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HIGH ACCURACY MEASUREMENT OF STRAIN DISTRIBUTION

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Abstract: A phase-shifting speckle shearing interferometer using a TV camera to measure the strain distribution is presented. In this interferometer, two diffraction gratings are used for the spatial shearing and the phase-shifting. A strain is obtained by the spatial differentiation of the in-plane component of the deformation. In this system, the in-plane component of the deformation is obtained by the laser light illumination with two directions that are symmetric with respect to a normal line of the object surface. Spatial differentiation is achieved optically by the interference of two sheared images formed with the diffraction grating. Then, the phase change of the speckle between before and after deformation corresponds to the strain of the object. In order to measure the phase change accurately, a 4-step phase-shifting method is used. The phase-shifting is applied to the sheared diffraction light by moving the diffraction grating. The phase-shifting images are taken in to the computer and the phase change is calculated. As this calculation is done at every point over the object surface, the strain distribution can be obtained accurately. An experiment for measuring a strain of the stretched thin plate is performed with the proposed method, and the strain distribution is obtained.

Keywords: speckle shearing interferometer, phase-shifting method, strain measurement

1 INTRODUCTION

A strain measurement is a very important problem in the field of engineering. To measure the strain a strain gauge is widely used. The strain gauge has an excellent sensitivity, linearity, stability, etc. The strain gauge, however, must be pasted on a specimen, therefore this influences the deformation. Moreover, in this method only one datum at the pasted position is obtained; it is very difficult to measure the strain distribution over the specimen surface. Another method to measure the strain is to perform spatial differentiation from the value of in-plane deformation data obtained by the method for measuring the displacement distribution. But the measuring error and the statistical random noise is magnified by numerical differentiation. On the other hand, the speckle shearing interferometer for measuring the deflection gradient, which is the spatial differentiation of the out-of-plane component of the displacement, is proposed [1] [2]. In this method, the spatial differentiation is achieved optically with the use of the diffraction grating. Moreover, by moving the grating, the phase-shifting method[3] can be applied. And this optical system is the common-path interferometer type which is insensitive to the disturbance like the vibration. Then, the distribution of deflection gradient can be obtained with high accuracy without touching the object by this method. If this method can be applied to the in-plane displacement, the strain distribution will be obtained in high accuracy.

In this paper we show a phase-shifting speckle shearing interferometer using a TV camera and a computer for measuring the strain distribution with high accuracy. The diffraction grating is used for the spatial differentiation and phase-shifting. In order to measure the in-plane component of the displacement, two illuminating lights whose directions of propagation are symmetric with respect to a normal line of the object surface. An experiment to measure the strain distribution of the stretched thin film is performed and this result shows the availability of this method.

2 THEORY

A schematic diagram of a phase-shifting speckle shearing interferometer to measure the strain distribution is illustrated in Fig. 1. The object rough surface is illuminated with laser lights in two directions which are symmetric with respect to a normal line of the object surface.

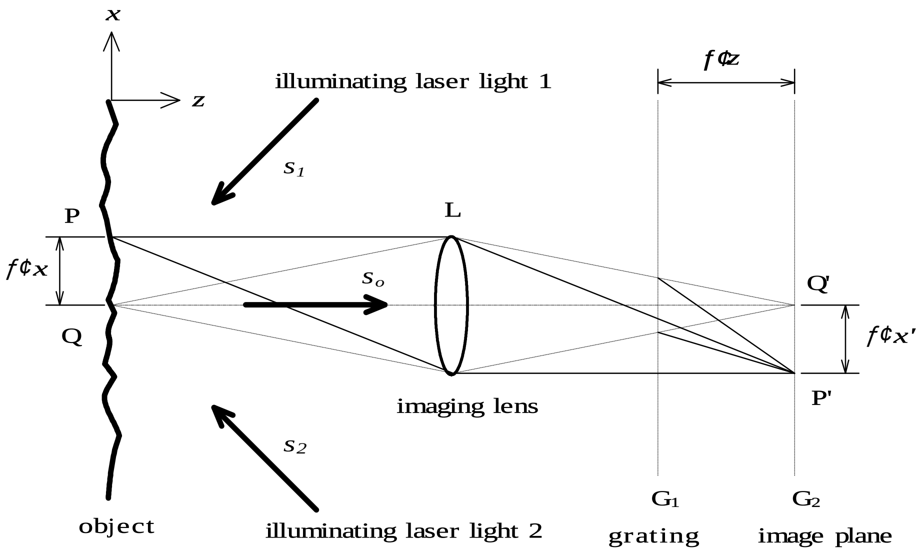

Figure 1. Optical arrangements of the phase-shifting speckle shearing interferometer.

At first, the object surface is illuminated by the light 1 whose direction of propagation is denoted by the unit vector ***s*₁**. The image of the surface is formed on the image plane by the imaging lens. A diffraction grating G_1 is placed in front of the image plane. By this grating, the light is diffracted in two directions, the 0-th order and the first order lights. In this case, the 0-th order light from the object point P and the first order light from the object point Q apart Δx from the point P are interfered at an image point P'. The light intensity at the point P' is represented as

$$I = I_P + I_Q + 2\sqrt{I_p I_Q}\cos f_1 \tag{1}$$

where I_P and I_Q are the intensities of the waves from points P and Q, which correspond to the ordinary image and the sheared image, respectively. A symbol f_1 denotes the phase difference between two waves, and this takes random value from speckle to speckle because of the statistical property of the speckle. To measure the phase f_1 precisely, the phase-shifting method is adopted. In this optical system, the phase shift can be attained by moving the diffraction grating G_1. When the grating with the period of the grooves *p* is moved by the distance *d* in the direction perpendicular to the grooves, only the phase of the first order wave is shifted by the amount $2pd/p$ rad. The phase shift 0, $p/2$, p and $3p/2$ rad can be applied by moving the grating by 0, *p*/4, *p*/2 and 3*p*/4, respectively. Then these four phase shifted images are expressed as

$$I_{b1n} = I_P + I_Q + 2\sqrt{I_P I_Q}\cos\left\{f_1 + (n-1)\frac{p}{2}\right\} \qquad (n = 1,2,3,4) \tag{2}$$

These four images are recorded in the RAM of the computer.

Next, the object surface is illuminated by the light 2 whose propagating direction is denoted by the unit vector ***s*₂** that is symmetric to ***s*₁** with respect to a normal line of the object surface. Four phase-shifted images are expressed in the same manner as equation (2).

$$I_{b2n} = I_P + I_Q + 2\sqrt{I_P I_Q}\cos\left\{f_2 + (n-1)\frac{p}{2}\right\} \qquad (n = 1,2,3,4) \tag{3}$$

A symbol f_2 denotes the phase difference between the ordinary image and the sheared image.

When the object is deformed by an amount ***u***(*x,y,z*), the phase of the speckle on the image plane is changed. The phase change df_1 for the illuminating light 1 is expressed as

$$df_1 = \frac{2p}{l}\left(s_1 - s_o\right)\cdot\frac{du}{dx}\cdot\Delta x \qquad (4)$$

where $\boldsymbol{s_o}$ is a unit vector in the observation direction. Similarly, the phase change df_2 for the illuminating light 2 is written as

$$df_2 = \frac{2p}{l}\left(s_2 - s_o\right)\cdot\frac{du}{dx}\cdot\Delta x \qquad (5)$$

In this condition, four phase-shifting images for the illuminating light 1 are written as

$$I_{a1n} = I_P + I_Q + 2\sqrt{I_P I_Q}\cos\left\{f_1 + df_1 + (n-1)\frac{p}{2}\right\} \qquad (n = 1,2,3,4) \qquad (6)$$

And four phase-shifting images for the illuminating light 2 are expressed as

$$I_{a2n} = I_P + I_Q + 2\sqrt{I_P I_Q}\cos\left\{f_2 + df_2 + (n-1)\frac{p}{2}\right\} \qquad (n = 1,2,3,4) \qquad (7)$$

From sixteen images expressed by the equations (2), (3), (6) and (7) that are recorded in the RAM of the computer, the phase changes df_1 and df_2 are calculated. The phase change df_1 between before and after deformation for the illuminating light 1 is calculated by the following equation using eight images expressed by the equations (2) and (6).

$$df_1 = \tan^{-1}\frac{(I_{b11} - I_{b13})(I_{a14} - I_{a12}) - (I_{b14} - I_{b12})(I_{a11} - I_{a13})}{(I_{b11} - I_{b13})(I_{a11} - I_{a13}) + (I_{b14} - I_{b12})(I_{a14} - I_{a12})} \qquad (8)$$

Similarly, the phase change df_2 for the illuminating light 2 is calculated by the following equation.

$$df_2 = \tan^{-1}\frac{(I_{b21} - I_{b23})(I_{a24} - I_{a22}) - (I_{b24} - I_{b22})(I_{a21} - I_{a23})}{(I_{b21} - I_{b23})(I_{a21} - I_{a23}) + (I_{b24} - I_{b22})(I_{a24} - I_{a22})} \qquad (9)$$

The difference df between phase changes df_1 and df_2 is written as

$$df = df_2 - df_1 = \frac{2p}{l}\left(s_2 - s_1\right)\frac{du}{dx}\Delta x \qquad (10)$$

In this arrangements, as a vector $\boldsymbol{s_2}$-$\boldsymbol{s_1}$ directs in the direction of the *x* axis, a scalar product ($\boldsymbol{s_2}$-$\boldsymbol{s_1}$) $\boldsymbol{u}$ is proportional to the *x* component of the deformation. Then, the differentiation of this value with respect to *x* corresponds to the *x* component of the strain. Therefore, by calculating the difference between the phase changes df_1 and df_2, the strain can be obtained with equation (10). These phase changes are accurately calculated from the equations (8) and (9) with a phase-shifting method. By subtraction of the calculated results the strain can be obtained accurately. Moreover, with carrying out this calculation whole over the object plane the distribution of the strain is obtained.

2 EXPERIMENT

To verify the usefulness of this method, a strain distribution of the stretched thin plate was measured. The experimental setup is shown in Fig. 2. An object is illuminated by the light from a He-Ne laser (l =632.8 nm). In this setup the unit vectors $\boldsymbol{s_1}$ and $\boldsymbol{s_2}$ lie on an x-z plane, and angle between $\boldsymbol{s_1}$ (or $\boldsymbol{s_2}$) and a normal line of the object surface is 45°. Then equation (10) is written as

$$df = \frac{2\sqrt{2}p}{l}\frac{du_x}{dx}\Delta x \qquad (11)$$

where u_x is an *x*-component of the deformation $\boldsymbol{u}$. The amount of a shear Δx on the object plane is

1.5 mm. The object is a rectangular thin plate (15 mm × 20 mm) whose circumference is fixed. The center point A is pulled by a weight as shown in Fig. 3. Before deformation, four phase-shifted images for illuminating light 1 and four images for illuminating light 2 are recorded in the RAM of the computer. After deformation, eight phase-shifted images for illuminating light 1 and 2 are recorded in the RAM. From these sixteen images, a shear is calculated using equations (8), (9) and (11).

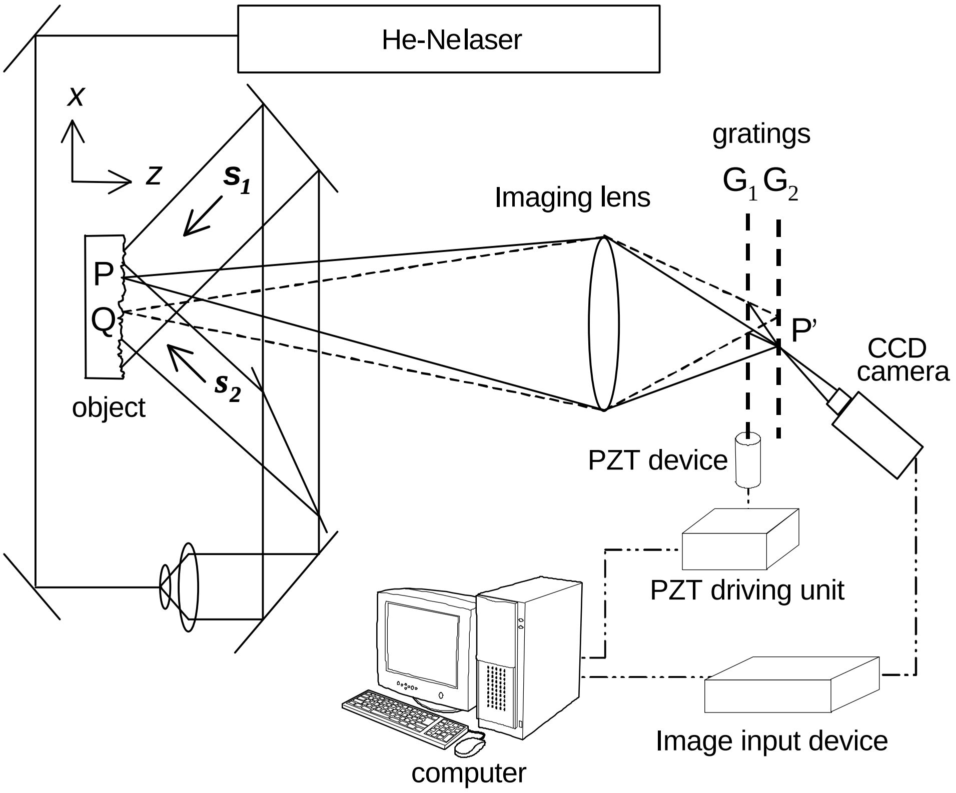

Figure 2. Experimental setup for measuring a strain distribution.

The experimental result is shown in Fig. 4. Figure 4 shows the TV monitor image of the phase difference at the hatched portion of the object in Fig. 3. In this figure the phase range $-p$ rad to p rad is expressed by the gray intensity levels from 255 to 0. The white points mean the positions of $df = -p$, and the black points mean the positions of $df = p$. In this setup, the phase difference p rad corresponds to the strain 1.5×10^{-4}.

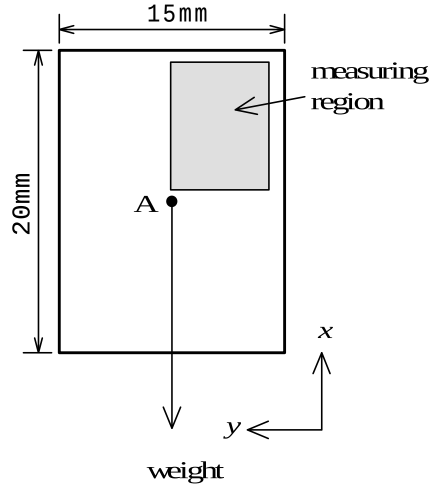

Figure 3. A measuring object

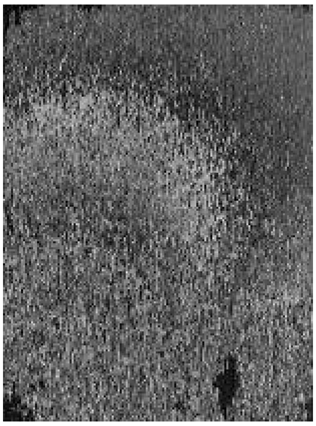

Figure 4. A strain distribution at the hatched portion of the object

4 CONCLUSIONS

The phase-shifting speckle shearing interferometer for measuring the strain distribution is proposed. In this system, the spatial differentiation of the in-plane deformation and phase-shifting are achieved by the diffraction grating. By using the images illuminated from two directions which are symmetric with respect to a normal line of the object surface, the in-plane component of the spatial differentiation of the deformation, i.e. the strain, is obtained. Therefore, the strain distribution is obtained accurately.

The experimental result with the deformed thin plate shows that the spatial distribution of the strain can be obtained by this method.

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