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Shearography for specular object inspection

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ABSTRACT

Digital shearography is a laser speckle pattern interferometry based, non-destructive testing (NDT) method, which has a great potential in revealing the defects inside the objects e.g. composite materials. It has been applied successfully in various industry applications. However, due to its essence of laser speckle utilization, the object surface needs to be rough enough, otherwise, the object surface has to be specially treated. Considering the situations that the surface treatment under some cases is not allowed, an improved optical setup has been introduced and described in this paper. A modified shearography setup which can be applied on samples with specular surface is introduced. The theory and experiment results are described and presented.

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1. Introduction

Shearography, also called speckle pattern shearing interferometry, is a laser based, whole field, non-contact and nondestructive optical method that is capable of directly measuring strain information [1–3], and thus suited well for non-destructive testing of composite materials, such as glass/carbon fiber reinforced materials, honeycomb structures etc [4–7]. As a laser interferometry technology, shearography utilizes speckle interferometry which is generated by a coherent light reflected from a rough object surface. When the object under test is deformed, the speckle pattern captured by the sensor will be slightly altered. When two speckle patterns corresponding to deformed and undeformed states are obtained and subtracted, a fringe pattern, i.e. a shearogram, is generated [8,9].

In order to utilize the shearography system, the first essential requirement is the speckle pattern generated on the object surface, which demands the surface to be a rough surface. If the object surface is a mirror-like surface, most of the light will be mirror reflected and there will be little speckle generated, so that the shearography cannot be applied. For solving this problem, a traditional solution is to treat the object surface, such as spraying. However, under some circumstances, it may be impossible or forbidden to treat the sample surface. Therefore, demand for shearographic inspection on smooth surface without surface treatment is increasing.

This paper introduces a methodology of shearography for non-destructive testing of specular or quasi-specular objects without treating the surface. The theory is expressed in detail, and experiment results shown the feasibility of shearography for nondestructive testing on specular objects are demonstrated.

2. The optical setup and theoretical analysis

The modified shearography setup schematic for testing the object with specular surface is shown in Fig. 1. Comparing to the traditional shearography setup, a flat and white (rough) plane M is embedded into the light path, which changes the direction of the light path. The laser reflected from the smooth surface hits the embedded rough plane M and generates the speckle pattern required in the shearographic testing.

A coherent laser is expanded to illuminate the object. The light reflected from the object surface normally consists of two parts, the specular reflected light and diffusive reflected light. Both of the two parts carry the deformation information. Typically, the diffusive part which can generate speckle pattern is useful in shearography but the other part is not. However, when the object surface is specular or quasi-specular, most of the laser energy is mirror reflected, the speckle generated by the diffusive light is not sufficient for the measurement. To solve this problem, a rough and white image plane is embedded into the light path. When the specular reflected light reaches the rough plane, the beam will be diffusively reflected and the speckle pattern is generated. Digital shearography can make use of the speckle pattern and measure the deformation.

Same as the standard shearographic testing procedure, the speckle pattern is separated into two beams by the shearing device. The two beams merge into the CCD camera and generate the interference. The difference between the two interferograms

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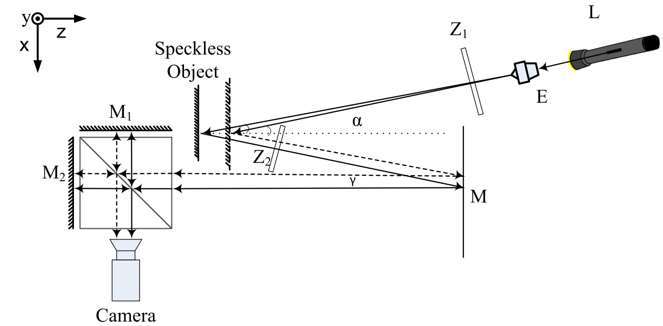

Fig. 1. Schematic of the modified shearography system; L is a laser; E is the expander; M is the embedded white and rough plane; M1 and M2 are the two mirrors in the Michelson Interferometer; α is the incident angle; γ is the image plane incident angle; $Z1$ and $Z2$ are a pair of orthogonal polarizers.

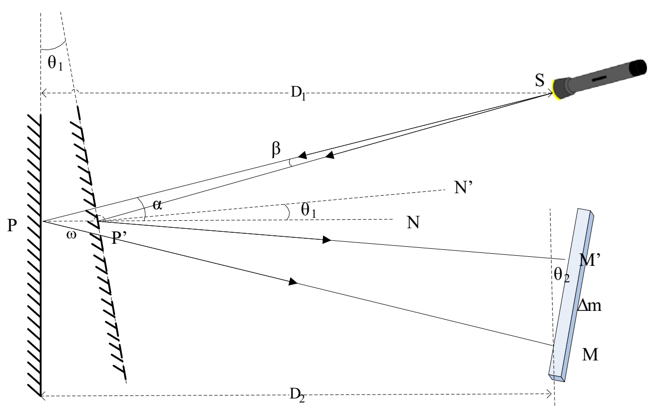

Fig. 2. The light path difference analysis. S is the laser source; P is the testing point; M is the corresponding point of P on the image plane; α is the incident angle; PN is the normal line at point P; D_1 is the distance from the object surface to the laser source and image plane; D_2 is the distance from the object to the image plane; ω is the out of deformation on point P; P' is the same point after deformation; θ_1 is the turning angle at point P due to the deformation; θ_2 is the tilting angle of the image plane; β is the incident light turning angle; $P'N'$ is the normal line at P'; Δm is the light shift on the image plane.

before and after deformation illustrates the first derivative of the deformation.

$Z1$ and $Z2$ in Fig. 1 are a pair of orthogonal polarizers. In the practical measurement, If the object is purely specular, the polarizes are not necessary, however, if the object surface is quasi-specular, the diffusive light reflected from the object is much stronger. The diffusive reflected laser will also interfere with the mirror reflected laser and generate unexpected speckle pattern mixed with the demanding signals. It will greatly influence the measurement. The orthogonal polarizers $Z1$ and $Z2$ in the system are to eliminate the disturbance and improve the measuring results. $Z1$ is located between the laser source and the object, so that the incident laser will be linearly polarized. After the laser is reflected from the object, the mirror reflected portion keeps linearly polarization but its polarization orientation is turned 90 degree, while the diffuse reflected portion will have random polarization orientations. In this case, the polarizer $Z2$ between the object to the CCD sensor, which is orthogonal to $Z1$, will allow only the mirror reflected laser to transmit and be received by the CCD sensor.

Fig. 2 shows the light path vectors and its change due to the object deformation. Because the specular reflected light does not carry the in-plane deformation, only the out-of-plane deformation ω will be discussed.

Because the distance from the image plane to the shearography sensor doesn't change during the object deformation, the light path change analysis will be only from the laser source S to the image plane M. Based on Fig. 2, the light path before deformation can be expressed by Eq. (1).

$$L_b = \frac{D_1}{\cos\,\alpha} + \frac{D_2}{\cos\,\alpha} \tag{1}$$

where D_1 is the distance from the light source to the object, D_2 is the distance from the object to the image plane and α is the incident angle; α is the incidental angle.

After deformation, due to the rotation of the point P in deformation, the reflected light on the image plane M will shift a small distance Δm. Considering rotation angle θ_1, the light path after deformation L_f can be expressed as Eq. (2).

$$L_f = \frac{D_1 - \omega}{\cos(\alpha+\beta)} + \frac{(D_2 - \omega + D_2\,\tan\,\alpha\,\tan\,\theta_2)\sin\,\theta_2}{\sin(2\theta_1 + \theta_2 - \alpha - \beta)} \tag{2}$$

where ω is the out-of-plane component of the deformation at point P; θ_1 is the rotation angle of point P; θ_2 is the tilting angle of the image plane; β is the angle change of the incidental light.

Making subtraction of Eqs. (1) and (2) on both sides, the light path difference due to the deformation is calculated by Eq. (3).

$$\Delta L = \frac{D_1 + D_2}{\cos\,\alpha} - \frac{(D_1 - \omega)}{\cos(\alpha+\beta)} - \frac{D_2(1 + \tan\,\alpha\,\tan\,\theta_2) - \omega}{\cos(\alpha + \beta - 2\theta_1 - \theta_2)}\sin\,\theta_2 \tag{3}$$

The incidental angle change β is related to the out-of-plane deformation and the original incident angle. This angle can be expressed by Eq. (4).

$$\beta = \arctan\frac{\omega\,\sin\,\alpha\,\cos\,\alpha}{D_1 - \omega\cos^2\alpha} \tag{4}$$

Considering the distance between the laser source to the object, D_1 is far bigger than the object size, so the incidental angle α is very small, and the term $\cos^2\alpha$ is close to 1. In this case, Eq. (4) can be simplified as Eq. (5).

$$\beta = \arctan\frac{\omega\,\sin\,2\alpha}{2(D_1 - \omega)} \tag{5}$$

With Eq. (5), the relationship between ΔL and ω shown in Eq. (3) is clear with all the other parameters measurable.

In the practical experiment, the optical setup can be more carefully built, so that the embedded image plane is parallel to the object plane and the laser source S is on the image plane as well. The light path vector chart is changed to Fig. 3. Comparing Figs. 2 and 3, the differences include $D_1 = D_2 = D$, $\theta = \theta_1$ and

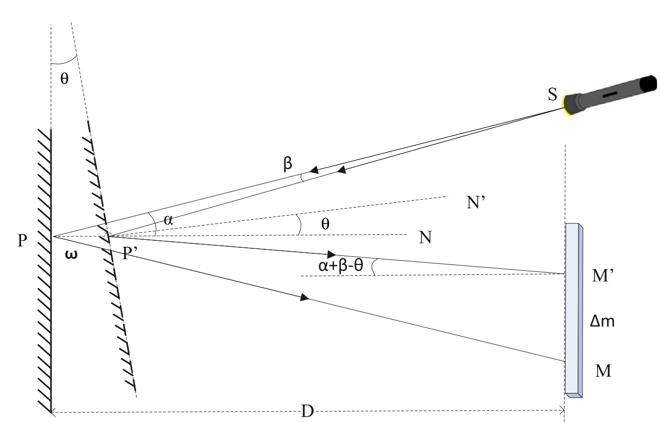

Fig. 3. The light path vector chart when the image plane is parallel to the object. D is the distance from the laser source to the object plane and the distance from the object to the embedded image plane; θ is the rotation angle of point P.

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