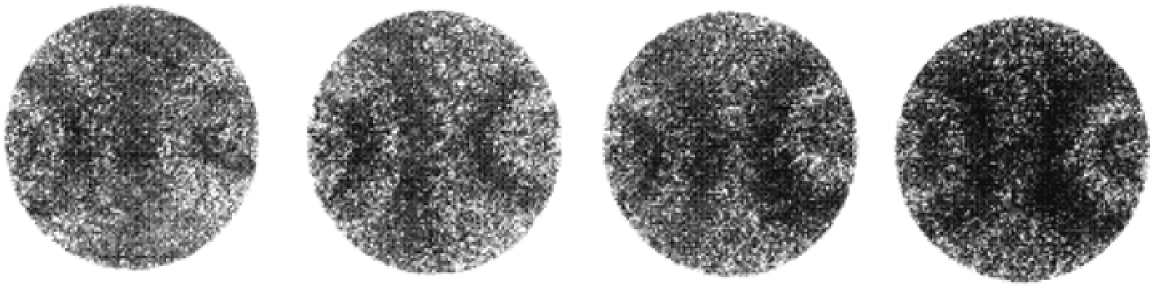
where k_1 and k_2 are constants, y is the coordinate perpendicular to carrier fringes. Again, we do not find constants k_1 and k_2 by math calculation. Instead, we find Δp by calibration. The operation sequence is: take the first exposure before the specimen is deformed, deform the specimen, rotate the wedge, take the second exposure, do subtraction between the first and second exposures. In the event of transient analysis, more exposures can be taken when the object is deformed continuously. The linear phase, Δp, is superimposed on the phase due to deformation. The factor that reveals fringes in eq. (1) is

$$I_{\text{fringe}} = \left|\sin\frac{\delta + (k_1 + k_2 y)}{2}\right| \tag{11}$$

The linear phase in the right side introduces a series equal spaced traight fringes.

5 Experiment result

A program is designed for executing the process. Real time subtraction mode is triggered immediately after an initial image is taken. Alive fringe patterns are shown on the monitor if one changes the load on the specimen. Phase shifted or carrier pattern is seen alive if the prism is moved laterally or the wedge is roated. The specimen is a disk under diametrical loads. Fig. 5(a) ~ (d) are patterns of 0, 90, 180, and 270 degree phase shifted. Since the patterns are heavily noised by speckle, Phase iteration algorithm has to be used in extracting the phase that represents the in plane displacement. Fig. 6 is the 3 D view of the phase due to disk deformation. Fig. 7 shows a carrier modulated fringe pattern of the disk obtained by the method developed in this paper. The unmodulated pattern is the same as Fig. 5(a). The modulated pattern is processed and demodulated by FTM[11] to obtain a phase that is the same as shown in Fig. 6.



(a) (b) (c) (d)

Fig. 5 Phase shifted patterns of: (a) o°, (b) 90°, (c) 180°, (d) 270°

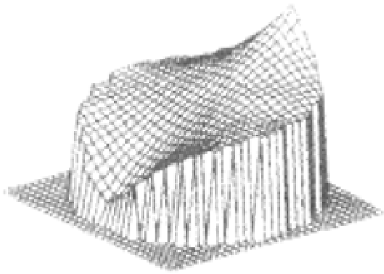


Fig. 6 3-D view of the phase

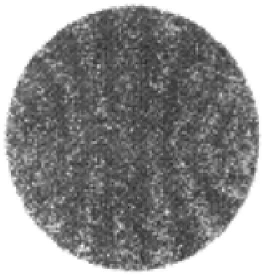


Fig. 7 Carrier modulated fringe pattern

6 Conclusion

Shear beam ESPI requires a simple optical set up, which relaxes the vibration isolation requirement, thue the technique is suitable for inspection in production environments. The coherent length requirement in shear beam ESPI is greatly reduced compared with the regular ESPI. The optical setting procedures for phase shift and carrier in this paper are simple and can be precisely achieved manually or by more advanced control system. The phase shift method in this paper is applicable to static analysis as well as transient analysis if the correct operation sequence is selected. In the carrier technique only one carrier modulated pattern is needed for extracting unambiguous information, and so the technique is good for both static and transient analysis. Both phase shift and carrier methods in this paper posses the potential of being developed into a fully automated practical tool for industrial usage.

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用于静态和动态平面内位移测量的剪切束电子斑纹图干涉术的相移和载波技术

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摘　要　报道了一种新颖的用于平面内位移测量的相移和载波技术。在剪切束电子斑纹图干涉度量术中, 照明光束由棱镜分为两个波前, 棱镜的侧面移动将引入相移。在棱镜后加一小角光楔, 则光楔的转动产生载波条纹。棱镜或光楔的转动可由机械或电学机构精密控制。形变信息由数字图像处理算法, 相位迭代和傅里叶变换法给出。文中介绍了理论及其实验演示的结果。

关键词　位相移动,　载体,　图像处理,　电子散斑干涉度量术,　剪切光束。