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Investigation of kinematics error influence on on-machine measurement for ultra-precision turning

Duo Li[1], Zhen Tong[1], Liam Blunt[1], Fei Ding[2], Xiangqian Jiang[1]

[1]*University of Huddersfield, Huddersfield, UK*
[2]*University of Strathclyde, Glasgow, UK*

Duo.li@hud.ac.uk

Abstract
Shift from offline measurement to on-machine measurement (OMM) is urgently needed for closed-loop control for ultra-precision machining processes. OMM can avoid the errors caused by repositioning workpieces and increases the inspection efficiency. In this work, an in-house designed interferometer probe was integrated on a 3-axis ultra-precision diamond turning machine for OMM. However, as the probe is carried on the motion slides, kinematics errors of the machine tool will inevitably affect the OMM results. To investigate the influence of kinematics errors, simulation analysis was performed and the four primary error components in the sensitive measurement direction were measured by capacitance sensors using the reversal method. Finally, an OMM experiment of an optical flat surface was carried out. The results prove that OMM error was dominated by the C axis tilt error E_{BC} with a 2 UPR (undulations per revolution) component along circumferential direction.
Key words: on-machine measurement, kinematics error, interferometry, ultra-precision machine tool

1. Introduction

Precision surface metrology is playing an increasingly important role in modern manufacturing. The shift from offline measurement to on-machine measurement (OMM) is urgently needed for closed-loop control of ultra-precision machining processes [1]. OMM can avoid the errors caused by repositioning workpieces and greatly increase the inspection efficiency. Optical type OMM is preferred for its fast data capture and non-destructive characteristics. Consequently, interferometry is regarded as an optimal choice for ultra-precision machining applications. Operating in the machine tool environment, the instrument needs to be robust to the presence of vibrations, temperature and other disturbance. Moreover, as the OMM instrument is carried on the motion slides, kinematics errors of the machine tool will inevitably affect the OMM results. Investigation of kinematics error influence on OMM should be carried out.

In this paper, the proposed OMM system is briefly described. Then, kinematics error influence on OMM is simulated and the error components are measured using the reversal method. Finally, OMM experiment of an optical flat surface is conducted to validate the previous analysis.

2. On-machine measurement system

The proposed machining-measurement integration system consists of an ultra-precision turning machine and a dispersed reference interferometry (DRI) probe, which is shown in Figure 1 [2]. DRI is a modified Michelson interferometer with chromatic dispersion added in the reference arm. It can achieve 0.6 nm axial resolution with 800 µm vertical range [3]. The measuring principle lends the method to an optical fibre based implementation and the potential for remote configuration. Measurement rates can be up to 10 kHz, making it insensitive to the environmental disturbance.

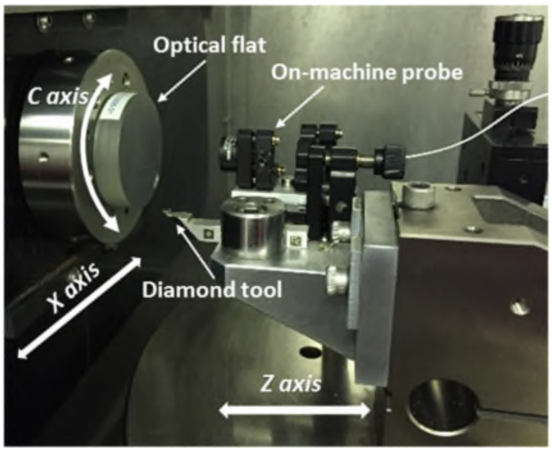


Figure 1. Experimental setup of OMM

3. Kinematics error influence

3.1. Kinematics error analysis

Four primary error components in the sensitive measurement direction are taken into consideration, including the *X* axis straightness in the Z direction E_{ZX}, C axis axial error E_{ZC}, C axis tilt error E_{BC} and squareness error between X and C axes E_{BOC}. With multi-body theory, the individual and combined effect of these errors on the OMM results are numerically simulated (shown in Figure 2). The results illustrate E_{ZX} will cause the wavy pattern along the radial direction while the squareness error E_{BOC} in the X-Z plane results in a cone shape surface. C axis motion errors, including E_{ZC} and E_{BC}, will induce several circumferential ripples, whose number depends on the spindle motion error characteristics. It also indicates that the squareness error and C axis tilt error tends to exaggerate the motion error in the Z direction with increasing measurement radius.

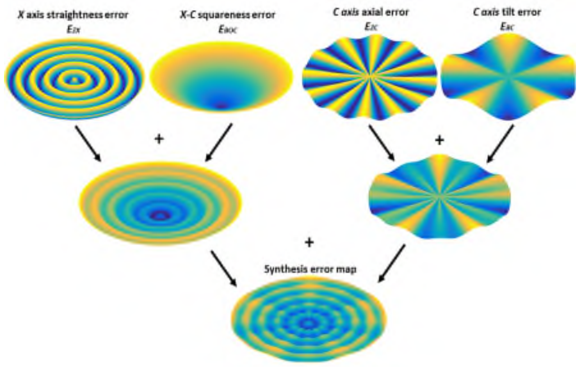


Figure 2. Simulation pattern of kinematics error influence on OMM

3.2. Kinematics error measurement

The reversal method is considered simple and accurate for measurement of part features without reference to an externally calibrated artefact [4]. This paper uses the reversal method for machine tool kinematics error measurement at the nanometric level with capacitance probes (Lion Precision). The measurement instrument and reversal measurement process for selected four error components are respectively shown in Figure 3 and Figure 4.

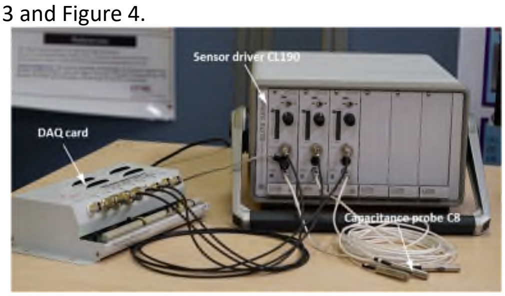
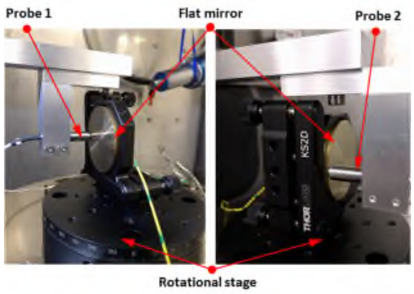
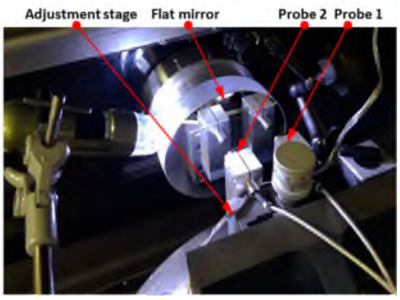


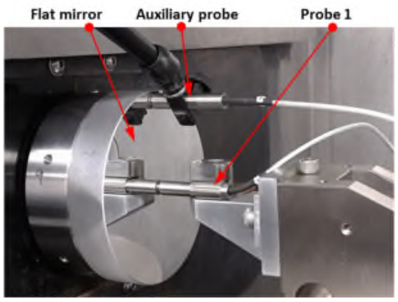
Figure 3. Kinematics error measurement device



(a) X axis straightness in the Z direction E_{ZX}



(b) C axis axial error E_{ZC} and C axis tilt error E_{BC}



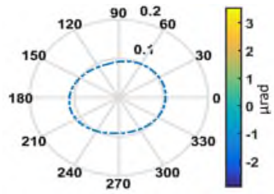
(c) Squareness error between X and C axes E_{BOC}

Figure 4. Kinematics error measurement process

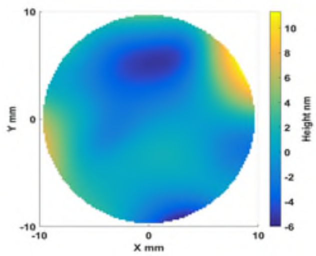
4. Experiment results

All measurement results of kinematics error agree with the specification provided by the machine tool manufacturer (Ametek, Precitech). A standard optical flat (Edmund optics) was measured on-machine by DRI probe in a spiral path with C axis rotational speed of 1 rpm and X axis feedrate of 2 mm/min. The measurement result is shown in Figure 5 (b).

By comparing with Figure 2, the OMM result is dominated by 2 UPR (undulations per revolution) component along the circumferential direction, corresponding to the polar graph shown in Figure 5 (a). The measurement results indicate that the OMM error mainly results from the C axis tilt error motion E_{BC}. In order to evaluate the OMM fidelity, C axis motion error (particularly the tilt error) needs to be paid more attention and compensated.



(a)



(b)

Figure 5. C axis tilt error E_{BC} (a) and DRI OMM results (b)

5. Conclusion

The paper investigates the influence of machine tool kinematics error on OMM. Simulation analysis is performed The kinematics error measurement results (using reverse method) and OMM experiment of a standard optical flat indicate that C axis motion tilt error E_{BC} is the most influential factor affecting OMM. The work is supported by the UK's Engineering and Physical Sciences Research Council (EPSRC) funding (Grant Ref: EP/P006930/1) and China Scholarship Council (CSC).

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