Measurement of Microdeformation by Transparent-Type Diffraction Moire Interferometry Using Light Control Plate*

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Moire interferometry is a method of measuring submicron displacement distribution using two or four collimated beams incident to a specimen diffraction grating. In this paper, in order to form these two or four beams, a transparent diffraction grating is used. Two types of transparent diffraction moire interferometry are developed. One uses oblique incident beams for measuring one-dimensional displacement. The other uses normal incident beams for measuring one- or two-dimensional displacement components. In the latter, the 0th-order diffraction beam is noise. This noise is removed using light control plates which were developed recently. By using this diffraction moire interferometry, a compact system for microdeformation measurement is developed.

Key Words: Experimental Stress Analysis, Material Testing, Nondestructive Testing, Moire Interferometry, Microdeformation, Light Control Plate

1. Introduction

Moire interferometry, developed by Post and colleagues⁽¹⁾, has become popular as a means of measuring displacement distribution on the whole field of a specimen. It can analyze smaller displacement than geometric moire, which uses a specimen grating and a reference grating, since it uses a diffraction grating with a considerably smaller pitch. The diffraction grating frequency is usually 1 000 to 2 000 lines/mm, and an interference fringe pattern formed by two collimated coherent beams with different incident directions is used as the reference grating. The interference fringe is called the virtual reference grating. There are two methods for separating one collimated coherent beam into a number of beams. One uses reflection from a beam splitter or mirrors.

The other uses diffraction beams from diffraction gratings. Guo⁽²⁾ put a diffraction grating (we call this grating the "base grating") just in front of the specimen grating. The method is resistant to vibration, because the specimen grating and the reference grating move almost simultaneously. However, the methods developed by Post and Guo use many diffraction gratings and mirrors, and the optical systems are slightly complicated. In particular, they become more complicated in the analysis of two-dimensional deformation which uses four beams. It is, therefore, difficult to make the optical system compact for two-dimensional analysis.

In this study, we propose a method for creating two or four collimated beams by using a diffraction grating and excluding the use of a mirror after obtaining a collimated beam. We call this method "transparent-type diffraction moire interferometry." In this method, when noise diffraction light appears from the diffraction grating, the undesired light is filtered by light control plates which were developed recently as a functional material⁽³⁾. The obtained fringe patterns are analyzed by the Fourier transform moire/grid method⁽⁴⁾⁻⁽⁷⁾ which we developed to analyze strain

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distributions accurately.

2. Principle of Transparent-Type Diffraction Moire Interferometry

2.1 Improved point compared with conventional moire interferometry

Figure 1 shows schematically the main part of a typical optical system for transparent-type moire interferometry. Two collimated beams are in the plane normal to the specimen grating lines and incident in symmetry with respect to the normal axis to the specimen grating plane. The diffraction beams are transmitted through the specimen grating. The incident angle α is adjusted so as to become the transmitted beams normal to the specimen grating plane. When the specimen is deformed, the diffraction beams are not normal slightly to the specimen grating plane and produce an interference fringe pattern showing equal-displacement lines. This fringe pattern can be regarded as the same as that in the conventional geometric moire, which is the superposition of a specimen grating and a reference grating, if the virtual grating made of the two incident collimated beams in moire interferometry is regarded as the reference grating in the geometric moire. For the diffraction moire interferometry, several systems categorized according to the combination of diffraction beams are proposed^{(1),(2)}. The two collimated beams are usually produced with some mirrors. Two mirrors are used in Guo's method for one-dimensional analysis. The method proposed in this paper uses only one transparent-type diffraction grating in order to produce two beams for one-dimensional analysis, or four beams for two-dimensional analysis. The system is more compact. The principle for measuring small displacement by using this method is shown in the following. Two methods in which the intensities of the two interference beams become equal to each other and the fringe contrast becomes optimal are described in this paper.

The interference between two beams going through a specimen grating and remaining normal to

Fig. 1 Conventional transparent-type diffraction moire interferometry

the specimen grating are used. The condition that a collimated beam is incident to the diffraction grating at angle α and the first-order diffraction beam diffracts perpendicular to the grating is⁽¹⁾

$$\sin \alpha + f_0 \lambda = 0 \quad (1)$$

where λ is the wavelength of the beam and f_0 is the spatial frequency of the diffraction grating. This equation is also used to determine the transmitted diffraction angle of the beam incident perpendicular to the grating.

2.2 Oblique incident-type diffraction moire interferometry

This method utilizes the interference of the beams that are incident to the specimen grating at an oblique angle α in the normal plane to the specimen grating lines and diffract normal to the specimen grating plane. The diffraction gratings and the diffracted beams are schematically shown in Fig. 2. A base diffraction grating with the same frequency as the specimen grating is put just in front of the specimen grating. The collimated beam A incident at angle α shown in Eq. (1) is separated into several beams by diffraction at the base grating. The 0th-order beam A_0 is incident to the specimen grating at angle α . The first-order diffraction beam A_1 is incident normal to the specimen grating. They are diffracted by the specimen grating. Both the first-order diffraction beam A_{01} of the beam A_0 and the 0th-order beam A_{10} of the beam A_1 pass through normal to the specimen grating. When the specimen is not deformed, the interference fringes do not appear, because the beams A_{01} and A_{10} coincide with each other. When the specimen, i. e., the specimen grating, is deformed, the two beams A_{01} and A_{10} are deformed and interfere with each other. The interference fringes show the equal displacement lines of the direction normal to the grating lines in the specimen grating plane.

This method gives a clear interference fringe pattern excluding the undesired diffraction beams in the normal incident type, as shown in the next section.

2.3 Normal incident-type diffraction moire interferometry

This is a method using beams incident normal to

Fig. 2 Oblique incident-type diffraction moire interferometry

the specimen grating to obtain an interference fringe pattern. Figure 3 shows schematically the optical system of the normal incident-type diffraction moiré interferometry using one-dimensional diffraction gratings to obtain an interference fringe pattern. The plane wave B incident normal to a specimen grating is diffracted at a base grating which is put just in front of the specimen grating and parallel to the specimen grating. The first-order diffraction beam B_1 from the beam B transmits the base grating at the diffraction angle α according to Eq. (1) and it is incident to the specimen grating at angle $-\alpha$. The minus first-order diffraction beam B_{-1} from the beam B is diffracted at angle $-\alpha$ at the base grating and it is incident to the specimen grating at angle α . These beams B_1 and B_{-1} are diffracted by the specimen grating. The minus first diffraction beam B_{1-1} from beam B_1 and the first diffraction beam B_{-11} from beam B_{-1} are transmitted normal to the specimen grating. These two beams produce an interference fringe pattern on the specimen grating plane according to the deformation of the specimen. It shows the equal lines of the displacement normal to the diffraction grating lines.

There is a big problem in this case. It is the existence of the 0th-order diffraction beam B_0 from beam B. It passes through the specimen grating normal to the specimen grating as beam B_{00} . The 0th-order beam B_{00} is usually stronger than the first-order beam B_{1-1} or the minus first-order beam B_{-11} . It is, therefore, difficult to observe the interference fringe pattern between the first-order and the minus first-order diffraction beams when a 0th-order beam exists. In order to remove the 0th-order diffraction beam B_0 , we use a light control plate which was developed recently. The plate can diffuse only the undesired 0th-order beam, as explained in the next section. The diffused light is removed by a spatial filter placed at the focal plane of an imaging lens.

This method can measure small displacement in the direction normal to the grating lines in the specimen grating plane. The sensitivity is a half of the

grating pitch. It is easy to adjust the system because the light source, the lens, the base grating, the specimen and the camera are parallel on the same one line. It is possible to make a compact optical system for two-dimensional displacement measurement, because it is easy to obtain four beams with the same intensity by using two-dimensional base diffraction gratings for base and specimen diffraction gratings.

3. Light Control Plate⁽³⁾

The light control plate for removing the undesired 0th diffraction beams in diffraction moiré interferometry is explained in this section. The light control plate is made of a sandwich of two glass plates and a polymer film with a layered structure like a Venetian blind. The polymer film has a light control function which diffuses the light from an incident angle within a range and passes it through, and it passes the light from the other range through itself without diffusion.

In order to express quantitatively the intensity of the luminance of a mist or a film, the 'haze factor' is used. The haze factor is defined as the following equation.

$$\text{Haze factor (\%)} = \frac{\text{Transmission factor of diffused light}}{\text{Total transmission factor}} \times 100 \quad (2)$$

If the haze factor is bigger, the transparency is lower. For example, the haze factor of a frosted glass plate is about 85%.

The total transmission factor of the light control plate is high; more than 90% in both of the transparent and translucent regions. The light control plate has excellent properties as a transparent material, and the diffusion occurs in the front region of the plate along the light path. About 80% of the transmitted light is diffused in the translucent region; then it looks like a frosted glass plate. The relationship between the incident angle of the light beam and the haze factor is shown in Fig. 4⁽³⁾.

By changing the incident angle, the transparency

Fig. 3 Normal incident-type diffraction moiré interferometry

Fig. 4 Relationship between incident angle and haze factor of light control plate

changes. The haze factor is about 80% in the diffused region but about 3% in the transparent region. The change between the two regions is steep. This steep change and the high transmittance in the translucent region, i. e., the brightness in the shielding state of view, are characteristic of this polymer material. The latter becomes noise in this study.

The factor of the diffused light to all the transmitted light is about 80% when only one light control plate is used. Since 20% of the light is transmitted as collimated light and appears on the interference fringes between the first and the minus first diffraction beams as noise, it is difficult to observe the interference fringes. We therefore use two light control plates which are superposed on each other; then the total factor of the transparency becomes about 4% and almost all of the 0th beam is diffused.

The diffused 0th beam becomes noise which is superposed on the interference fringes between the first and minus first diffraction beams. In this study, however, almost all of the noise is cut by setting a spatial filter at the focal plane of an imaging lens, and by extracting the first harmonic of the Fourier spectrum of the interference pattern.

The ideal light control plate should not affect the oblique incident beams, such as the first and minus first diffraction beams, which are incident at about 60 degrees in this study. However, the phases of the oblique incident beams are changed because of the bad flatness and bad parallelism of the glass plate. In this study, the phase of the first harmonic of the fringe pattern is analyzed, as shown in the next section, and the effect of the phase change due to the glass plate is canceled by calculating the phase difference before and after deformation. The effect of the initial deformation of the specimen is simultaneously canceled.

4. Fourier Transform Moire/Grid Method⁽⁴⁾⁻⁽⁷⁾

As automated analysis of fringe patterns using image processing, the fringe center detection method, the phase stepping method, and the Fourier transform moire/grid method are commonly used⁽⁸⁾. Since the fringe center detection method uses only the position data of the fringe center, the accuracy is not good. However, it is useful for already obtained fringe images. The accuracy of the phase stepping method is good, but it is difficult to analyze dynamic phenomena and two-dimensional phenomena because it requires some images obtained by changing phases, and it is not resistant to noise. The Fourier transform moire/grid method can analyze the phase from only one image, but it requires an almost equally spaced fringe pattern which is obtained by using carrier fringes. This method is resistant to noise. The accuracy is not

good at the regions near the edges of the image.

In the moire interferometry proposed in this study, two beams for one-dimensional analysis or four beams for two-dimensional analysis are simultaneously produced by one diffraction grating plate. It is easy to set up the system, but it is difficult to adjust each directional beam so that no interference fringes occur in both directions of the two dimensions in the initial state. If the Fourier transform moire/grid method is used and a carrier pattern is introduced, it is possible to analyze accurately the net displacement by subtracting the phase in the initial state from the phase after deformation.

The discrete Fourier transform calculates the frequency by regarding the brightness data at both edges of the image as continuous with each other. The error of the analyzed results near the edges becomes large when the fringe pattern has discontinuity at the edges.

The procedures of the analysis using the Fourier transform moire/grid method for two-dimensional diffraction moire interferometry are as follows:

(1) A carrier pattern is produced by rotating the specimen a little in the specimen plane. In this case two kinds of carrier patterns are produced simultaneously. One carrier pattern shows fringe lines perpendicular to the x -axis, and the other shows fringe lines perpendicular to the y -axis.

(2) The image of these carrier patterns is recorded with an image processor, and the two-dimensional Fourier transform of the image is calculated. Only the x -directional first harmonic is extracted.

(3) The first harmonic is shifted by the frequency of the carrier, and the inverse Fourier transform of the shifted first harmonic is calculated to obtain the complex moire fringe pattern showing the x -directional displacement distribution. If the first harmonic is not shifted and the inverse Fourier transform of the extracted first harmonic is calculated, a complex carrier pattern including the information of the x -directional deformation is obtained.

(4) By calculating the arctangent of the ratio of the imaginary part to the real part of the complex moire pattern or the complex grating pattern, we can obtain the phase distribution and calculate the displacement and strain distributions.

(5) By extracting only the first harmonic showing the y -directional deformation in procedure (2) and performing procedures (3) and (4) with respect to the y direction instead of the x direction, we can calculate the y -directional displacement and strain distributions.

In the one-dimensional analysis, only the x -directional or y -directional first harmonic can be used.

The carrier pattern obtained by mismatch can also be used.

5. Experimental Examples

In order to examine the proposed method, diffraction gratings are formed on a transparent glass plate, and they are used as base and specimen gratings. The displacement distributions are measured when the plate has only rotational deformation or it is loaded as a three-point bending beam.

5.1 Measurement by oblique incident type

Rotational deformation is applied to a specimen for oblique incident-type moire interferometry. The optical system is shown in Fig. 5. Two diffracted beams which are transmitted normal to the specimen grating image a fringe pattern with a Fourier transform lens. The pattern is recorded in an image processor with a CCD camera. A one-dimensional transparent-type diffraction grating is used as the specimen grating, as mentioned above. A diffraction grating with the same frequency as the specimen grating is used as the base diffraction grating. The spatial frequency is 1365 lines/mm. Instead of applying a deformation, the specimen is rotated by θ round the z -axis, which is perpendicular to the specimen surface, as shown in Fig. 6. The angle θ is 3.47×10^{-2}

Fig. 5 Optical system for oblique incident-type diffraction moire interferometry

Fig. 6 Rotation of specimen grating

degrees.

The fringe pattern before deformation obtained by applying the carrier due to mismatch is shown in Fig. 7(a). The image size is horizontally 445 by vertically 240 pixels. The Fourier transform of the image is calculated and the first harmonic is extracted

(a) Carrier pattern before deformation

(b) Fourier spectrum of Fig. (a)

(c) Carrier pattern after deformation

(d) Analyzed displacement distribution

(e) Theoretical displacement distribution

Fig. 7 Analyzed example of oblique incident-type diffraction moire interferometry

according to the procedures mentioned in section 4. Although this experiment is a one-dimensional analysis to obtain the x -directional displacement, the Fourier transform in the y direction is also calculated in order to eliminate y -directional high-frequency noise. That is, the two-dimensional Fourier transform of the image is calculated. The obtained two-dimensional power spectrum is shown in Fig. 7(b). From this spectrum, the first harmonic is extracted and the inverse Fourier transform is calculated to obtain a complex carrier pattern. The ratio of the imaginary part to the real part of the complex moiré pattern gives the phase value before deformation. Similarly, the phase calculation after the rotational deformation is performed for the carrier pattern image shown in Fig. 7(c). The x -directional displacement distribution obtained from the phase difference between before and after deformation is shown in Fig. 7(d). The theoretical distribution is shown in Fig. 7(e). The displacement value in Fig. 7(c) is defined as the relative displacement from the right bottom of the image. Although the error near the edges of the image is slightly large because of the Fourier transform of the discontinuous data, the accuracy of this method is fairly good.

5.2 Measurement by normal incident type

As an experiment in normal incident-type diffraction moiré interferometry, three-point bending of a glass beam is performed and the small deformation is measured. The optical system is shown in Fig. 8. The main difference between this system and the optical system shown in Fig. 5 is to input the laser beam normal to the base grating and to eliminate the undesired 0th-order diffraction beam by diffusing it with two light control plates and cutting the diffused light with a spatial filter set at the focal plane of the imaging lens. The specimen size and the coordinate axes are shown in Fig. 9.

The carrier patterns before and after deformation

Fig. 8 Optical system for normal incident-type diffraction moiré interferometry

(a) Specimen and direction of grating lines

(b) Dimensions of measured area

Fig. 9 Specimen and observed region for experiment of normal incident-type diffraction moiré interferometry

(a) Carrier pattern before deformation

(b) Carrier pattern after deformation

(c) Analyzed displacement distribution

(d) Comparison between experimental and theoretical displacement distributions along x -directional center line

Fig. 10 Analyzed example of normal incident-type diffraction moiré interferometry

are shown in Figs. 10(a) and (b), respectively. The displacement distribution is shown in Fig. 10(c). It is obtained by the Fourier transform moiré/grid method calculating the phase difference between the complex carrier patterns before and after deformation. Every $0.1\text{ }\mu\text{m}$ contour is shown in the figure.

The theoretical displacement distribution along the x -directional center line of the specimen is calculated by regarding the specimen as a straight beam under three-point bending with simple supports. The theoretical displacement is compared with the experimental results, as shown in Fig. 10(d). The origin is at the left supporting point.

The experimental displacement curve coincides well with the theoretical one. This proposed method is effective in measuring microdeformation.

6. Discussion and Conclusions

In order to develop a measurement system for microdeformation, an oblique incident type and a normal incident type of diffraction moiré interferometry have been proposed.

Since the oblique incident type uses the 0th-order diffraction beam of the first diffraction beam and the first-order diffraction beam of the 0th diffraction beam, the sensitivity is half that of the conventional moiré interferometry. However, fairly accurate results were obtained by combining it with the Fourier transform moiré/grid method.

In the normal incident type, the 0th beam with the strongest intensity becomes noise. A method for eliminating the noise has been proposed. That is, the 0th beam is diffused by the light control plate and the diffused light is filtered with a spatial filter. The remaining noise has been reduced by using the Fourier transform moiré/grid method.

Only the one-dimensional light control plate is manufactured at the present time. If a two-dimensional one is developed, it will be possible to obtain four beams simultaneously by using a two-dimensional diffraction grating. The adjustments of the four beams are simultaneously performed. Although the x - and y -directional fringe patterns are simultaneously superposed on each other, separation of the two displacement components is easily performed using the superposed fringe pattern with the two-dimensional Fourier transform moiré/grid method.

It is possible to create a compact system for small displacement measurement by improving this diffraction moiré interferometry. In order to develop a reflection-type system applying to translucent specimens, a one-way light control plate should be developed.

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