Shape measurement by the grating projection technique in a microscope

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1. Introduction
Many methods for measuring the three-dimensional shape of electronic components and small parts in a short time have been proposed. For nocontact measurement optical techniques, such as, confocal imaging, moire and grating projection methods, are desired [1-2]. In the moire method and the grating projection method, to illuminate the object from the oblique direction, the structure of optical systems becomes complex. We focus on the grating projection method and improve the method.

The accuracy of measurement by the grating projection method is low. To raise the accuracy, a suitable analytical method is necessary. The phase shift [3-4], the FFT [5-6], and wavelet methods [7-9] are used for the analysis of modulated gratings. The phase shift method is suitable for a static analysis because several images recorded at different times are used. The FFT method and the wavelet method are suitable for dynamic analysis because only one image is used. We use the sine-cosine transform method to analyze the modulated gratings, because the process is simple and the spatial resolving power can be suitably chosen.

In this paper, shape measurement by a grating projection technique using a microscope and the analysis by a two-dimensional sine-cosine method are proposed.

2. Optical system
In a microscope, the optical intensity of the conventional light source is irregular. The light beams with uniform intensity distribution are needed to illuminate the grating. The Koehler illumination system is used to eliminate the irregularity of optical intensity in the microscope and is adapted in this proposed system. To project a grating at a fixed illumination angle on the object, the optical axis of the objective lens should be parallel to the optical axis of the illumination lens. The optical system is shown in Fig. 1.

The light beam radiated from the light source is collimated by lens 1, and the grating is illuminated with a uniform intensity. An image of the light source is formed near objective lens 3 by lens 2 and the image is transformed to parallel light by the objective lens. The collimated light, which is sinusoidal and has high intensity, illuminates the object. The grating is projected onto the object. The optical axis of the objective lens is parallel to the axis of lenses 2 and 3, in order that the grating

![Fig. 1 Optical setup](image-url)
is projected at a fixed illumination angle on the object. The object and the projected grating are imaged on the charge coupled device (CCD) by lenses 3 and 4, and a grating modulated by the object shape is obtained.

3. One-dimensional sine-cosine transformation

For simplicity, the one-dimensional sine-cosine transform is explained as shown in Fig. 2. The broken line $h(x)$ in Fig. 2(a) represents the intensity distribution of the modulated grating to be analyzed, and it is phase-modulated by the shape of the object. The solid line in the figure is the product of the Gaussian window multiplied by the sine waveform, and we call the solid line a sine-packet, which is an imaginary component $s(x)$. In the figure, the frequency $v$ of the analyzed intensity distribution $h(x)$ agrees with the frequency of the sine-packet $s(x)$. Similarly, a cosine-packet which is a real component $c(x)$ is shown in Fig. 2(b). The sums of the products of each of the two packets multiplied by the analyzed intensity distribution, that is, $si$ and $sr$, are given by the following equations.

$$si = \int h(x) \cdot s(x) \, dx$$  \hspace{1cm} (1)

$$sr = \int h(x) \cdot c(x) \, dx$$  \hspace{1cm} (2)

Spectrum $S$ is given by the following equation.

$$S = \sqrt{si^2 + sr^2}$$  \hspace{1cm} (3)

The value of $S$ is maximum when the frequency of the packet is the same as that of the analyzed intensity distribution. The phase $\theta$ of the intensity distribution when the value of $S$ is maximum is describe by the following equation.

$$\theta = \tan^{-1}\left(\frac{si}{sr}\right)$$  \hspace{1cm} (4)

Using this phase, the shape of the object is calculated.

4. Two-dimensional sine-cosine transformation

In the two-dimensional sine-cosine transformation, two-dimensional packets are used. The analysis packets of various frequencies are considered as well as the one-dimensional sine-cosine transformation. Furthermore the rotations of the analysis packets are also varied. Figs. 3(a), 3(b) and 3(c) show analysis packets $s(x, v, \alpha)$ for selected frequencies and rotational angles $\alpha$. The sum of the products of the two-dimensional analysis packets $s(x, v, \alpha)$ multiplied by analysis packet $h(x,y)$ is calculated. The frequency $v$ and the angle $\alpha$ of the analysis packet at which the spectrum becomes maximum are obtained. The phase $\theta$ of the grating on the point is obtained using Eq. (4).
5. Experimental results and discussion

In the experiments, the sensitivity of the system was obtained as follows. Some objects with known height difference were measured, and the sensitivity of the system was determined from the result. By combining multiple block gauges, height differences of 10µm units were generated, and the quantity of shear of the modulated grating was measured. The measurable range of height difference was 300µm in this system because of the depth of focus.

An example of a modulated grating image projected onto an object with a height difference of 90µm is shown in Fig. 4(a). Stripes are modulated gratings and a wide line perpendicular to the stripes is the boundary between the two block gauges. Fig. 4(b) shows a phase distribution obtained by the two-dimensional sine-cosine transformation. The phase difference between the two block gages with a height difference of 90µm is 3rad. Some objects with height differences were tested, and the results are shown in Fig. 5. In the figure, the horizontal axis is the phase difference obtained by the analysis, and the vertical axis is the measured height difference \( Z \) of the object. The relation of \( Z=30.02\alpha \) was obtained in the experiments. The error of about 5µm (2%) occurred for the measurement range of 300µm.

The shapes of some objects were measured. Fig. 6 shows a modulated grating pattern on a coin, and shows the analytical result. The results are shown as a gray-scale image and a height representation. About 40 seconds are necessary for the analysis of 300x300 pixels by two-dimensional sine-cosine transformation, where the computer had a Pentium 4 Processor 2.60C GHz with 1GB of RAM.
6. Summary

In this paper, shape measurement by a grating projection technique using a microscope and analysis using a two-dimensional sine-cosine method were proposed. In a microscope system, a grating can be projected onto an object from an oblique direction with uniform optical intensity.

For example of micro-objects, a coin was measured by the grating projection technique and the two-dimensional sine-cosine transformation. The measurement error was about 2% for the measurement range of 300 µm. The frequency, the direction and the phase of the modulated grating were obtained continuously. The phase connection in the two-dimensional image analysis could be accomplished.

References