Machine vision based interferometry for measurement of flatness error in micro and nano manufacturing

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Abstract: Interferometer and machine vision both are very trending technologies in the manufacturing industry for quality inspection purpose. Interferometers are commonly used to measure surface contour, flatness, surface finish. Machine vision also plays a vital role in the evaluation of the surface quality and surface profile of components under inspection. In this paper, a combination of interferometer and machine vision principles is used to count the number of fringes to determine taper angle and parallelism error in micro and nanometer range. An interferogram is captured by a camera and image acquisition algorithm. Image processing algorithms are used to count the number of fringes and calculating taper angle as well as flatness (parallelism) error for slip gauge surface

1. INTRODUCTION

Measurement of Surface topography is critical for any machined component to control the manufacturing process and relate the parameters with functional requirements. Measurements techniques are classified into two types depending on the interaction with the work piece: contact type and non-contact type. Contact type measurement techniques make use of instruments making contact with the workpiece for measurement, which suffers from the danger of damaging the workpiece if the object is delicate. Noncontact techniques analyse surface by laser or digital method. Blunt (2006) reported that an optical interferometer is the most widely used noncontact measurement technique. An interferometer works on the principle of interference of two or more waves producing interference fringe pattern, called as interferograms [1]. The work reported in [2] states that an interferometer is an essential tool for optical metrology when high precision and accuracy are required.

Machine vision refers to the technique based on image acquisition, image processing and image analysis. Nowadays, it is increasingly used in the manufacturing industry especially for quality inspection purpose. It facilitates the analysis of surface profile of an object just by capturing its image. It includes image acquisition, preprocessing, segmentation, recognition and measurement of fringes using machine vision [3].

Interferometry principle, which results in the formation of bright and dark fringe under monochromatic light source, has wide applications in many engineering domains. Many methods such as holographic, speckle, digital speckle, electronic speckle, phaseshift, 3D holography have been developed from interferometry principle over the years.

Novák, n.d. developed techniques for automatic numbering and identification of fringes using image processing algorithms [4]. Mohamed Suhail et al. (2018) used speckle interferometry for measuring
the vibration mode shape [5]. Work reported in [6] describes the use of electronic speckle interferometry for surface roughness calculation of silver nanoparticle sheet. Blunt (2006) presented an experimental study using white light interferometry for the measurement of roughness on a semiconductor wafer. Yoshino et al. (2017) conducted an experiment on a tensile test specimen to evaluate its surface roughness [7]. Suriyasirikun et al. (2014) used phase-shifting interferometry method on Michelson interferometer to measure the roughness of the glass substrate [8]. De Groot (2000) emphasized on removing the background reflection so that analysis of transparent flat surface was done easily [9]. Manukhin et al. (2014) developed a method for studying a transparent object using a digital holography method [10]. Cheng & Fan (2011) demonstrated an experiment in which SIOS interferometer was used for converting angular displacement to angle value [11]. Cexianga et al., n.d. Proposed a method for calculating the angle of rotation for flat objects [12]. A method for calculating the small angle based on total internal reflection was presented by [13]. Work reported in [14] used a parallel plate interferometer, which converted angular phase difference to interference signal and analysis of this signal gave the angle value. Limited amount of work is reported in nano and micro metrology for measurement of flatness error by machine vision-based interferometry providing scope for research and development in this field.

In this research work, an attempt is made to develop a novel and simple method to determine the error in flatness by counting the number of fringes and counting taper angle and parallelism error using interferometer coupled with machine vision technique.

2. EXPERIMENTAL SETUP

The interferometer setup used in the analysis of flatness error in slip gauge is shown in Figure 1. Main components of the setup include a simple interferometer with a sodium vapor lamp as a monochromatic light source with wavelength of 589 nm, slip gauge as a workpiece, master optical flat of diameter 50 mm and 20 mm thickness as a reference surface, and a mobile camera of resolution 2886 × 4085 pixels to capture image of fringe pattern.

![Interferometer setup](image)

**Figure 1. Interferometer setup**  
(Experimental setup for Interferometry in Metrology lab at Fr. Conceicao Rodrigues College of Engineering, Bandra)

3. METHODOLOGY

In the experiment, taper angle and taper error of the slip gauge is measured using interferometer
principle and machine vision principle. Sequence of steps performed for determining taper angle and taper error are mentioned in the flowchart in Figure 2. Initially, an optical flat is placed on the slip gauge and monochromatic light is allowed to pass through the transparent optical flat surface to the slip gauge. Interferometric fringe pattern is observed on the top surface of the slip gauge. The image of the fringe pattern is captured by a mobile camera. Then the image is processed by image processing algorithms using Matlab R2013a. One more fringe pattern image is captured after rotating the slip gauge by 180°. Numbers of fringes are counted for both the images as N1 and N2 using image processing algorithms discussed below.

Figure 2. Methodology flow chart

Figure 3. Steps for the fringe count

Figure 3 represents the flowchart for counting number of fringes using image processing algorithms. The image of fringe pattern, acquired in MATLAB is preprocessed using a sequence of activities, including conversion of RGB (color) image into a grayscale image by removing hue and saturation while retaining luminance, followed by conversion into a binary image using thresholding and binarization. It is an effective image segmentation technique to separate the foreground from the
background. Then noise filtration is carried out using Gaussian filter followed by pixel-wise adaptive low-pass ‘Wiener’ filter. Furthermore, fringe thickness is increased using erosion and finally the number of fringes is counted.

**Figure 4.** Taper angle calculation process

The taper angle is calculated using the equations (1) to (4) explained with supporting sketches in figure 4 [15]. N1 and N2 refer to fringe count for case 1 and case 2 respectively and \( \lambda \) refers to the wavelength of monochromatic light.

Flatness or parallelism error is calculated using formula given below in equation (1).

\[
\text{Flatness Error} = \frac{N_2 - N_1}{2} \times \lambda
\]

**4. RESULTS AND DISCUSSION**

Figure 5 indicates the process followed for counting fringe patterns along with the output of each stage.

**Figure 5.** Fringe counting process
Images of the fringe pattern obtained using interferometer principle are processed using image processing algorithms discussed above, and the output for two positions of the slip gauges are shown in figure 6. Interferometric fringe patterns are obtained for two cases, with the first case showing number of fringes $N_1$ as 5 and second case with $180^\circ$ rotation of slip gauge showing number of fringes $N_2$ as 39.

![Figure 6](image_url)

Figure 6. (a) Image of fringe pattern ($N_1 = 5$)  (b) Image after rotation through $180^\circ$ ($N_2 = 39$)

Flatness error is calculated by considering the lowest taper angle and results of flatness error obtained using the proposed integration of interferometer principle with machine vision are shown in the following table 1.

| Case    | Case2          |
|---------|----------------|
| $Wavelength$ of Monochromatic light ($\lambda$) | 589 nm | 589 nm |
| Length of work piece (L) | 3.5 cm (35000000 nm) | 3.5 cm (35000000 nm) |
| No of fringes | $N_1 = 5$ | $N_2 = 39$ |
| Taper angle | $\Phi_1=0.0024^\circ$ | $\Phi_2=0.018^\circ$ |
| Flatness error | 10013 nm or 10.013 µm |

**Table 1. Results of Flatness Error obtained using Integration of Interferometer and Machine Vision**

5. CONCLUSION

The proposed technique of interferometer principle coupled with machine vision, can be used to measurement of flatness error. Experimental results indicate that the taper angle and parallelism error are calculated using fringe count. Fringe pattern image obtained using interferometer is captured and processed using image processing algorithms in Matlab R2013a. The number of fringes is easily counted and accordingly, taper angle and flatness error (parallelism error) have been calculated. The technique can be implemented successfully for measuring flatness error in micro and nanomanufacturing.
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