A New Method for Strain Measurement by Using Multiple Color Filtering

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Abstract

A semi-quantitative measurement of the strain distribution by two-dimensional color display is presented. The strain components are converted into color band intensity distributions in the image of the specimen. The method is based on an optical technique with the aid of the spatial filtering theory. To show a usefulness of the method, it was carried out to measure the strain distribution of a plane plate with a round hole.

Introduction

There are several methods for measuring two-dimensional strain (or stress) distribution in a plane plate. The Holographic method\textsuperscript{[1]} and moire analysis\textsuperscript{[2]} are most widely used at present. In the former method, the stress distribution is obtained indirectly by using interference fringes obtained for the actual specimen. In the latter method, the information about the lines of equal displacement is converted into the fringes on the specimen. In both methods, further time-consuming numerical calculations are to be made at each point of the specimen in order to get the strain values. In addition, further supplementary experiments must be made in order to determine the sign (elongation or contraction). The strain measurement using the optical differentiation is based upon the direct display of the strain in an analog light intensity\textsuperscript{[3,4]}. However, when it comes to an intuitive observation by the naked eye instead of the micro photometric procedure, it is better to display the strain distribution with the aid of colors, because colors give much information to human eye.

In this study, a semi-quantitative measurement of the strain distribution by two-dimensional color display is presented. A light source yielding multiple colors is used in the modified optical arrangement adopted in the foregoing experiments.

Principle

The optical system for the processing is shown in Fig. 1, together with the coordinates. Without loss of generality, we can discuss the one-dimensional case, which leads to a simpler mathematical treatment. In this case, we consider the measurement of $\varepsilon_u$, where the grating grooves on the object are parallel to V-axis. The axis is vertical to U-axis on the object plane. G\textsubscript{1} is a diffraction grating to disperse the white light from a source S\textsubscript{0}. S\textsubscript{1} is a plate having many

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rectangular slits, which is placed in the back focal plane of lens L2 with the slits in such a position that vertical direction of the slit is at right angle to X-axis. When we set that the focal length of the lens L2 is $F_1$, and the grating constant of the grating $G_1$ is $D_1$, the central position of the $k$-th slit on $S_1$ is put in a position expressed by the following equation:

$$ (X_{-1})_k = \frac{F_1}{D_1} (\lambda_g + k\Delta\lambda) \quad k = 0, \pm 1, \pm 2, \cdots $$

where $(X_{-1})_k$ is the distance to the optical axis, $\lambda_g$ is the wavelength of the light transmitted through the center of the 0-th slit and $\Delta\lambda$ is the difference between the two wavelengths transmitted by the two adjacent slits. Subscript g shows green.

Now, a transparent grating $G_2$, whose grating constant is $D_2$, is placed in the object plane $P_2$ and illuminated by plane parallel light waves from the apertures in $S_1$. Then the position of the +1 st order spectral component produced by $G_2$ from a light wave transmitted by the $k$-th aperture of $S_1$ is:

$$ (X'_{-1,+1})_k = \left( \frac{F_1}{D_1} - \frac{F_2}{D_2} \right) (\lambda_g + k\Delta\lambda) $$

where $(X'_{-1,+1})_k$ is the distance to the optical axis and $F_2$ is the focal length of lens $L_4$. Just behind the spectrum plane, a single slit $S_2$ is placed in such a position, that its center line is positioned at the distance $(X'_{-1,-1})_0$ under the
condition that \( k = 0 \). If the grating \( G_1 \) is unevenly strained and consequently the grating constant \( D_2 \) changes to \( D_2' \) on a region under being stressed, the wavelength of the light which passes through the single slit aperture changes to \( \lambda' \), if an integer \( k \) exists to fill the relation, \( \lambda' = \lambda + k \Delta \lambda \). Then the image of the region will appear in another color having the wavelength \( \lambda' \). If such the integer \( k \) does not exist, the region becomes dark because no light will arrive there. Since the strain at the region in the U-direction can be given by \( (D_2' - D_2) / D_2 = \varepsilon_u \), we have from Eq. (2),

\[
\varepsilon_u = \frac{k(N_2 - N_1)\Delta \lambda}{N_2 \lambda \Delta \varepsilon + k \Delta \lambda N_1}
\]

where \( N_1 = F_1 / D_1 \) and \( N_2 = F_2 / D_2 \). By counting the number \( k \) and knowing the sign from the color at the region to be investigated, we can measure the strain values as the two-dimensional color information over the whole field of the specimen. The other components of the strain \( \varepsilon_x \) and \( \varepsilon_{x/4} \) can be analogously obtained by rotating the grating \( G_2 \) over \( \pi / 2 \) and \( \pi / 4 \) in the plane \( P_2 \).

**Experiments**

To prove the validity of the above principle, the following simple experiment was performed. We prepared a grating \( G_2 \) whose pitch is parallel to the V-direction, and its pitch was gradually increased and decreased in the both edges. The specimen was made of a stainless steel sheet of 0.1mm in thickness, on which such a grating as described above had been engraved by photo-etching. The pitch in the center was 35 \( \mu m \) and linearly changing by a stress of \(-21\%\) (contraction) and \(+15\%\) (eloggation) at the respective edges. The optical dimensions of the system were \( F_1 = 200mm \) and \( F_2 = 600mm \) and the aperture size of \( S_2 \) was 40 \( \mu m \). The aperture of the multiple slits were designed to make the standard wavelength \( \lambda_s = 546.1nm \) and \( \Delta \lambda = 8.0 \) nm. Figure 2 shows the resultant image after processing. The central arrow makes the center of grating (\( \varepsilon_u = 0.0\% \)) and this region corresponds to \( \lambda_s \) (green color). The left hafe corresponds to \( \lambda' < \lambda_s \) and the right hafe corresponds to \( \lambda' > \lambda_s \). By knowing the number of \( k \) by counting the black bands in the image, the strain values can be calculated from Eq. (3). The comparison between the strain values obtained by this experiment and those obtained by measuring directly with a tool maker’s microscope confirmed the validity of the present principle.

Other experiment of practical importance was also carried out for a plane plate with a round hole made by aluminum as shown in Fig. 3. Tension test was done for the direction of U-axis. Figure 4 shows a sketch of the resultant image. Each color corresponds to the wavelength. The numerals in the figure show the strain values which were computed from Eq. (3). The result of Fig. 4 lends us to the conclusion that the measuring accuracy of the method of optical differentiation is superior to the present one, but that the intuitive observation in the present method is superior to the method of optical differentiation. A flat specimen with notches is submitted to the action of tensile forces uniformly distributed over the ends as shown in Fig. 5. Figures 6 (a) - (e) show the measuring results recorded with increases of forces. It is found out clearly by each color that the strain distributions in the neighborhood of notches are changed with increases of forces.
Fig. 3 Schematic diagram of the specimen with a round hole. It was 1.6mm in thickness. A cross grating, whose grating constant $D_j$ is 75 $\mu$m, is placed on the area of 50$\times$75 mm$^2$ as shown in the figure.

Fig. 4. The resultant sketch of the specimen used in Fig. 3. The numerals in the figure show the strain values ($\varepsilon_{v}$) in percentage. Letters correspond with colors as shown in Fig. 2.

Fig. 5 Schematic diagram of the specimen with notches submitted to a uniform tension.
Fig. 6 (a)-(e) The measuring results recorded with increases of forces. Forces were increased gradually from (a) to (e).
Conclusions

The present method has same merits as optical differentiation for the representation of the strain of the plane plate. However, the measuring accuracy of the strain by means of optical differentiation is superior to the present one. On the other hand, the most attractive merit of this method is its easy processing, given much information on the strain distribution, especially when either contraction or elongation occurs in the plane plate.

References


和文抄録

多重カラーフィルタリングによるひずみ測定の新しい方法

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白色光源を用いた再回折光学系によって、ひずみの分布を色相の帯の分布として表示する方法を開発した。この方法により、ひずみが像面で色相の分布に変換されるので、肉眼により試料の全視野的なひずみの分布ならびに縮みおよび伸びの区別が行える。ひずみ量の定量が可能である。その原理と検証実験について述べ、応用実験として円孔および切欠きを有する平板の引っ張り試験による実験結果を述べた。