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Real-time motion error compensation in optical surface fabrication using a 2-DOF linear encoder

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Abstract

Recent optical components and molds for high-grade camera lenses, x-ray and neutron optics with aspherical or free-form surfaces demand form accuracy of a few nanometers. Optical performances of such high-grade optics are often compromised by surface waviness with short spatial period that introduces significant slope errors. Traditional polishing techniques prove ineffective for mitigating these errors, especially when the waviness have spatial frequencies ranging from 0.1 mm^{-1} to several mm^{-1}. These deviations are largely attributed to motion inconsistencies such as minute waviness in stage motion straightness and rotational motion errors. To address this issue, we introduce a novel position detection and compensation method implemented on an ultra-precision machine tool equipped with dual 2-DOF (degrees of freedom) linear encoders. The uniquely designed encoder, resembling a fish-bone pattern, is crucial for capturing positional changes in two orthogonal directions on a horizontal plane. By introducing the 2-DOF linear encoders, in-plane positioning errors can be compensated in a straightforward manner. To validate the efficacy of our approach in reducing minute waviness and slope errors, a machining experiment was conducted by single crystal diamond turning of a spherical surface of 200 mm in radius made of electroless nickel phosphate plating on aluminum substrate. The result shows about 49% reduction of minute waviness and slope errors by compensation.

Keywords: Compensation, Diamond Turning, Ultraprecision Machining, Optics manufacturing

1. Introduction

With a rising demand for ultraprecision optical elements, addressing micro waviness on optical surfaces is a key challenge. These waviness patterns, typically spanning 0.1 mm to several millimeters in wavelength, significantly degrade optical performance. Traditional polishing methods struggle to efficiently remove this waviness [1], often attributed to machine tool motion errors during the optical surface machining process, caused by machine-related issues, which significantly impact form accuracy [2].

To tackle this challenge, Shibaura Machine Corp. has developed an innovative compensation system for an ultra-precision machine tool. This system employs a novel 2-DOF linear encoder to detect straightness errors [3]. In this paper, we introduce this system and present the results of a diamond turning experiment conducted on two identical optical surfaces. Our aim is to evaluate the extent to which this system improves the mitigation of waviness resulting from machine tool motion errors.

2. Compensation System with 2-DOF Encoder

2.1. Features of 2-DOF Encoder

Machine tool motions are tracked by encoders. Standard 1-DOF linear encoders, as seen on the X-axis in **Figure 1**, detect forward shifts but not lateral ones. Lateral shifts are often due to guide rail waviness, affecting workpiece accuracy.

For simultaneous X and Y detection, a 2-DOF linear encoder is essential. Traditionally, it uses two scales on X and Y axes, but precise straightness on a long Y-scale is challenging and affects accuracy.

To solve this, we've developed a fish-bone 2-DOF linear encoder, detecting X and Y motions using a short scale tilted ±45°. Position shifts are calculated with these equations:

(1)

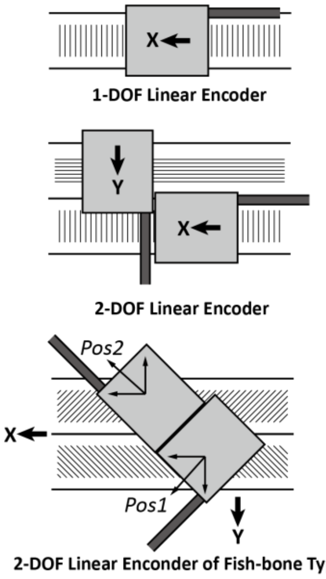

Figure 1. Linear Encoder with Multi Degrees of Freedom.

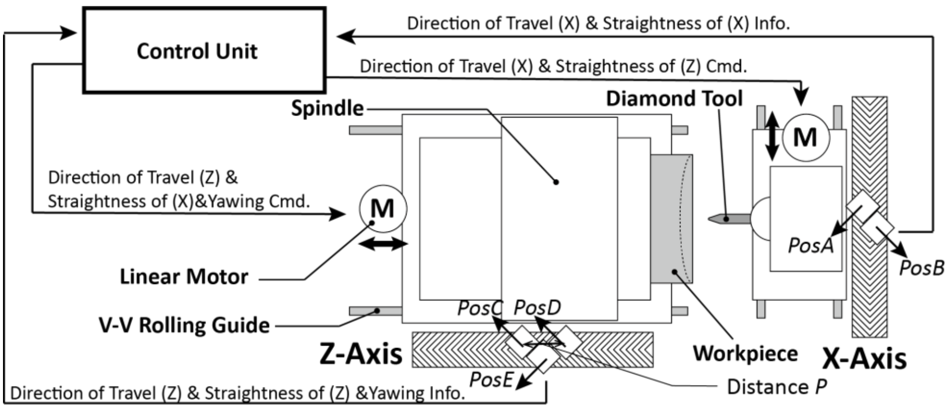

Figure 2. Configuration of Compensation System featured with 2-DOF Linear Encoders.

$$X = \frac{\sqrt{2}}{2}(Pos1 + Pos2)$$
$$Y = \frac{\sqrt{2}}{2}(Pos1 - Pos2) \qquad (2)$$

By applying the fish-bone type of 2-DOF encoders to the machining axis, we can capture orthogonal position shifts on the guide way. This makes it easier to compensate for motion errors in real-time, leading to improved machining precision.

2.2. Configuration of Compensation System

The machine system configuration equipped with 2-DOF encoders is depicted in **Figure 2**. In this system, the X-axis represents the feed axis of the machine tool, while the Z-axis represents the cutting axis on the spindle. The X-axis is equipped with a 2-DOF linear encoder to detect the straightness error of the motion in the X-direction. Meanwhile, the Z-axis is equipped with three detection unit to measure not only the straightness error but yawing motion error. The yawing angle θ can be calculated using Equation (3).

$$\theta = \frac{\sqrt{2}}{2}\left(\frac{PosD - PosC}{P}\right) \qquad (3)$$

By providing feedback regarding the position shifts of both the X and Z axes to each other, most of motion errors on horizontal plane can be corrected. This system was integrated into the ultraprecision lathe turning machine tool (ULC-100F(S); Shibaura Machine Corp.), which is equipped with V-V roller guides driven linear motors and pneumatic spindle with porous restrictor.

3. Turning of Optical Surfaces with Real-time Compensation

3.1. Diamond Turning of Optical Spherical Surfaces

We conducted a diamond turning experiment to assess the effectiveness of the compensation method using 2-DOF encoders on workpiece accuracy. Two identical workpieces were prepared, consisting of Al-Mg alloy substrates plated with Ni-P. These workpieces had 100 mm diameter optical surfaces, which were shaped into spheres with a 200 mm curvature radius using a diamond tool with a 1.0 mm cutting edge radius. The surfaces were then machined to achieve a theoretical roughness of 0.125 nm (P-V) by running the spindle at 1000 min^{-1} and feeding at 1 mm/min. During this process, one surface incorporated the compensation system, while the other did not.

3.2. Evaluation of Optical Spherical Surfaces

To assess the form accuracy of the optical surfaces we fabricated, we employed a laser interferometer (Verifire QPZ; Zygo Corp.) to measure the slope error of the waviness present on the surfaces. We removed profile errors of long wavelengths by subtracting profile fit data consists of quartic plane curve, then waviness errors along diameter direction is integrated through 180 degree by step of 5 degrees and average was calculated. In addition, wavelengths above 10 mm were filtered out to enhance the distinction of waviness. As shown in **Figure 3**, a noticeable distinction in waviness was evident along the line segment stretching from the sphere's center to its periphery when comparing the compensated and non-compensated surfaces. The amplitude of waviness on the compensated surface was approximately ±4.7 nm p-v (peak-to-valley), while the non-compensated surface exhibited an amplitude of around ±9.2 nm p-v, representing a reduction about 49%. Furthermore, the slope error for each optical surface measured 7.88 µrad p-v with compensation and 12.50 µrad p-v without compensation, representing a substantial 43.3% reduction. This significant decrease in slope error underscores the effectiveness of the compensation system in mitigating waviness on the optical surface.

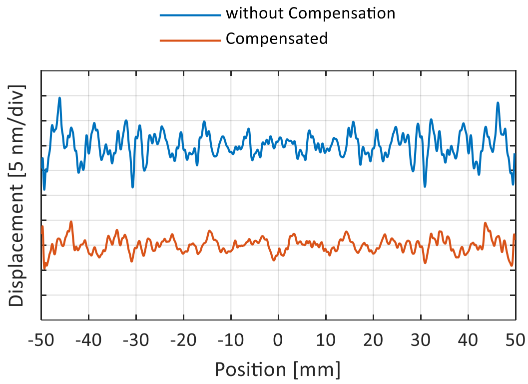

Figure 3. Form Displacement of Diamond Turned Optical Surfaces.

5. Summary

A novel compensation system for the ultra-precision lathe turning machine equipped with 2-DOF linear encoders is introduced and a diamond turning experiment was conducted. Two sphere optical surfaces were fabricated while one with compensation and the other without. Results showed a significant improvement in reduction of waviness and slope errors, which indicates the accessibility of this new compensation system.

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