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Study on machining errors analysis of optical surface/system by performance constraint

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Optical performance is the final evaluation specification for the applications of optical surfaces/systam. However, the traditional evaluation criteria in manufacturing have been the form error and surface roughness, which are compensated to control optical performance indirectly. There are different error distributions, not just the symmetry error, for the freeform surfaces. Previous studies have found that optical performance can differ significantly despite a similar value of form error due to different underlying error distributions. This paper, therefore, proposes a novel approach to directly achieve compensation of optical performance. The mapping model between machining errors and wavefront aberration was established by multi-body system (MBS) theory and optical ray tracing. Simulations were conducted based on the mapping model. The effect of machining errors on the wavefront aberration was obtained, and the main machining error was identified. This study provides an innovative assistance to directly improve the optical performance and machining accuracy of optical mirrors.

1. Introduction

Multi-reflective imaging systems (MRIS) find wide applications in optical imaging and space detection owing to its merits of large aperture, high resolution and broad band. Ultra-precision turning can realize the nanoscale roughness and sub-micron surface form accuracy, which is considered as one important machining method for optical surfaces/system. But there still exist many factors affecting the machining accuracy, geometric errors, kinematic errors, thermally induced errors, cutting-force-induced errors, fixture-dependent errors, etc [1]. For the above errors, the geometric error is the main machining errors, which has a big influence on the machining accuracy and optical performance. The geometric error includes many errors, the compensation of all errors is unrealistic and ineffective.

In addition, traditional manufacture of freeform optics is usually focused on the machining accuracy, through evaluating and controlling the machining error or form error of an individual freeform surface to improving the machining accuracy [2-4]. But our previous studies found that optical performance can be different for the similar value of the form error with different error distributions [5]. Also, optical performance is the final evaluation specification for the applications of optical surfaces/system. It is, therefore, insufficient to control only the machining accuracy for the final application. The ultimate focus of the manufacturing process ought to evaluate and control the optical performance. The effect on optical performance of machining errors and how to control machining errors effectively by evaluating the optical performance needs to be investigated in this paper.

This paper established one mapping model to explore the relati onship between the machining errors and optical performance. A nd simulations were conducted through this model. The effect o n optical performance of machining errors were studied, and the main machining errors was identified.

2. Establishment of mapping model

Wavefront aberration has the direct relationship with the surf ace form errors, so the wavefront aberration was chosen as the optical performance parameter for the mapping model. In order t o obtain the relationship between machining errors and wavefron t aberration, one mapping model was established based on the fl owchart in Fig. 1. Firstly, the quantitative relationship between machining errors and form errors was established based on the multi-body system (MBS) [6] and the quantitative relationship b etween form errors and wavefront aberration was established by using the ray-tracing method. The relationship between the mac hining errors and wavefront aberration can be got by the above relationships. The effect on wavefront aberration of machining errors is obtained and the main machining errors are identified. Eventually The controllable scheme will be obtained to improve the optical performance.

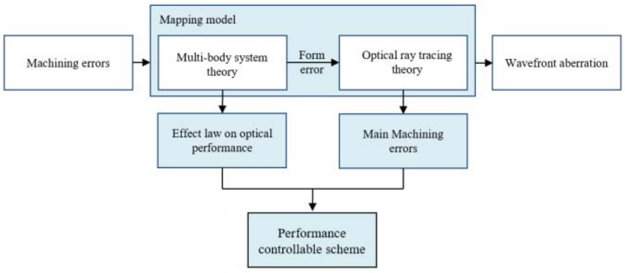

Fig.1 Flowchart of the mapping model

A three-axis ultra-precision machine was used to ultra-precision turning as shown in Fig 2. This machine tool has 21 geometric errors, three tool alignment errors as shown in Table 1. And the model process of the relationship between machining error and form error can refers to [6].

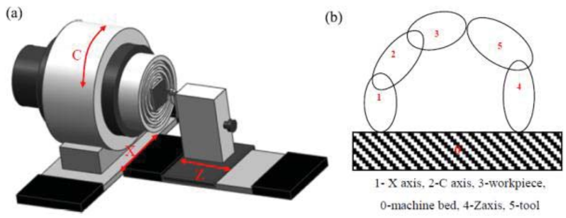

Fig.2 Schematic diagram and kinematic chain diagram of the three-axis machine tool.

Table 1 Errors of Ultra-precision turning

Axis	Error terms
X axis	$\delta_{xx}, \delta_{xy}, \delta_{xz}, \theta_{xx}, \theta_{xy}, \theta_{xz}$
Z axis	$\delta_{zx}, \delta_{zy}, \delta_{zz}, \theta_{zx}, \theta_{zy}, \theta_{xz}$
C axis	$\delta_{cx}, \delta_{cy}, \delta_{cz}, \theta_{cx}, \theta_{cy}, \theta_{cz}$
Squareness errors	$\alpha_{zx}, \beta_{cx}, \beta_{cy}$
Tool alignment errors	X_t, Y_t, Z_t

In this paper, One two-reflective system was machined by ultra-precision turning. The configuration of two-reflective system and the model process between machining error and wavefront aberration are shown in Fig 3. The model is established by using the ray-tracing method to compute the path of a real geometrical ray. The light path was calculated by rectilinear propagation in homogeneous medium, and abided by Snell's laws for reflection [7]. The modeling process is established as follow.

(1) Determining the incident rays O_mA_m and the intersection points A_m of incident rays on the reflecting surface1.

(2) According to the law of reflection, finding the direction vector of reflected light A_mB_m by surface1.

(3) According to the law of reflection, finding the direction vector of reflected light B_mC_m by surface2.

(4) According to the principle of equal optical path, calculating the equal optical path points C_m, then interpolating and fitting these points, and obtaining the final wavefront passing through the two surfaces.

(5) Comparing the actual wavefront and ideal wavefront to obtain the wavefront aberration.

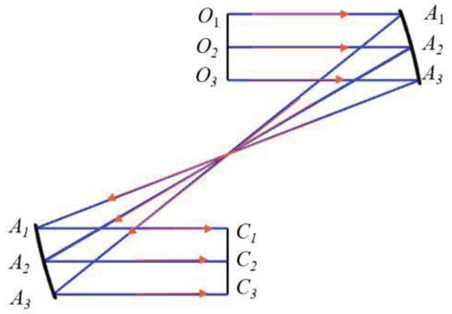

Fig. 3 Configuration of two-reflective system and its model

3. Simulations

According to the machining error model, the 24 error items can be divided into 12 error categories, δ_x, δ_y, δ_z, θ_x, θ_y, θ_z, δ_{cx}, δ_{cy},θ_{cx}, θ_{cy}, α_{zx} and θ_{zz}, refer to [6]. Simulations were conducted to explore the effect on optical performance of these machining errors based on the mapping model.

Each machining error was imported into the model. the value of each error is 0.001mm or 0.001°. The wavefront aberration caused by each machining error were obtained as shown in Fig.4. It can be seen that the styles of wavefront aberration were mostly spherical aberration and astigmatism. And sensitivity of the effect on optical performance for the machining errors is counted and calculated as shown in Fig. 5. The errors δ_x, δ_y and θ_{cy} are the main machining errors which should be considered in the ultra-precision turning of the two-reflective system. The future plan is to identify the main machining errors by machining the special workpiece, and then compensate the main machining errors before machining the actual surface or system to ensure the good optical performance.

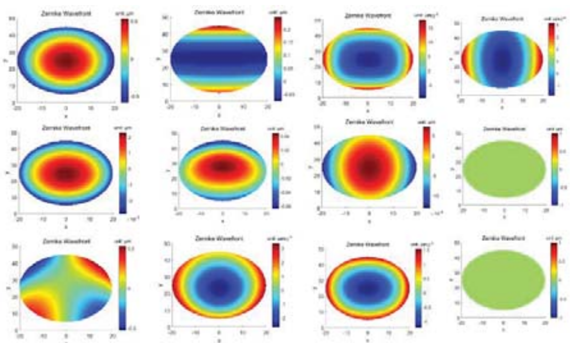

Fig.4 Wavefront aberration caused by 12 machining errors

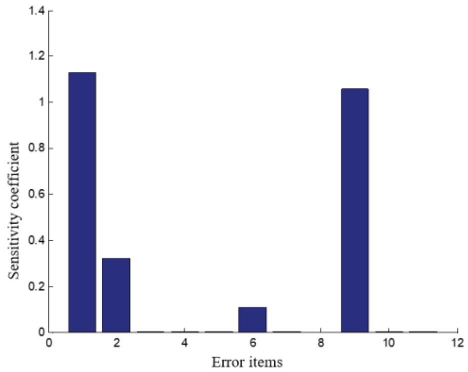

Fig. 5 Sensitivity of the effect on optical performance for the m achining errors

3. Conclusions (Times New Roman 10pt)

The mapping model between the machining errors and wavefront aberration was established. And the effect law on wavefront aberration of the machining errors was obtained, two styles-spherical aberration and astigmatism. The main machining errors was identified, which is error δ_x, δ_y and θ_{cy} for the two-reflective system.

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