High-Sensitivity Measurement of Strain by Moire Interferometry*

Yoshiharu MORIMOTO**, Takuo HAYASHI**
and Kouzou WADA***

Moire interferometry is a useful method of measuring small displacement distribution in the whole field of a specimen. However, it is difficult to make diffraction gratings and to measure small strains of less than 10^{-3} . In order to facilitate the use of moire interferometry, we attempted to mass-produce sheets of diffraction grating by hot-press printing. By transferring the grating of one such sheet, we were able to create a diffraction grating on a specimen. To improve the sensitivity of moire interferometry, we applied a multiplication method to it. As a result, strain of the order of 10^{-4} was measured.

Key Words: Experimental Stress Analysis, Moire Interferometry, Moire, Diffraction Grating, Strain Measurement, Laser, Moire Shift Method, Hot Press

1. Introduction

Moire interferometry⁽¹⁾⁻⁽³⁾ is a method for measuring displacement. It was developed by Post from the fringe multiplication method⁽⁴⁾, which improved the sensitivity of the moire method. Because moire interferometry utilizes interference fringes of laser lights, which have 1 000~4 000 fringes/mm, as specimen and reference gratings, small displacements can be measured. It is attracting attention throughout the world as a breakthrough in the improvement of the sensitivity of the moire method.

The specimen grating for moire interferometry is made by replicating a photographic plate, which records Young's interference fringes, for use as a mold⁽⁵⁾⁽⁶⁾. However, the complicated techniques and large amounts of labor and time involved in this process

have deterred the popularization of moire interferometry in strain measurement. If molds could be easily and inexpensively produced in large quantities, this method would be more practical. Hence, we set out to manufacture polyester sheet molds with diffraction gratings very thinly overcoated with metal. We succeeded in mass-producing such molds using a hot press and vacuum vapor deposition.

By applying moire interferometry to an actual specimen, we were able to measure strain of the 10^{-3} order. Though this value was far superior to that obtainable by the ordinary moire method, it was still difficult to measure strain below the elastic limit of metals. A smaller strain could not be measured by this method without an improvement in the sensitivity of the measurement. In this paper, we apply a multiplication method to moire interferometry in an effort to obtain fringes which show higher sensitivity than those obtainable through the ordinary moire interferometry method.

2. Theory of Moire Interferometry

We shall begin by presenting an explanation of the principle of moire interferometry based on Base-

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** Department of Mechanical Engineering, Faculty of Engineering Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka, 560, Japan

*** Mitsubishi Heavy Industries, Ltd., 4-6-22 Kannonshinmachi, Hiroshima, 733, Japan

hore and Post's paper⁽²⁾. Figure 1 is a schematic of the moire interferometry method. Here, a diffraction grating with spatial frequency f_0 has been attached to a specimen. A parallel beam, A, of coherent light with a plane wavefront is incident to the specimen surface at the angle α . If we select the angle α as follows:

$$\sin \alpha = f_0 \lambda, \quad (1)$$

a diffraction beam of the first order appears vertical to the specimen surface, wherein λ is the wavelength of the light. For another beam, B, the incident angle is set $-\alpha$ in the same manner. A three-dimensional grating, i.e., a virtual grating, exists in the area where beams A and B cross each other. The frequency of this virtual grating on the specimen is exactly twice that of the specimen grating. Therefore, this system can be considered to be a moire method in which a reference grating with frequency f and a specimen grating with $f/2$ are superposed.

When the specimen is not deformed, beams A and B are reflected, and the diffraction beams Ad and Bd appear with the plane wavefront parallel to the specimen surface. Thus, no interference fringe appears between the diffraction beams. If the specimen grating is deformed in the same way as the specimen, the diffraction angles of the beams tilt slightly; the wavefronts of beams Ad and Bd are not parallel. The interference fringes appear due to superposition of beams Ad and Bd. These fringes show the contour line of displacement in the same way as the ordinary moire method, i.e., as follows:

$$U = N/f, \quad (2)$$

where N is the fringe order, and U is the displacement perpendicular to the direction of the grating lines.

One of the features of moire interferometry is that the mismatch method or the misalignment method used for the ordinary moire method can be performed easily by changing the incident angles of beams A and/or B slightly. The fringe pattern obtained by these methods is approximately parallel

Fig. 1 Schematic representation of principle of moire interferometry method

and has a constant pitch. It is called the carrier pattern. The carrier pattern includes information on specimen deformation. When the carriers before and after deformation are superposed, the deformation information can be extracted by examining the interference between the carriers.

The optical arrangement⁽¹⁾ for the moire interferometry experiment is shown schematically in Fig. 2. In this system, a symmetrical beam is produced by setting a large plane mirror perpendicular to the specimen surface. The image of the specimen surface is focused on a film in a camera by a lens in front of the camera. By making a double exposure of carrier patterns before and after deformation on the same film, or by making a single exposure on another film and overlapping the two after the development of the film, it is possible to obtain fringes which show the displacement caused by specimen deformation.

3. Shift Method

When the same two films that recorded the fringes from a deformed specimen grating or a moire fringe pattern are overlapped with a slight shift of one film, new moire fringes appear. They show the differential of the displacement, i.e., the strain distribution. For example, when a grating perpendicular to the x direction, with the spatial frequency f , is shifted to the x direction by δ_x and overlapped with the original, moire fringes appear which exhibit the strain contour given by the following equation:

$$\epsilon_x = \frac{dU}{dx} \approx \frac{\Delta U}{\delta_x} = \frac{N'}{f\delta_x}. \quad (3)$$

Because the grating used in moire interferometry has a higher frequency than that used in the ordinary moire method, even a small strain can be measured. As the shift distance δ_x , which was the disadvantage in the shift method, can be made smaller in moire interferometry than it can in the moire method, it is very effective to apply the shift method to moire interferometry.

Since the fringe pattern mentioned above is

Fig. 2 Optical arrangement for moire interferometry

Fig. 3 Process for producing specimen grating

known to be independent of the existence of a mismatch⁽⁷⁾, a shift method can be used under the condition of a carrier pattern. The shift is achieved by parallel translation of the camera and double exposure before and after the measurement, or by shifting one of the two films having the same image and overlapping following development.

4. Production of Specimen Grating

4.1 Conventional method⁽⁵⁾⁽⁶⁾

The first step in the general method is to produce a mold of the specimen grating by recording interference fringes on a high-resolution photographic plate. There are two ways of making a grating on a specimen by replication from the mold. One way is to replicate the mold using silicon rubber. In this technique, the rubber grating is used as a specimen, or as a submold, a replica of which is made on the specimen. The other way is to affix a metallic film, which is produced by vapor deposition of metal on the mold, to the surface of the specimen with adhesive. The latter method appears to be superior to the former because the metallic film grating has a high diffraction efficiency. The process we employed, which was based on Post's method⁽⁵⁾ for producing the specimen grating, is shown in Fig. 3.

The mold in Fig. 3 (a) is a photographic plate which records a grating pattern. Its surface is covered with an aluminum vapor deposition film. A mold with aluminum grating is attached to a specimen with epoxy adhesive (Fig. 3(b)). When the mold is removed from the specimen after the adhesive has cured, a wave-shaped amplitude-type grating is left on the specimen (Fig. 3(c)).

4.2 Mass production of specimen gratings

The production of the specimen grating shown in Fig. 3 involves the recording of interference fringes, development of a holographic plate, and vapor deposition of a metallic film. This process is lengthy and laborious. In particular, it is difficult to control the thickness or quality of the aluminum film in the vapor deposition process, the last process in the making of the mold. Thus, molds with metal gratings do not lend

Fig. 4 Mass-produced specimen grating

themselves to production in large quantities.

Therefore, we attempted to mass-produce diffraction grating sheets. Sheets of this type have a grating consisting of an aluminum vapor deposition layer on a polyester base film, as shown in Fig. 4. Such a sheet was used in our experiment instead of the conventional type of mold shown in Fig. 3. This sheet was created by applying techniques⁽⁸⁾ for mass-producing rainbow hologram sheets using a hot press to the diffraction grating of moire interferometry. The thickness of the aluminum layer was about $0.1\ \mu\text{m}$, and that of the grating layer was about $2\sim 3\ \mu\text{m}$. Several kinds of base films with thicknesses of $70\sim 180\ \mu\text{m}$ were made. The diffraction grating produced had the following special features:

(1) Because the grating was produced by a hot press, it had a deep groove and an excellent diffraction efficiency (about 10%). This value is almost ten times that of a specimen grating produced by the conventional method. This high diffraction efficiency makes it possible for moire interferometry experiments previously conducted only in a dark room to be performed in a lighted room.

(2) Because the gratings are mass produced, they lend themselves to use in large quantities.

(3) As a result of mass production, the cost per sheet was low. In our research, we used one such sheet as a specimen and investigated its effects.

5. Multiplication Method⁽⁴⁾⁽⁷⁾

Moire interferometry is regarded as a multiplication method of the reflection type which utilizes diffraction light of the first order. Because the frequency of the specimen grating is very high and the

diffraction angle is accordingly large, diffraction light of the second or higher order cannot be used. Therefore, moiré interferometry has a limited sensitivity. In order to increase its sensitivity, we apply a multiplication method to the carrier pattern of high frequency which is obtained by moiré interferometry. The interference pattern obtained by moiré interferometry has the same geometrical fringes as that obtained by the conventional moiré method. Therefore, it is possible to apply the multiplication method used in the conventional moiré method to moiré interferometry. Because the interference fringes in moiré interferometry are directly recorded on the film, high contrast fringes with a very small pitch can easily be recorded by producing the carrier pattern. In the multiplication method, first employed by Post⁽⁴⁾, a real reference grating was put in front of the specimen grating, and the fringes were multiplied by diffraction and interference of the beam incident to the reference grating. This method was improved by Kato⁽⁷⁾, who exchanged the real reference grating for a virtual reference grating.

The optical system of the multiplication method used in this investigation is shown in Fig. 5. The film obtained by moiré interferometry was set as shown in the figure. The fringes on the film were coarse for a diffraction grating, and thus the diffraction angle was small. Therefore, the arrangement for Michelson interferometry was used, and the half mirror was adjusted by slight turning to obtain symmetric beams incident to the film.

Let us consider a case in which the specimen deforms uniformly in the direction perpendicular to the grating lines, and the multiplication method is applied to the moiré fringes obtained by moiré interferometry.

The relationship between the pitch D' of the interference fringes and the strain ϵ is as follows

$$D' = d / (2n\epsilon), \quad (4)$$

where n is the order of the diffraction beam employed and d is the pitch of the specimen grating before deformation.

When the reference grating, which has the same

Fig. 5 Optical arrangement for multiplication method

pitch as the specimen grating before deformation, is superposed on the specimen grating after deformation, the following relationship is obtained:

$$D_0 = d / \epsilon, \quad (5)$$

where D_0 is the distance between neighboring moiré fringes. Comparing Eq. (4) with Eq. (5), we find that D' is $1/(2n)$ multiplied by D_0 for the same strain. In other words, the multiplication method using n th-order diffraction light increases both the density of the fringe and the sensitivity $2n$ times.

It is well known that the fringes obtained by the multiplication method are independent of the quantity of the mismatch of the carrier pattern⁽⁹⁾⁽¹⁰⁾. In order to multiply the fringes of moiré interferometry, the film recording the carrier pattern, which is obtained under the state without specimen deformation, is set on the optical system depicted in Fig. 5.

In the situation in which the diffraction beams of the $+n$ th and $-n$ th order agree with each other, a new carrier pattern, different from the original carrier pattern, is recorded on the film in the camera when the half mirror is turned slightly. Next, the film of the carrier pattern before deformation is replaced by the film of the carrier pattern after deformation. When a second exposure is done on the same film in the camera, only the multiplied fringes, which show the equal displacements without the initial deformation, are recorded.

6. Experimental results

The sheet of diffraction grating was processed to the specimen, as shown in Fig. 6. It was subjected to tension perpendicular to the grating lines. The results are shown in Figs. 7 and 8. They were obtained by the double exposure of carrier patterns using the apparatus depicted in Fig. 2. Figure 7 shows the full field of the sheet and Fig. 8, the partial field near the hole. As the specimen sheet had a grating of about 1 000 lines/mm, these lines are regarded as the grating lines of a moiré method in which the grating frequency is about 2 000 lines/mm.

The results of the multiplication method are shown in Fig. 9 under the same load condition as in Fig. 8. Figure 9(a) shows the fringes multiplied by two using the first-order diffraction beams, and Fig. 9

Fig. 6 Specimen (Diffraction grating sheet with hole)

Fig. 7 Fringes showing equal displacement lines at intervals of $0.49\ \mu\text{m}$

Fig. 8 Equal displacement lines (near hole)

(a) Multiplied twice (at intervals of $0.24\ \mu\text{m}$)

(b) Multiplied four times (at intervals of $0.12\ \mu\text{m}$)

Fig. 9 Equal displacement lines obtained by multiplication method

(a) At intervals of 7×10^{-4}

(b) At intervals of 3.5×10^{-4}

Fig. 10 Equal strain lines obtained by shift method

(b) shows the fringes multiplied by four utilizing beams of the second order. They therefore correspond to moire fringes in which gratings of 4 000 lines/mm and 8 000 lines/mm, respectively, are used. These values are superior to the best sensitivity ever obtained by ordinary moire interferometry.

The fringes obtained by applying the shift method to moire interferometry are shown in Fig. 10 (a). Also visible in this figure is the strain distribution. The result of applying the multiplication to the fringes, obtained by utilizing the first diffraction beam, is shown in Fig. 10 (b). As the shift amount δ_y is 0.7 mm, the fringes of Fig. 10 (a) show the strain at intervals of 7×10^{-4} and the fringes of Fig. 10 (b) show the strain at intervals of 3.5×10^{-4} .

7. Conclusions

(1) Mass-produced sheets of a diffraction grating, made from polyester sheet using a hot press, were developed and applied to the moire interferometry.

(2) The multiplication method was applied to the carrier pattern obtained by moire interferometry. A fringe pattern with a higher sensitivity of displacement than that achievable by ordinary moire interferometry was obtained.

(3) The shift method yielded the fringe pattern with the highest sensitivity. Strain of the order of 10^{-4}

was measured.

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References

- (1) Post, D. and Barakat, W. A., High-sensitivity Moire Interferometry—A Simplified Approach, *Exp. Mech.*, Vol. 21, No. 3 (1981), p. 100.
- (2) Basehore, M. L. and Post, D., Moire Method for In-plane and Out-of-plane Displacement Measurements, *Exp. Mech.*, Vol. 21, No. 8 (1981), p. 321.
- (3) Weissman, E. M. and Post, D., Full-field Displacement and Strain Rosettes by Moire Interferometry, *Exp. Mech.*, Vol. 22, No. 9 (1982), p. 324.
- (4) Post, D., Analysis of Moire Fringe Multiplication Phenomena, *Appl. Opt.*, Vol. 6, No. 11 (1967), p. 1938.
- (5) Basehore, M. L. and Post, D., High-frequency High-reflectance Transferable Moire Gratings, *Exp. Tech.*, Vol. 8, No. 5 (1984), p. 29.
- (6) Kato, K., Murota, T. and Takahashi, T., Improvement of Technique of Replicating High Density Grating for the Moire Method, *J. of NDI, Jpn. Soc. for Nondestructive Inspection*, (in Japanese), Vol. 33, No. 11 (1984), p. 851.
- (7) Kato, K., Moire Method Using Interference of Diffraction Light, *Science of Machine* (in Japanese), Vol. 29, No. 7 (1977), p. 830.
- (8) Koderu, T. and Yamazaki, S., Practical Method for Mass-Producing Hologram Replicas, *PIXEL*, (in Japanese), No. 14 (1983), p. 124.
- (9) Kato, K., Murota, T. and Morita, K., On the Method of Measuring Strain by Use of diffraction at Mis-matched Moire Fringes, *Bull. JSME*, Vol. 19, No. 128 (1976), p. 81.
- (10) Kato, K., Murota, T. and Ishida, A., On Interferometry for Measurement of Shear Strain and Rotation by Using Diffraction Beams, *Bull. JSME*, Vol. 21, No. 158 (1978), p. 1222.