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Crosstalk Compensation for Three-Wavelength Interferometry

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A crosstalk compensation technique is proposed for three-wavelength single-shot interferometry. This technique is essential when a commercially available RGB LED illuminator and a color camera are used for the imaging system. Based on a linear model, the crosstalk compensation algorithm is derived. The crosstalk coefficients are obtained from the linear regression analysis of the R,G,B signals in three images captured with a different LED illumination. The effectiveness of the proposed technique has been confirmed by several methods. Finally, it has been applied to the single-shot interferometric measurement of 1 μm step height. The algorithms used and experimental results are presented.

Key words: crosstalk compensation, three-wavelength, interferometry, surface profiler, single-shot

1. Introduction

In recent years, in various industrial fields such as semiconductors and LCD panels, there is an increasing demand for accurate measurement of surface profiles on the order of nanometers. The surface profile measurement method using optical interference is the most promising measurement method from the viewpoint of speed, measurement accuracy, and maintainability.

In the phase shifting method [1)], which is a typical optical interferometry method, multiple interference images are taken while changing the relative distance between the measurement surface and the reference surface of the interferometer, and the surface profile is estimated from that information. With this method, it is necessary to capture multiple images, so there is a problem that the accuracy is greatly reduced in an environment with disturbance such as vibration. As a solution to this problem, a single-shot measurement method for obtaining the surface profile from a single image has been proposed. A typical method is to generate carrier fringes by tilting the reference plane, which is called spatial carrier fringe method [2)-8)] (**Fig. 1**). From one interference fringe image (**Fig. 2**) obtained by this method, the surface profile can be obtained by Fourier transform method [3)], spatial phase synchronization method [4)-6)], or local model fitting method (LMF method) [7)8)].

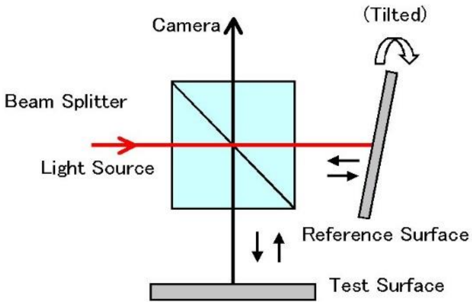

Fig. 1 Optics of spatial carrier method.

Fig. 2 Interferogram with carrier fringes.

However, since the fringe order cannot be determined from one fringe image, there is a problem that correct phase unwrapping cannot be performed when there is a step difference of 1/4 or more of the light source wavelength between adjacent pixels. In order to solve this problem, the author realized a dual-wavelength simultaneous imaging system using a color camera and two blue and red color LEDs, and succeeded in measuring a step of 350 nm by two-wavelength single-shot interferometry.[9)10)] In this method, only the B and R signals of the color camera are used in order to avoid the crosstalk between the signals of two wavelengths.

However, crosstalk compensation is indispensable in order to realize a three-wavelength single-shot measurement using G signals for the purpose of further expanding the measurement range. Crosstalk here means that the R, G, B components of a color camera do not completely correspond to the illumination light of three colors because the spectral sensitivity distributions of the R, G, B components of the camera overlap. It means that, for example, the signal from the B illumination is also mixed in the G component of the camera.

By the way, Pfortner et al.[11)] proposed an interferometric method using a multi-wavelength simultaneous illumination light source and a three-chip color CCD camera as in this report. There, three lasers are used as a light source. The three-wavelength phase shifting method is realized. However, details of the optical system have not been reported, and crosstalk compensation is not performed as unnecessary.

On the other hand, in the field of three-dimensional measurement using the color projection method, there have been some reports regarding crosstalk compensation.[12-16)] For example, Sato et al.[14)] performed crosstalk compensation between RGB channels of a LCD projector and a color camera in a range finder study based on the color pattern projection method.

The author applied the concept of compensation in the color projection method to single-shot interferometry, and obtained good results. In addition, a method of confirming the effectiveness of crosstalk compensation was examined by utilizing the fact that the light source for interferometric measurement is approximately monochromatic. In this paper, we report the algorithm of crosstalk compensation, how to obtain the crosstalk coefficients, how to confirm the compensation effectiveness, and some experimental results.

2. Imaging system

The imaging system consists of a commercially available 3-color LED lighting device (CCS, model HLV-3M-RGB-3W) and a color camera (Bastler, model sca640 -70gc) shown in **Fig. 3**. **Table 1** shows the specifications of the lighting system. The LED peak wavelengths (catalog value)[†1] are 470 nm, 530 nm, and 627 nm. The bandwidth (FWHM) is 20-35 nm. This means that the coherent length is approximately 10 to 20 µm, and interference fringes can be obtained over the entire imaging surface unless the relative tilt angle between the reference surface and the sample surface is too large.

Figure 4 shows the spectral sensitivity characteristics of the color camera used and the peak wavelengths of the three LEDs. When these three LEDs are turned on and a color camera is used for imaging, a three-wavelength interference image is obtained. However, since the R, G, B spectral sensitivity curves of the camera overlap each other, crosstalk occurs between each signal. In particular, the crosstalk from the B wavelength component to the G signal is estimated to be several tens of percent, and crosstalk compensation is necessary.

Table 1 Specifications of LEDs (typ.)

Color	Peak Wavelength (nm)	FWHM (nm)
R	627	20
G	530	35
B	470	25

3. Crosstalk compensation method

As described in Chapter 1, the concept of crosstalk compensation in the color projection method [12-16] can be applied to interferometry. That is, it is assumed that crosstalk is represented by the following linear model.

$$\begin{cases} B' = B + aG + bR \\ G' = cB + G + dR \\ R' = eB + fG + R \end{cases} \tag{1}$$

where *B', G', R'* are the observed intensity values, *B, G, R* are the true values, and *a, b, c, d, e, f* are the coefficients representing the crosstalk. Since the coefficients are as small as a few percent except for *c*, the true values can be calculated by the following equation, ignoring the product terms of the coefficients.

$$\begin{cases} B = B' - aG' - bR' \\ G = -cB' + G' - dR' \\ R = -eB' - fG' + R' \end{cases} \tag{2}$$

How to find the coefficients is described in Section 4.2.

4. Experimental results and discussion

4.1 Experimental method

The experimental setup is shown in **Fig. 5**. It was made for three-wavelength single-shot measurement: the light source is a three-color (RGB) LED lighting device, and the interference image is captured by

†1 Only the dominant wavelength is described in the catalog, and the peak wavelength is unknown. However, since the difference between them is estimated to be around several nm, it is referred to as the peak wavelength in this paper.

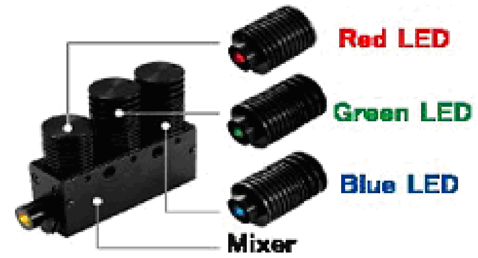

Fig. 3 RGB-LED illuminator.

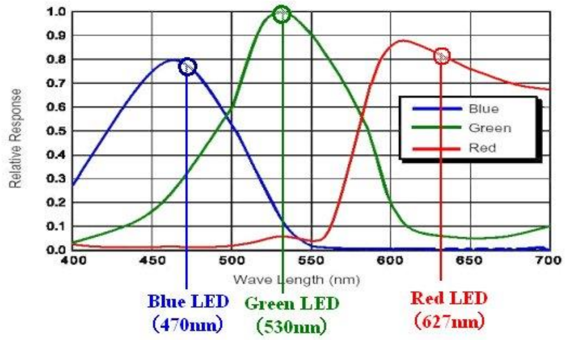

Fig. 4 Spectral sensitivity of the color CCD camera, with the peak wavelengths of three LEDs.

a color camera. **Figure 6** shows an interference image of a 1 µm standard step sample. There is a concave step at the bottom center. When this image was decomposed into the RGB color components, **Fig. 7** was obtained. It is observed that the fringe period changes depending on the wavelength.

4.2 Estimation of crosstalk coefficients

First, the crosstalk coefficients of this imaging system was estimated. The first row of **Fig. 8** shows the three color images obtained by turning on only one LED. When these images are color-decomposed, they become as shown in columns 2 to 4 of Fig. 8, and the approximate crosstalk magnitude can be estimated visually. From the R, B, and G values at each pixel of the color image, for example, the correlation diagram shown in **Fig. 9** is obtained. This figure shows the correlation between *B*, *G*, and *R* when the B-LED is turned on. From the regression coefficient, the crosstalk coefficient $c = 0.28$ and $e = 0.01$ were obtained. From similar experiments, the coefficient matrix was obtained as shown below. It is close to the value expected from the spectral characteristics in Fig. 4.

$$\begin{pmatrix} 1 & a & b \\ c & 1 & d \\ e & f & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0.05 & 0.00 \\ 0.28 & 1 & 0.04 \\ 0.01 & 0.04 & 1 \end{pmatrix}$$

4.3 Crosstalk compensation and effectiveness confirmation methods

Using these coefficients, the crosstalk was compensated by Eq. (2), and its effectiveness was confirmed by the following multiple methods.

(1) Intensity correlation

Figure 10 shows the correlation among the RGB values after compensation. Compared with the correlation diagram before compensation (Fig. 9), it shows that the crosstalk is completely

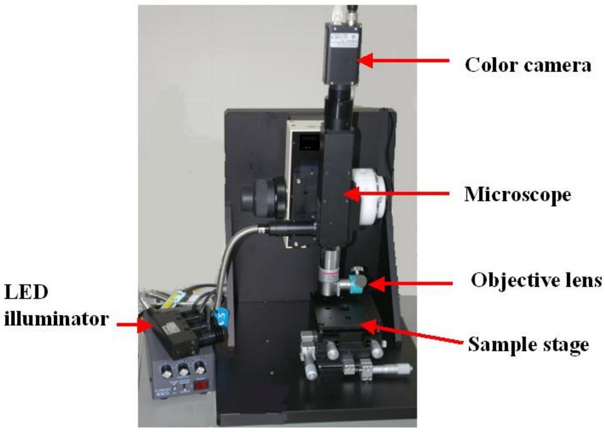

Fig. 5 Experimental setup.

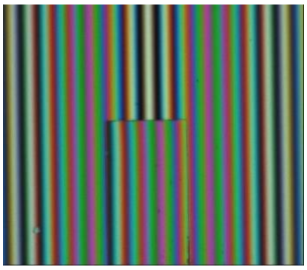

Fig. 6 Captured color image.

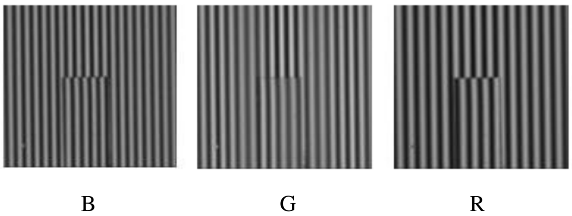

Fig. 7 Extracted B, G and R components.

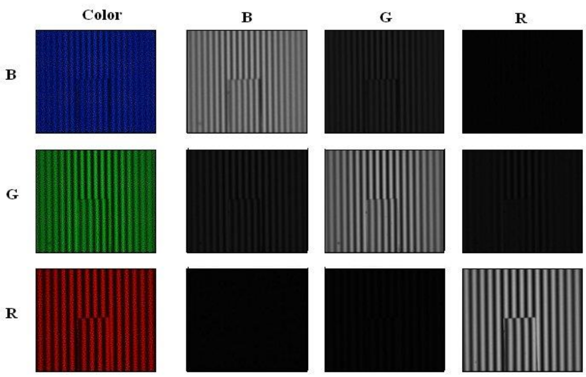

Fig. 8 Crosstalk effects between color channels.

removed.

(2) Comparison of signal waveforms

Figure 11 shows the G-signal waveforms before and after the compensation. A beat signal due to the mixture of two frequencies is observed in the waveform before compensation, but it disappears after compensation.

(3) Comparison of frequency spectra

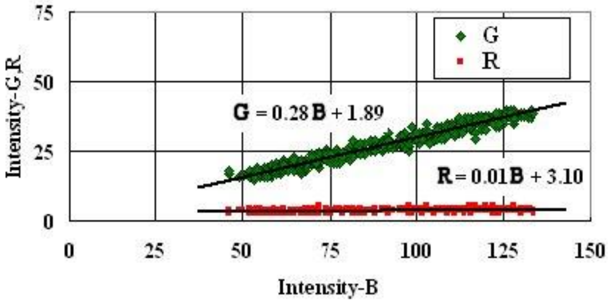

Fig. 9 Correlation among the RGB values before compensation.

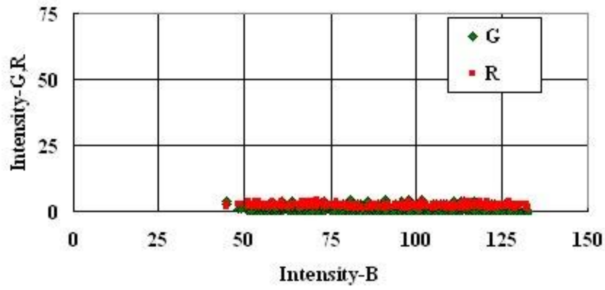

Fig. 10 Correlation among the RGB values after compensation.

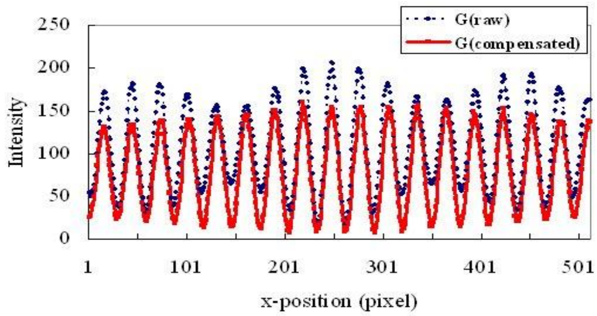

Fig. 11 Effect of crosstalk compensation: comparison of signal waveforms.

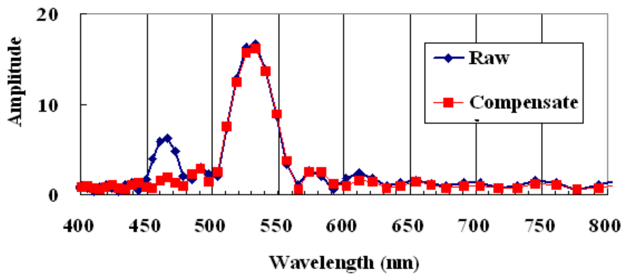

Fig. 12 Effect of crosstalk compensation: comparison of signal spectra.

Figure 12 shows the frequency spectra of the G-signal before and after compensation. It was confirmed that the wavelength component around 470 nm was removed by the compensation.

5. Application to single-shot interferometry

The proposed crosstalk compensation method was applied to three-wavelength single-shot interferometry. **Figure 13** shows the flowchart of the measurement. Crosstalk compensation was performed on all BGR signals, and the height of each pixel was obtained through phase calculation and unwrapping. The measurement results are shown in **Fig. 14**. This result agrees well with the measurement result by the white light interferometry, confirming the validity and effectiveness of the proposed method.

6. Conclusion

In this report, we proposed a crosstalk compensation method for three-wavelength single-shot interferometry. A linear model of crosstalk was used, assuming that the RGB signals of the color camera are the sum of the signals from the three-wavelength light source. The crosstalk coefficients were obtained from the correlation analysis of the RGB signals which were taken by turning on only one LED light source. The compensation effectiveness was confirmed by the evaluation method using the fact that the light source is almost monochromatic. Furthermore, using this compensation method, we succeeded in measuring a 1μm step height by the three-wavelength single-shot interferometry. High-speed single-shot interferometry that is not affected by vibration is suitable for on-machine or on-line measurement, and is expected to find wide application fields in industry.

References

1) J. H. Brunning et al.: Digital wavefront measuring interferometer for testing optical surfaces and lenses, Appl. Opt., **13**, 2693/2703 (1974).
2) J. Kato: Real-time fringe analysis for interferometry and its applications, J. Jpn. Soc. Precis. Eng., **64**-9, 1289/1293 (1998) (in Japanese).
3) M. Takeda, H. Ina, and S. Kobayashi: Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry, J. Opt. Soc. Am., **72**, 156/160 (1982).
4) S. Toyooka and M. Tominaga: Spatial fringe scanning for optical phase measurement, Opt. Commun. , **51**, 68/70 (1984).
5) K. H. Womack: Interferometric phase measurement using spatial synchronous detection, Opt. Eng., **23**, 391/395 (1984).
6) J. Kato, I. Yamaguchi, T. Nakamura, and S. Kuwashima: Video-rate fringe analyzer based on phase-shifting electronic moire patterns, Appl. Opt., **36**, 8403/8412 (1997).
7) M. Sugiyama, H. Ogawa, K. Kitagawa and K. Suzuki: Single-shot surface profiling by local model fitting, Appl. Opt., **45**, 7999/8005 (2006).
8) M. Sugiyama, T. Matsuzaka, H. Ogawa, K. Kitagawa and K. Suzuki: One-shot profiling of sharp bumpy surfaces, JSPE Spring Meeting, 585/586 (2007) (in Japanese).
9) K. Kitagawa, M. Sugiyama, T. Matsuzaka, H. Ogawa, and K. Suzuki: Two-wavelength single-shot interferometry, Proc. of SICE Annual Conference 2007, 724/728 (2007).
10) K. Kitagawa, M. Sugiyama, T. Matsuizaka, H. Ogawa and K. Suzuki: Two-wavelength single-shot interferometry, J. Jpn. Soc. Precis. Eng., **75**-2, 273/277 (2009) (in Japanese).
11) A. Pfortner and J. Schwider: Red-green-blue interferometer for the metrology of discontinuous structures, Appl. Opt., **42**, 667/673 (2003).
12) D .Caspi, N .Kiryati and J .Shamir: Range imaging with adaptive color structured light, IEEE Trans. on Patt. Anal. Machine Intell., **20**, 470/480 (1998).
13) P. S. Huang, Q. Y. Hu, F. Jin, and F. P. Chiang: Color-encoded digital fringe projection technique for high-speed three-dimensional surface contouring, Opt. Eng., **38**, 1065/1071 (1999).
14) T. Sato and H. Tsukune: Range finder using color space coding patterns, Proc. of Technical Meeting, IEE Japan, SC-00-5, 23/28 (2000) (in Japanese).
15) Z. Zhang, C. E. Towers, and D.P. Towers: Time efficient color fringe projection system for 3D shape and color using optimum 3-frequency selection, Opt. Express, **14**, 6444/6455 (2006).
16) Z. H. Zhang, C. E. Towers and D. P. Towers: Phase and colour calculation in colour fringe projection, J. Opt. A: Pure Appl. Opt., **9**, 81/86 (2007).

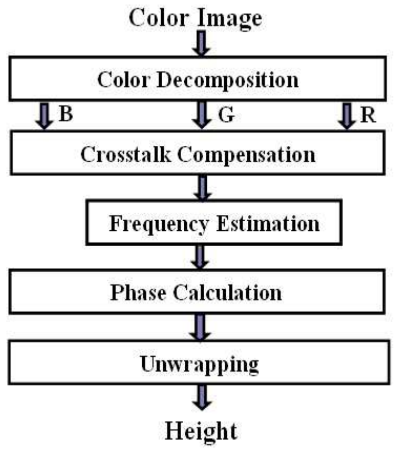

Fig. 13 Flowchart of three-wavelength single-shot interferometry.

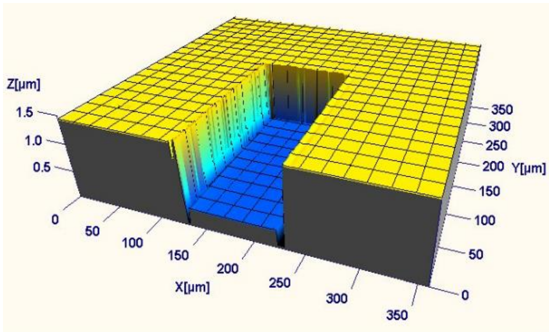

Fig. 14 Measurement result of 1μm step height.

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Graduated from the Department of Engineering, University of Tokyo in 1964. In the same year, joined Toray Industries, Inc. Since 1989, engaged in R&D of semiconductor inspection equipment based on the image processing technology. Since 2000, worked at Toray Industries, Inc. Received the 2001 Technology Award of SICE (the Society of Instrument and Control Engineers), the ViEW2003 Odawara Award, the Tejima Memorial Foundation Invention Award. Advanced Measurement and Control Engineer (authorized by SICE).

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