Single-shot interferometry: past, present, and future

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This review provides an overview of the progress in single-shot interferometry. After summarizing the past techniques, we introduce some examples of our developments in the spatial carrier method. Future possibilities are also described.

1. Introduction

A single-shot measurement method for measuring height from a single interference fringe image has been proposed for the purpose of speeding up measurement and improving vibration resistance. Here, we review this technology and introduce the recent technological developments by the authors.

2. Conventional single-shot interferometry

2.1 Fringe analysis

In the 1980s, automatic fringe analysis by computer was put to practical use [1]. The fringe peak position is obtained by image processing and the resolution is increased by interpolation. In order to distinguish between concave and convex, a tilt component is introduced.

2.2 Carrier fringe introduction method

Carrier fringes are introduced by tilting the reference plane and the phase is detected. The surface profile is obtained by the Fourier transform method [2] or the spatial phase synchronization method [3-5]. However, since these fringe analysis methods are derived under the assumption that the uneven frequency of the measurement target surface is sufficiently lower than the frequency of carrier fringes, there is a problem that high-frequency components are lost and horizontal resolution decreases [6].

2.3 Use of color information

In the latter half of the 1980s, the flying height of a magnetic disk head was measured from the color image of white light interference, using the relationship between the hue and the gap, that was obtained in advance [7].

2.4 Optical method

Various optical techniques were developed to simultaneously obtain three or four phase-shifted interference images, such as using multiple cameras [8-10], four quadrants of one camera using a holographic element (HOE) (Fig. 1) [11], a polarization imaging camera (Fig. 2) [12-13]. Complicated optical systems are required, and there are commercial products [10][13] with high cost.

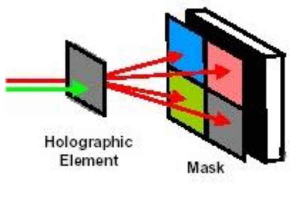

Fig. 1 Optical method using HOE

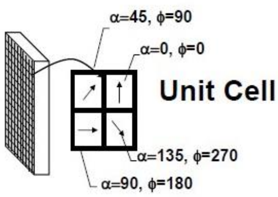

Fig. 2 Polarization imaging camera

3. Latest technologies for single-shot measurement

Among the various methods described above, the carrier fringe method has a simple device configuration and low cost. However, due to the horizontal resolution problem and the measurement range problem, the application in industry was limited [14]. The technologies developed by the authors to solve these problems are introduced below.

3.1 Phase calculation algorithm

To solve the horizontal resolution problem, the authors have developed a local model fitting method (abbreviated as LMF method) [15]. In this method, the fringe model function is applied to the local intensity data to obtain the phase (Fig. 3). Compared with the conventional method, the lateral resolution is high and the calculation cost is low. Figure 4 compares the measured profiles of the 50 nm step sample by the Fourier transform method and LMF method. The Fourier transform method sets a Hanning window, and the LMF method applies a 21-point median filter after fitting 25 points. As an extension of this method, an adaptive optimal setting method for local regions has also been proposed [16].

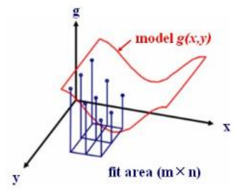

Fig. 3 Principle of LMF method

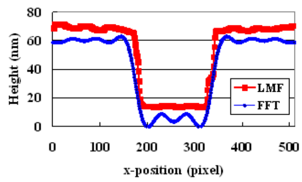

Fig. 4 Profile comparison of LMF method and FFT method

3.2 Range expansion: multi-wavelength single-shot method

Multiwavelength interferometry is a solution to the measurement range problem. The authors succeeded in measuring the surface shape with a steep step exceeding 4μm from a color image obtained by a 3-wavelength simultaneous imaging system [17].

(1) Three-wavelength simultaneous imaging system

In the first experimental device, an inexpensive and compact 3-wavelength simultaneous imaging interference optical system was constructed with a commercially available 3-wavelength LED lighting device and a color camera. Crosstalk is corrected by software. After that, in order to optimize the wavelength and increase the coherence length, a three-wavelength mixed illumination system with a three-branch light guide was constructed. Figure 5 shows the spectral sensitivity characteristics of the color camera and the three wavelengths used. Furthermore, we have developed a compact illumination system (Fig. 6) with a multi-bandpass filter [18].

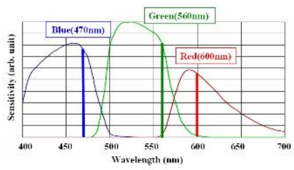

Fig. 5 Spectral sensitivity of color camera and three wavelengths

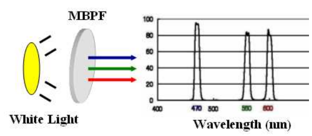

Fig. 6 Transmission of MBPF

(2) Multi-wavelength unwrapping

To find the height from the phase data of three wavelengths, the “coincidence method” that searches for the combination with the smallest error from the height candidates of each wavelength is suitable. This calculation can be speeded up by the LUT (Look-up table) method [18].

(3) Wavelength optimization

We found that the wavelength optimization problem that maximizes the measurement range of multi-wavelength interferometry can be solved by the coincidence error analysis (Fig. 7). Utilizing this, we selected 470nm(B)-560nm(G)-600nm(R). As a result, a measurement range exceeding 4μm is possible (Fig. 8).

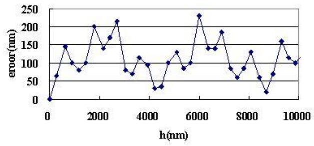

Fig. 7 Coincidence error diagram of the optimum wavelengths

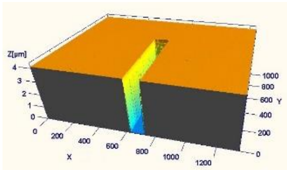

Fig. 8 Measurement of 4μm step height

(4) Application

We developed an automatic film thickness measurement system (Fig. 9) for inkjet color filters (IJCF) using the three-wavelength single-shot method [18]. The measurement accuracy is on the order of nm even without a vibration isolation mechanism (Fig. 10). The measurement speed is about 1.5 s per field of view (1.4 million pixels).

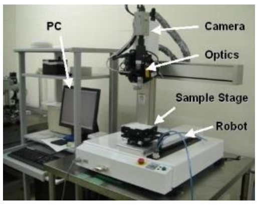

Fig. 9 Automatic IJCF thickness measurement system

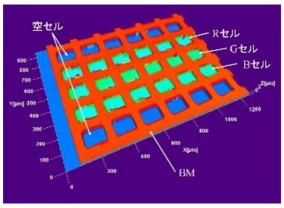

Fig. 10 Measurement result of IJCF

3.3 Optimum fringe direction

Probably because the single-shot interferometry using the carrier fringes method was studied since the 1990s, most of the reports analyze the waveforms of horizontal video signals of TV cameras by introducing vertical fringes in the screen. From theoretical considerations and experiments, it was confirmed that the horizontal fringe direction is the best for horizontal (x-axis) profiling (Fig. 11), and the vertical fringe direction is the best for vertical (y-axis) profiling.

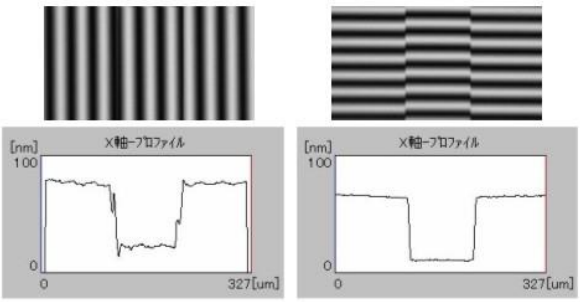

Fig. 11 Comparison of fringe directions in horizontal profiling

4. Single-shot measurement perspective

4.1 Range expansion

As an extension of multi-wavelength, four-wavelength is considered, and according to the coincidence method simulation, a range of several tens of μm is possible. As the hardware, a four wavelength (RGB + near infrared) camera can be used. It is expected that stabilization of wavelength and correction of chromatic dispersion of optical system will be necessary.

4.2 No need to introduce carrier fringes (GMF method)

The authors have developed a global model fitting method (GMF method) that does not require the introduction of carrier fringes [19]. The interference signal model is least-squares fitted to the RGB intensity data of three or more points in the three-wavelength interference image, and the surface height and model parameters are collectively obtained. The calculation of the height of each pixel does not require the information of neighboring pixels and has the feature that the resolution in the horizontal direction does not decrease. From the three-wavelength interference image shown in Fig. 12, the three-dimensional profile shown in Fig. 13 was obtained. A thin slit profile with a depth of 50 nm was measured.

5. Conclusion

The inexpensive and robust single-shot measurement method can be applied to on-machine measurement and in-line measurement. The former involves on-machine measurement in machine tools. In the past, precise measurement was not possible due to the vibration environment. The latter involves measuring moving objects. For example, there is a need for non-contact measurement of surface roughness and protrusion height of sheet-like objects such as plastic films during running. Further technological development is expected in the future.

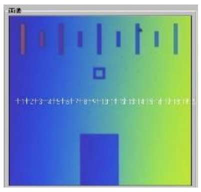

Fig. 12 Three wavelength interference image of 50nm step height

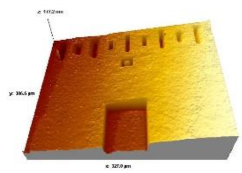

Fig. 13 Measurement result of GMF method

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This is an English translation of the paper:
Katsuichi Kitagawa: [Keynote speech] "Single-shot interferometry: past, present, and future",
Proc. of JSPE Spring Meeting, 1027-1028
(Tokyo, March 2011).
(original in Japanese; translated by the author)