ACCURACY ASSESSMENT FOR A LATERAL SHEARING INTERFEROMETER

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Introduction

For precision surface form error measurement under machining conditions, a new interferometer is proposed based on the shearing interference principle with a self-reference property. The interferometer is simple and compact in structure. It has a complete common optical path and is based on polarized phase shifting interference. It is less sensitive to vibration and environmental disturbances and is suitable for precision surface form aberration measurement.

The principle of the interferometer is introduced and its simplified optical model is presented. Several error factors of the interferometer are investigated. The results show that the accuracy of the proposed interferometer is less than $\lambda/80$. To confirm the results, experimental tests were conducted on the prototype of the interferometer.

Working Principle

The proposed shearing interferometer is shown schematically in Fig. 1. A single plate SP is the specially designed shear generator made of calcite crystal. By a laser source, a spatial filter and a collimated lens $L_1$, a standard plane wave is produced. The plane wave incidents onto the test surface and is reflected back as an approximate plane wave whose wave front shape is double the test surface aberration. The reflected plane wave with the surface aberration information passes back through $L_1$ and another collimated lens $L_2$ and incidents into the shear generator SP. In SP, it breaks down into two perpendicularly polarized waves with different refraction indexes. When they come out from the plate, the two waves have parallel propagation directions and the same aberration information of the test surface, with a little amount of shift between them. After they pass through a quarter wave plate $Q_3$ and a polarizer $P_2$, they interfere with each other, thus shearing interference happens. By CCD, the interference pattern corresponding to shearing is obtained. $Q_3$ and $P_2$ consist of a polarized phase shifting device for multi-step phase shifting. In the phase shifting device, when $P_2$ is rotated to change its polarization direction by an angle $\alpha$, a $2\alpha$ phase shifting of interferometric phase can be produced. The obtained phase shifting shearing interference patterns
are sampled and analyzed to obtain shearing interferometric phases. Then by wave front reconstruction algorithm, the description of the wave front, hence the test surface topography aberration, is achieved.

**Error Analysis**

For the interferometer, several error factors are analyzed.

1) System error from distortions of optical components. In the built shearing interferometer, distortions induced into test wave front by optical component aberrations can be constant, so the system error can be erased by calibrations. Since the surface quality of the standard mirror for calibration is 1.6nm, the error induced by optical system will be $e_{ss} < 1.6$nm.

2) Laser stability error in wavelength. Wavelength of laser source is used as the length standard. The adopted Uniphase 1125/p He-Ne laser frequency stability is 300MHz, which means its wavelength drift range is $632.8 \pm 0.0004$nm. The relative measurement error caused by laser stability therefore can be

$$\delta_{\lambda} = \frac{0.00004}{632.8} \times 100\% = 0.00006\% .$$

3) Shear error. The amounts of shear are obtained by edge discerning of interference patterns. Suppose the two interfering sheared beam size $r_b$ and their relative displacement $q$ in pixels can be obtained by pixel counting, relative error of shear ratio $s_r$ will be [1]

$$\frac{\Delta s_r}{s_r} = \left[ \left( \frac{\Delta r_b}{r_b} \right)^2 + \left( \frac{\Delta q}{q} \right)^2 \right]^{1/2} ,$$

where the fractional errors $\Delta r_b$ and $\Delta q$ are both 0.5. In the adopted LCL-902C CCD, the effective pixel number is 752(H)×582(V), cell size is 8.6µm(H)×8.3µm (V). The sampling field of the capture card is 576(H)×768(V), and usual sampling image sizes are more than 400(H)×400(V).

**Fig. 2(a)** shows the relationship between shear ratio $s_r$ and shear ratio error $\Delta s_r$. By **Fig. 2(a)** from **Eq. (1)**, when shear ratio $s_r=0.03$~$0.3$ is adapted, the relative error of shear ratio will be 0.5~4%. From **Fig. 2(b)** the relative measurement error will be 1~4%.

![Graph](image)

(a) Shear effect on the shear ratio error   (b) Shear ratio error effect on the reconstruction result

**Fig. 2** Shear effect on measurement result
4) Phase shifting error. In the interferometer, the polarizer \( P_2 \) is driven by a stepping motor for phase shifting. Since stepping resolution of the motor is \( 6400/r \), and amplification ratio of the transition gears is \( 20/100 \), rotation accuracy of the polarizer \( P_3 \) can be \( \frac{2\pi}{6400} \times \frac{20}{100} = \frac{\pi}{1600} \), which means the relative phase shifting error is 0.0031%. According to the analysis results by Creath [2], the interferometric phase recovery error by 5-step phase shift algorithm will be ignorable, so is the final measurement error.

5) System noise and sampling digitization error. By experimental testing, the practical noise error level induced to recovered interferometric phase by CCD noise and sampling digitalization is 4.98nm in RMS. According to error propagation characteristics of the improved Zernike polynomial reconstruction algorithms [3] shown in Fig. 3, the induced error will be 1.25nm.

![Fig. 3 Effect of noise on the reconstruction](image1)

![Fig. 4 Effect of the focus coincidence error](image2)

6) Effect of focus point coincidence aberration. Focus coincidence deviation of \( L_1 \) and \( L_2 \) can be limited to \( e_v<0.01\text{mm} \) by manual adjustment in the course of configuration. From Fig. 4, the induced error in RMS will be \( e_{fc}<2.5\text{nm} \) [3].

7) Effect of surface tilt. Error induced by surface tilt \( e_{til}<1\times10^{-7}\text{nm} \) [3].

8) Reconstruction error. By improved Zernike polynomial fitting algorithm for circular symmetry wave front reconstruction, relative reconstruction error \( \delta_{re} \) can be less than 0.002% [3].

The above errors are now summed together to estimate the total error of the interferometer. The errors induced by shear ratio error, laser stability error and reconstruction algorithm are relative contributions: \( \delta_{sr}<4\% \), \( \delta_{\lambda}<0.00006\% \), \( \delta_{re}<0.002\% \). We may sum these errors quadratically and conclude that the total relative inaccuracy is \( \delta=4\% \). The errors induced by optical system, phase shifting error, system noise and sampling digitization error, focus coincidence error, surface tilt and surface position error, are all absolute errors: \( e_{ss}<1.6\text{nm} \), \( e_{ps}\approx0 \), \( e_{sr}=1.25\text{nm} \), \( e_{fc}=2.5\text{nm} \), and \( e_{til}=1\times10^{-7}\text{nm} \). So for a surface whose surface aberration is 0.2\( \mu\text{m} \) in RMS is test, the total measurement error will be

\[
e_{pl} < \sqrt{(200\times4\%)^2 + 1.6^2 + 1.25^2 + 2.5^2 + (10^{-7})^2} = 8.62\text{nm}.
\]
Experimental Testing and Discussion

A plane surface whose aberration is 0.074µm P-V is measured. Fig. 5 is the obtained bi-directional shearing interference patterns. Fig. 6 is the final measurement result through interference pattern analysis including interferometric phase recovery and reconstruction. Compared the result with the one by a Zygo interferometer, the measurement error is 0.0074µm. The result of accuracy assessment for the interferometer is confirmed. The repeatability is shown to be less than $\lambda/400$.

Conclusions

A new shearing interferometer is proposed for precision surface form error measurement in a manufacturing environment. The principle of the interferometer is introduced and the optical path analyzed. Several error factors in the interferometer are investigated. The results show that the accuracy of the interferometer can reach $\lambda/80$. Experimental testing results on the prototype of the interferometer validated the results of error analysis.

References