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Dual-mode snapshot interferometric system for on-machine metrology

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Abstract. For the first time, we present a dual-mode snapshot interferometric system for measuring both surface shape and surface roughness to meet the need for on-machine metrology in optical fabrication. Two different modes, interferometer mode and interference microscopy mode, are achieved using Linnik configuration. To realize snapshot measurement, a pixelated polarization camera is used to capture four phase-shifted interferograms simultaneously. We have demonstrated its performance for off-line metrology and on-machine metrology by mounting it on a diamond turning machine. © 2019 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.58.4.044104](https://doi.org/10.1117/1.OE.58.4.044104)]

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1 Introduction

During the optical fabrication process, surface shape and surface roughness measurements are often required to validate the fabricated surface. Typically, commercial measurement tools are designed for off-line metrology and not suitable for on-machine metrology. It is usually necessary to remove the part from the machine for off-line metrology and then remount it back to the machine if the part is not fabricated to the specification, increasing the fabrication time and introducing extra errors. Various on-machine metrology or in-process inspection techniques,^{1,2} including hybrid vision system,³ chromatic confocal,^{4–6} deflectometry,⁷ and interferometry,^{8–10} have been developed to address this issue. However, all these methods are designed for either measuring surface shape or surface roughness, but not both. The ability for measuring both surface shape and surface roughness is essential for fabricating optical components. Four fundamental requirements for on-machine metrology are: compact, fast measurement speed, accuracy, and less sensitive to environment. Pixelated phase-mask interferometer is developed in Refs. 11–13, which is less sensitive to environment noise and has a fast measurement speed.

In this paper, we proposed a dual-mode snapshot interferometric system (DMSIS) for on-machine metrology for diamond turning optical fabrication. This system combines a laser interferometer for measuring surface shape and a low-coherence interference microscope for measuring surface roughness. Using a pixelated polarization camera, snapshot measurement is achieved.^{11–13} Thus the influence of environment noise is reduced and the measurement speed is increased. This DMSIS is built and tested on a Moore Nanotech 350FG diamond turning machine (DTM). Section 2 presents the principle of DMSIS, error analysis using Jones vectors, and camera calibration. Section 3 shows the experiment results, measurements of different diamond

turned parts are taken in both modes and compared with commercial interferometer and interference microscope.

2 Dual-Mode Snapshot Interferometric System

2.1 System Layout

DMSIS is based on a Linnik interferometer as shown in Fig. 1. It contains two light sources: a HeNe laser source with wavelength of 632.8 nm for measuring surface shape and a red light-emitting diode (LED) with a center wavelength of 630 nm and a bandwidth of 10 nm for measuring surface roughness. L1 and L2 are collimating lenses to collimate light from the laser and LED. A beam expander (BE) is added after L1 to increase the beam size of the laser. The beam size after BE is 20 mm. A polarizer (P) is placed between a nonpolarizing beam splitter (BS) and a polarizing beam splitter (PBS) allowing adjustment of the relative intensities of the test arm and reference arm for better fringe contrast. After the polarizer, polarized light is incident on a PBS and divided into two beams with orthogonal polarization. Both beams pass twice through quarter wave plates (QWP) with fast axis at 45 deg relative to the horizontal axes before returning to the PBS. Two identical long working distance microscope objectives (MO1 and MO2, Edmund M Plan Apo 10×) with NA 0.28 are used for matching the optical paths, forming a Linnik interferometer. QWP3 with its fast axis at 45 deg is placed in front of the camera and transforms the two orthogonal linear polarized beams to opposite circular polarized beams. L3 is an imaging lens. A pixelated polarization camera (PolarCam, 4D Technology, Inc.) is used to capture four interferograms simultaneously. Without physical phase shift, four phase-shifted interferograms can be extracted from a single image. The whole system is mounted on a linear translation stage on DTM. In interference microscopy mode, the measurement accuracy would be limited due to the coherent noise¹⁴ if the laser is used as the light source. Thus, LED is chosen as the light source for

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Fig. 1 Dual-mode snapshot interferometric system. QWP1 to QWP3, quarter wave plates; P, polarizer; BS, nonpolarizing beam splitter; PBS, polarizing beam splitter; BE, beam expander; L1 to L3, lenses; M1 and M2, mirrors; MO1 and MO2, microscope objectives; and PolarCam: 4D Technology pixelated polarization camera.

measuring surface roughness. In interferometer mode, the microscope objective in reference arm (MO2) is removed, forming a standard Twyman–Green interferometer. The test sample with different radii of curvature can be measured by adjusting the location of DMSIS with the translation stage. The laser source is used for measuring surface shape due to its long coherence length.

2.2 Operating Principle

The Jones vector of test beam and reference beam before PolarCam are

$$E_T = Q_3 * T_{\text{pbs}} * Q_1' * M_T * Q_1 * R_{\text{pbs}} * E_i, \quad (1)$$

$$E_R = Q_3 * R_{\text{pbs}} * Q_2' * M_R * Q_2 * T_{\text{pbs}} * E_i, \quad (2)$$

where $E_i = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ is the Jones vector of incident beam after passing through a 45-deg linear polarizer; Q_1' , Q_1 , Q_2 , Q_2' , and Q_3 are the Jones matrix of QWP1, QWP2, and QWP3, respectively, defined as $Q = \begin{bmatrix} \cos^2 \theta + i \sin^2 \theta & (1-i) \cos \theta \sin \theta \\ (1-i) \cos \theta \sin \theta & \sin^2 \theta + i \cos^2 \theta \end{bmatrix}$ where θ is the fast axis angle of QWP to the horizontal axis; T_{pbs} and R_{pbs} are the transmittance and reflectance Jones matrix of PBS, defined as $T_{\text{pbs}} = \begin{bmatrix} T_p & 0 \\ 0 & T_s \end{bmatrix}$ and $R_{\text{pbs}} = \begin{bmatrix} R_p & 0 \\ 0 & R_s \end{bmatrix}$, respectively; T_p and T_s are the transmittance factor of the PBS for p and s light, respectively; R_p and R_s are the reflectance factor for p and s light, respectively; M_T is the Jones matrix of the test sample, defined as $M_T = e^{i\phi} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$; and M_R is the Jones matrix of a dielectric mirror, defined as $M_R = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$.

For ideal component, test and reference beams after QWP3 should be opposite circular polarized state, which could be simplified as $E_T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix} e^{i\phi}$ and $E_R = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}$. After passing through the micropolarizer array, the Jones vector is $E = P * (E_T + E_R) = \begin{bmatrix} E_x \\ E_y \end{bmatrix}$, where $P = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix}$ is the Jones matrix for linear polarizer with transmission axis at θ . The final intensity recorded on CCD is

$$I = E^2 = E_x^2 + E_y^2, \quad (3)$$

where I is the total irradiance behind a linear polarizer. For the linear polarizers in each superpixel at 0 deg, 45 deg, 90 deg, and 135 deg, phase shifts of 0 deg, 90 deg, 180 deg, and 270 deg are introduced. A basic four-step phase shift algorithm can be used to calculate the surface phase information:

$$\phi = \arctan \frac{I_4 - I_2}{I_1 - I_3}. \quad (4)$$

2.3 Error Analysis

While DMSIS is less sensitive to the environment error than standard PSI since it can obtain four phase-shifted interferograms simultaneously, this system still suffers from imperfect optical component. Errors caused by retardance and orientation of QWP, diattenuation and orientation of micropolarizer array in PolarCam are discussed in Ref. 15. In addition to that, there may still be some errors caused by nonideal PBS and misalignment between micropolarizer array and CCD pixels.

The misalignment between micropolarizer array and camera pixel is analyzed below. As shown in Fig. 2, the new

Fig. 2 Misalignment between micropolarizer array and camera sensor.

intensity on certain pixel of camera sensor is a linear combination of four parts of I_1 , I_2 , I_3 , and I_4 :

$$\begin{bmatrix} I'_1 \\ I'_2 \\ I'_3 \\ I'_4 \end{bmatrix} = \begin{bmatrix} a & b & c & d \\ b & a & d & c \\ c & d & a & b \\ d & c & b & a \end{bmatrix} * \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}, \quad (5)$$

$$\varphi = \arctan \frac{I'_4 - I'_2}{I'_1 - I'_3}, \quad (6)$$

where I'_1 , I'_2 , I'_3 , and I'_4 are the intensity on each subpixel after considering the misalignment, a is the percentage of the primary polarized state, and b , c , and d are the percentage of other polarized states. For $a = 0.855$, $b = 0.095$, $c = 0.005$, $d = 0.045$, the phase error is shown in Fig. 3(a). These values are just used for simulation and do not represent the real micropolarizer array offsite.

For a nonideal PBS (Thorlabs CMM1-PBS251) with 96.9% transmission for P -polarized light and 0.07% for S -polarized light, assume there is no energy loss in PBS, then the transmittance and reflectance matrices of PBS are $T_{\text{pbs}} = \begin{bmatrix} 0.984 & 0 \\ 0 & 0.026 \end{bmatrix}$ and $R_{\text{pbs}} = \begin{bmatrix} 0.176 & 0 \\ 0 & 0.999 \end{bmatrix}$. The phase error caused by the error of nonideal PBS is shown in Fig. 3(b).

Fig. 3 Phase error due to (a) micropolarizer array misalignment error and (b) nonideal PBS.

Fig. 4 Calibration results of PolarCam with uniform illumination: image (a) before and (b) after calibration.

Fringe-print-through error is caused by the imperfect optical components, such as PBS, QWP, and micropolarizer array in front of the pixels. Lissajous ellipse fitting algorithm can be used to address this issue.^{16–18}

In addition to the fringe-print-through error, other error sources, including component error, system error, and alignment error, can degrade the test accuracy as well. Those errors can be subtracted after the calibration.

2.4 Camera Calibration

PolarCam contains several errors such as fixed pattern noise, photon response nonuniformity, nonuniformity in the micropolarizer extinction ratio, micropolarizer array orientation misalignment, and pixel cross talk. Camera calibration is necessary for high accuracy measurement. The calibration method designed by Chen et al.¹⁹ is used for camera calibration. Figure 4 shows uniform images before and after calibration. The reflected beam of the polarizer array and sensor introduces background interferograms, as shown in Fig. 4(a). The background interferogram is removed after camera calibration, as shown in Fig. 4(b). The images are captured in 12 bit.

Experimental data of a diamond turned flat copper are shown in Fig. 5. Figures 5(a) and 5(b) show one of the four phase-shifted interferograms before and after calibration. Intensity distributions of four phase-shifted interferograms before and after calibration are shown in Figs. 5(c) and 5(d). The background pattern is removed and the interference

Fig. 5 Calibration results of a diamond turned flat copper surface: interferogram (a) before and (b) after calibration. Intensity distribution in four channels of PolarCam (c) before and (d) after calibration.

fringes are normalized after calibration, demonstrating that the calibration method is effective.

3 Experimental Results

DMSIS, using commercial off-shelf components, was built and tested on a Moore Nanotech 350FG DTM. The dimension of the prototype is $12 \times 12 \times 3$ in. The dimension is compact enough for on-machine metrology as shown in

Fig. 6(a), where DMSIS was mounted between two tool holders on the linear translation stage. Figure 6(b) shows the system layout inside the box. Before the measurement, the optical axis of the DMSIS was aligned parallel with the spindle axis by placing a flat mirror on the spindle. The two objectives (MO1 and MO2) were removed and the laser source was turned on. The tilt between the optical axis of the DMSIS and the spindle axis was minimized by nulling the interferogram.

Different materials were diamond turned and tested with DMSIS mounted on the Z axis slide of the DTM. The on-machine measurement results were compared with the off-machine measurement results from a Zygo NewView 8300 optical surface profiler and Zygo Verifire™ laser interferometer. Figure 7 shows the measured surface roughness of a diamond turned copper and polymethyl methacrylate (PMMA) concave surface. The radius of curvature is 50 mm for both copper and PMMA surface. The measurement area is about $800 \mu\text{m} \times 800 \mu\text{m}$. Tip, tilt, and power terms of Zernike polynomial are removed in the surface roughness measurement. The surface-root-mean square (RMS) of the copper surface is 10.36 nm in off-machine (Zygo NewView 8300 optical surface profiler) and 10.62 nm in our DMSIS, whereas the RMS of the PMMA surface is 20.87 nm in off-machine and 21.02 nm in our DMSIS, respectively. The measurement result of our DMSIS shows a good agreement with off-machine measurement. On-machine RMS surface roughness from DMSIS is slightly larger than the off-line measurement Zygo Newview8300; the difference could be the cutting debris. Another possible reason could be the fact that the red LED with narrow bandwidth is used in DMSIS and white LED is used in Zygo Newview 8300.

Figure 8 shows the comparison of the measured surface shape of the same diamond turned copper and PMMA concave surfaces with 50-mm radius of curvature and 25-mm diameter. The peak-to-valley (PV) of the copper surface is 1.002 waves in off-machine (Zygo Verifire™ laser interferometer) and 1.038 waves in DMSIS, whereas the RMS is 0.182 waves in off-machine and 0.184 waves in DMSIS, respectively. The PV of the PMMA surface is 0.494 waves in off-machine and 0.552 waves in DMSIS, whereas the RMS is 0.101 waves in off-machine and 0.113 waves in DMSIS, respectively. The speckle pattern is more clear in PMMA surface since deeper tool mark and lower reflectance of PMMA surface.

Fig. 6 (a) DMSIS mounted on Moore Nanotech 350FG DTM. (b) DMSIS layout inside the box.

Fig. 7 Surface roughness measurement of a diamond turned copper surface: (a) interferogram in DMSIS, (b) off-machine measurement, (c) DMSIS measurement, and (d) line profile comparison. Diamond turned PMMA surface: (e) interferogram in DMSIS, (f) off-machine measurement, (g) DMSIS measurement, and (h) line profile comparison.

Fig. 8 Surface shape measurement of a diamond turned copper surface: (a) interferogram in DMSIS, (b) off-machine measurement, (c) DMSIS measurement, and (d) line profile comparison. Diamond turned PMMA surface: (e) interferogram in DMSIS, (f) off-machine measurement, (g) DMSIS measurement, and (h) line profile comparison.

4 Conclusion

In this paper, we propose a compact, DMSIS for on-machine metrology to measure surface shape and roughness. Its

unique dual-mode and snapshot features are particularly suitable for on-machine metrology. The measurement results demonstrate the DMSIS is a feasible system for on-machine

metrology. Since it is a reasonably compact system using a commercial microscope objective as the transmission sphere, the measurement range for a convex surface is limited by the working distance of the objective. A custom objective can be developed to address this issue.

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References

1. K. Vacharanukul and S. Mekid, "In-process dimensional inspection sensors," *Measurement* **38**(3), 204–218 (2005).
2. U. Persson, "In process measurement of surface roughness using light scattering wear," *Wear* **215**(1–2), 54–58 (1998).
3. G. Y. Tian and R. Lu, "Hybrid vision system for online measurement of surface roughness," *J. Opt. Soc. Am. A* **23**(12), 3072–3079 (2006).
4. Y. Quinsat and C. Tourmier, "In situ non-contact measurements of surface roughness," *Precis. Eng.* **36**(1), 97–103 (2012).
5. H. Nouira et al., "Characterization of the main error sources of chromatic confocal probes for dimensional measurement," *Meas. Sci. Technol.* **25**(4), 044011 (2014).
6. X. Zou et al., "Non-contact on-machine measurements using a chromatic confocal probe for an ultra-precision turning machine," *Int. J. Adv. Manuf. Technol.* **90**(5–8), 2163–2172 (2017).
7. P. Su et al., "Precision aspheric optics testing with SCOTS: a deflectometry approach," *Proc. SPIE* **8788**, 87881E (2013).
8. D. Lin et al., "High stability multiplexed fibre interferometer and its application on absolute displacement measurement and on-line surface metrology," *Opt. Express* **12**(23), 5729–5734 (2004).
9. F. Xie et al., "Large range and high resolution on-line displacement measurement system by combining double interferometers," *Opt. Express* **18**(24), 24961–24968 (2010).
10. F. Xie et al., "Multiplexing optical fiber low coherence and high coherence interferometric system with large range and high resolution for on-line measurement," *Measurement* **46**(1), 171–176 (2013).
11. J. Millerd et al., "Pixelated phase-mask dynamic interferometer," *Proc. SPIE* **5531**, 304–314 (2004).
12. J. E. Millerd and J. Wyant, "Simultaneous phase-shifting Fizeau interferometer," U.S. Patent No. 7,230,718 (2007).
13. D. Wang and R. Liang, "Simultaneous polarization Mirau interferometer based on pixelated polarization camera," *Opt. Lett.* **41**(1), 41–44 (2016).
14. I. Abdulhalim, "Competence between spatial and temporal coherence in full field optical coherence tomography and interference microscopy," *J. Opt. A Pure Appl. Opt.* **8**(11), 952–958 (2006).
15. M. Novak et al., "Analysis of a micropolarizer array-based simultaneous phase-shifting interferometer," *Appl. Opt.* **44**(32), 6861–6868 (2005).
16. Y. Zhang, X. Tian, and R. Liang, "Fringe-print-through error analysis and correction in snapshot phase-shifting interference microscope," *Opt. Express* **25**(22), 26554–26566 (2017).
17. Y. Zhang, X. Tian, and R. Liang, "Random two-step phase shifting interferometry based on Lissajous ellipse fitting and least squares technologies," *Opt. Express* **26**(12), 15059–15071 (2018).
18. Y. Zhang, X. Tian, and R. Liang, "Three-step random phase retrieval approach based on difference map normalization and diamond diagonal vector normalization," *Opt. Express* **26**(22), 29170–29182 (2018).
19. Z. Chen, X. Wang, and R. Liang, "Calibration method of microgrid polarimeters with image interpolation," *Appl. Opt.* **54**(5), 995–1001 (2015).

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