Developed of a Multi-Degree of Freedoms Measuring System and an Error Compensation Technique for Machine Tools

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Abstract. In this paper, a new measuring system, Multi-Degree of Freedoms Measuring System(MDFMS), is presented. It is integrated a miniature laser interferometer with a DVD pickup and straightness measuring optical system. The five-degrees of freedoms motion errors to simultaneously measure machine tools. And, it reduces the overall time for measuring the geometric errors. The resolution and accuracy of straightness measurement are about 0.3μm and the resolution and accuracy of the angular error measurement are about 0.6arcsecs within the measuring range of 150mm. MDFMS is characteristic by simple set up, low cost, fast measuring and high accuracy for machine tools.

1. Introduction
The verification and positioning techniques of the linear axis of five axes machine tools are an orientation towards modifying simultaneously or multi-degree of freedoms measurement, however, online or offline. Laser interferometers by which positioning, straightness, pitch and yaw can be measured are one of the most reliable measuring systems in industry. Laser interferometers are difficult to set up, many optical components and the ways of setting up of each measurement are different. Thus, the new multi-error measuring methods are researched and developed. The measuring methods, however, online or offline can be distinguished into interferometer multiple optical path design, integration two-dimensional position detector and interferometer multiple optical path design, plane encoder multiple-dimensional measurement and other etc..

Continuing, the measuring methods are introduced, respectively, follow by:

The interferometer multiple optical path design: Presently, the laser measuring system(HP/Aglient) with double plane mirrors and multiple interferometers is used in industry. And it can be implemented to measure five degrees of freedoms errors, two straightness, pitch, roll and yaw. In 1989, Sommargren [1] presented a measuring system with double laser interferometers. This system can be implemented to measure two straightnesses and yaw for wafer stages. In 1993, Nakamura [2]
presented a new method with four laser interferometers and a corner cube. This method can be implemented to measure three-dimensional positioning of microscopic scanning stages, but only applies to small measuring range.

The integration two-dimensional position detector and interferometer multiple optical path design: In 1992 and 1995, J. Ni presented a multi-degree of freedoms measuring system with four position silicon detectors (PSD) [3,4]. This system can be implemented to measure the geometry errors of CMMs, two straightness, pitch, roll and yaw. In 1994, Shimizu presented a measurement system [5] with three PSDs and a laser interferometer. This system can be implemented to measure six degree of freedoms error of one linear axis.

The plane encoder multiple-dimensional measurement: The grid encoder developed by Heidenhein co. in Germany. This system can resist higher disturbance which machines motion resulted. In 2004, Jywe et al. developed the four degree of freedoms measuring system with a grating and the optical diffraction theorem [6].

Other methods: In 1997, Chou et al. developed the five degree of freedoms measuring system with CCD which was substituted for quarter detector [7].

In industry, Automated Precision Inc.(API) developed the six-degrees-of freedom measuring system and sells. But this measuring system is expensive. The micro-interferometer and the micro-angler measuring system are integrated into the measuring system that developed in this paper. This system can be to verify five axes machine tools and is characteristic by simple set up, low cost, fast measuring and high accuracy for machine tools.

2. The Structure and measurement of MDFMS

This system includes a fixed part and a moved part. The fixed part is composed of a micro-interferometer, a DVD pickup, a lens (L1), a bean splitter (BS1) and a quarter detector (QD1). And the moved part is composed of a plane mirror (PM1) and a corner cube (CC1). The structure and optical path of MDFMS is shown in Figure 1. In addition, this system is also distributed into two parts, the micro-interferometer part and the DVD pickup part. In the micro-interferometer part, a laser light to the CC1 from the interferometer, then, the reflection is shot to the bean splitter. The light is split up two lights that one shoots to the interferometer, other passes through the L1 and shoots to the QD1. The positioning, vertical straightness and horizontal straightness can be obtained via the micro-interferometer part. In the DVD pickup part, as shown in Figure 2, the voice coil motor and the lens are moved out from the DVD pickup. A collimation laser light is shot to the PM1 from the DVD pickup, then, the reflection is shot back the DVD pickup. This measurement likes the autocollimator. The pitch and yaw can be obtained with the DVD pickup part.

![Figure 1. The sketch of the optic path of the five degree of freedom measuring system.](image-url)
2.1. Position Measurement
The positioning of tables can be obtained with the interferometer. The formula of the positioning is described as following:

\[
\text{Positioning} = L_1 - L
\]  

(1)

where \(L_1\) symbolizes the displacement that is obtained with the interferometer and \(L\) symbolizes the actual displacement of the table.

2.2. Straightness Measurement
As shown in Figure 1(a), the moved part is fixed to the table. When the table is moved along motion axis, CC1 is also moved. The design theorem of corner cubes is that a light shot to corner cube, then, it shot out corner cube via twice reflexes. And the incident light and the reflect light are parallel. The distances form the apex of the corner cube to the incident light and the reflect light are equidistance. As shown in Figure 3, the corner cube moved down micro-displacement, \(\delta\), then, the distance form the incident light to the apex of the corner cube adds micro-displacement, \(\delta\), i.e., the reflect light is alike. The double straightness is obtained with QD1. Let the data of QD1 divided by 2, then, the actual straightness is obtained. The movements of the laser light are gauged with QD1, so the horizontal straightness and the vertical straightness are obtained. The formulas of the straightness follow:

\[
\delta_h = \frac{x_1}{m_h}
\]  

(2)

\[
\delta_v = \frac{y_1}{m_v}
\]  

(3)

Where \(\delta_h\) and \(\delta_v\) respectively symbolize the horizontal straightness and the vertical straightness, \(x_1\) and \(y_1\) respectively symbolize the output of the x-direction and the y-direction of QD1 and \(m_h\) and \(m_v\) respectively symbolize the gain of the x-direction and the y-direction of QD1.

2.3. Pitch and Yaw Measurement
The pitch and the yaw are measured with the theorem of autocollimators. The measurement theorem of autocollimators is that a laser shoots pass a plane-convex lens and shoots to QD2. The distance
between QD2 and the lens is about the focal distance of the lens. Then, the pitch and yaw which are obtained with QD2 don’t correlate with the distance. The formulas of the pitch and yaw follow:

\[ \theta_p = m_p y_2 \]

\[ \theta_y = m_y x_2 \]

(4)

(5)

where \( \theta_p \) and \( \theta_y \) respectively symbolize the pitch and the yaw, \( a_x \) and \( x_2 \) respectively symbolize the output of the x-direction and the y-direction of QD2 and \( m_p \) and \( m_y \) respectively symbolize the gain of the y-direction and the x-direction of QD2.

3. System Verified and Error Analyzed

3.1. Resolution Verified

3.1.1. Straightness. The straightness of MDFMS is verified with the interferometer (HP 5529A). The data of the straightness of MDFMS are calculated with the Least Square Method, and then compared with the data of HP 5529A. The linearly range of QD1 is ±50μm and the error is under ±0.2μm. Therefore, the gains that are in the linearly range are obtained. The \( K^+ \) and the \( K^- \) are respectively about 0.08945 mm/V and 0.08904 mm/V. In additional, two gains of the small measuring range, 0-1μm and 0-10μm, are respectively about 0.099165 mm/V and 0.099202 mm/V. The foregoing explains that MDFMS is higher accuracy when the measuring range is smaller.

3.1.2. Pitch and yaw. In order to obtain the best result, a micro-angle rotation table with a piezoelectric is invented for verifying the resolution of MDFMS. The angle of the rotation table is changed when a controller outputs the different voltages to the piezoelectric. The verified system is composed of a micro-angle rotation table, a micro-interferometer (SIOS SP-2000D), a DVD pickup and two plane mirrors. The verified result of the measuring range of pitch and yaw are both about 30 arcsecs. The resolution of pitch and yaw are both under 0.6 arcsecs.

![Figure 4. The results of the experimenting.](image-url)
3.2. Experimenting and Error Analyzed
In this section, a CNC machine tool is measured with MDFMS. And a HP 5529A is placed for verifying the accuracy of MDFMS at the same time. The measuring results are shown in Figs. 4. The measuring range of the straightness is 200mm and the data are sampled at 25mm intervals. The measuring range of the pitch and yaw is 240mm and the data are sampled at 30mm intervals. Repeat sampling three times is in order to obtain the closer actual performance. Comparing with HP 5529A, the straightness, pitch and yaw of MDFMS are respectively ±0.8μm, ±0.8μm, ±0.6arcsecs and ±0.6arcsecs. The results proved that MDFMS possesses good performance.

In additional, the vertical straightness and horizontal straightness of the machine tool is respectively within from -1μm to 2.5μm and from -1.4μm to 0.2μm. The pitch and yaw of the machine tool are respectively under 12arcsecs and under 7arcsecs.

4. Conclusion
In this paper, a multi-degree of freedoms measuring system, MDFMS, is developed and proved. MDFMS can be applied CNC machine tools, CMM, multiple axes machine tools and micro-tables. Through forward sections explained that MDFMS is not only characterized by lower cost, simpler set up, more convenience operation and faster measuring speed, but also following:

(1) Better resolution: the straightness, pitch and yaw is respectively ±0.2μm, ±0.6arcsecs and ±0.6arcsecs.

(2) Higher accuracy: the straightness, pitch and yaw is respectively ±0.8μm, ±0.6arcsecs and ±0.6arcsecs.

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