

A STUDY ON LASER-CCD SPINDLE ERROR MEASUREMENT SYSTEM

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Abstract

Machining accuracy depends on the static and dynamic relative positioning between the spindle and machine table. It is theoretically and practically important to measure the spindle positioning error relative to the machine table. A novel measuring system, which is referred to as the Laser-CCD Spindle Error Measurement System (LCSEMS), is proposed based on the concept of direct and simultaneous measurement for real-time machine error and compensation in regular manufacturing environments.

Keywords: Error compensation, CNC machine tool, Laser, CCD, Spindle error motion

1. Introduction

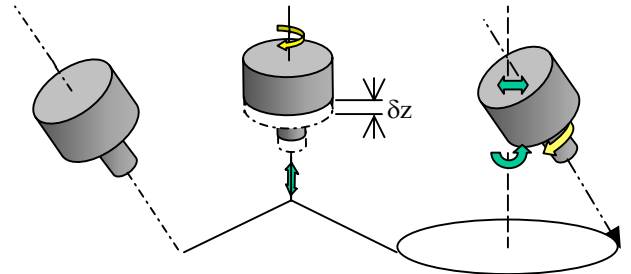
High machining accuracy is one of the most essential factors for modern manufacturing industries. High machining accuracy depends substantially on the reduction of machine tool system errors. According to their sources, machine tool errors mainly include geometric errors, thermal errors, cutting force induced errors and dynamical errors. Many methods and strategies have been employed to reduce these errors are many. According to Blaedel [1], they can be divided into two major categories: error avoidance [e.g. 1, 2-4] and error compensation [e. g. 5, 6].

The basic concept of the error avoidance method is to build accuracy into machine tools and to try to eliminate possible error sources through design and manufacturing efforts. However, this method is limited by several problems such as cost and physical limitation of machine tools. Error compensation is to first measure and then model or map the existing errors of a machine, and finally take compensatory actions during the subsequent machining process to eliminate or reduce these errors. Error compensation method provides possibility to manufacture parts with high accuracy using the machine tools of low accuracy. However, the effectiveness of error compensation practice is limited by the lack of real-time machine error information. Apparently, error compensation would be more effective if real-time machine error information can be obtained. For this purpose, a real-time and direct error measuring system for machine tools is needed.

A machine spindle rotates at high speed to cut workpieces and it slides along the rotational axis for positioning. It is very important to be able to detect the erroneous motion of the spindle because it is the part that comes in contact with the workpieces. The goal of this research is to develop a system, called Laser-CCD Spindle Error Measurement System (LCSEMS) that can measure several major motion errors of one machine

spindle simultaneously, in-process, and in real-time. In this paper, the major erroneous features are identified. The required accuracy and test methods by ISO are mentioned. The theoretical basis for simultaneously measuring the errors has been established. A system prototype has been designed and a simulation to find the optimal parameters for the design has been performed.

2. Types of Spindle Positioning Errors



Inclination Thermal Expansion Radial Error Motion

Figure 1 Three types of spindle errors studied

There are four types of spindle positioning errors: inclination, thermal expansion, four-degree-of-freedom radial motion error and four-degree-of-freedom linear motion error.

Inclination is where the spindle is tilted at an angle to its ideal orientation while at rest, therefore a static error. A spindle will expand when its temperature rises. There are many causes that might raise the temperature of a spindle: change in room temperature, electrical current, or friction. Some of the causes occur when the spindle is at rest and others occur when it is in motion; therefore, thermal errors can either be static or dynamic. The other two errors are dynamic errors. Four-degree-of-freedom radial motion error occurs when the spindle is in rotation. Ideally a spindle should be rotating against a single point; however, it is in reality rotating in a circular path around the ideal point of rotation due

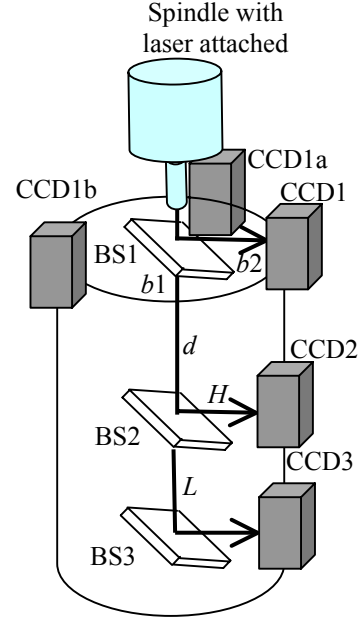
to errors introduced by spindle. Four-degree-of-freedom linear motion error occurs when the spindle is sliding along the rotational axis linearly. Instead of moving in a perfectly straight line, there are some unwanted four degree-of-freedom motions incurred in the motion. Figure 1 shows the three types of errors this research is concerned. Linear motion error measurement was covered by previously research in IMS lab [7], though the current system should be able to measure it as well.

3. Conceptual Design of the System

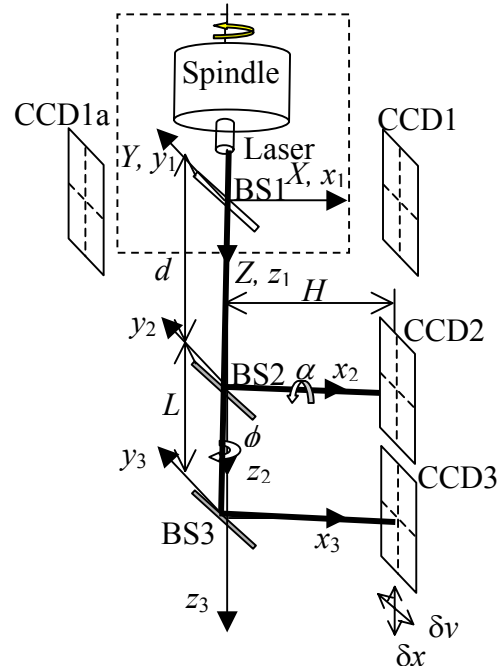
LCSEMS has two main modules: a laser module and a CCD module. Laser module includes a laser and a beam splitter. The laser is attached to the tip of a machine spindle. One beam splitter is fixed at the tip of the laser. CCD module includes five CCD cameras and two beam splitters. The laser provides a stable laser beam, which can be detected by the CCD cameras. When the spindle is in motion, either rotating or sliding, the laser moves with the spindle. The laser beam image captured by the CCD cameras will reflect the movements of the laser or spindle. Knowing the correlation between the laser beam movement and its image on the CCD cameras, we can determine the exact movement of the spindle. To ensure the simplicity and efficiency, the system should be designed in such a way that it will be able to measure all errors simultaneously and in real time. Also, the system should be portable for different types of CNC machines.

Figure 2(a) shows the conceptual design of the system. LCSEMS has two main modules: a laser module and a CCD measuring module and a computer system. The laser module consists of a single laser and a beam splitter (BS1) to provide dual laser beams as the two-metrology bases for LCSEMS. One laser beam (b1) lies in Z-axis, and the second laser beam (b2) lies perpendicular to the Z-axis. The CCD module consists of five CCD cameras: CCD1, CCD1a, CCD1b, CCD2, and CCD3; two beam splitters, BS2 and BS3, are also included in the CCD module. The CCD module will be rigidly fixed on the machine table in the reference frame. As shown in Figure 2(b), uppercase X, Y, Z is the coordinate system of the spindle and laser module; lowercase x, y, z is the CCD module coordinate system, which is fixed in the reference frame.

H is the shortest distance between the CCD cameras and z-axis, L is the distance between BS2 and BS3 or CCD2 and CCD3, and d is the distance between BS1 and the CCD module. The beam positions on each CCD will change when the spindle rotates or moves up and down along the z-axis. The spindle inclination, thermal expansion, straightness errors δx and δy , and angular errors α and ϕ can be determined simultaneously from the beam positions on each CCD.



(a) Schematic of the system



(b) Coordinate systems of LCSEMS

Figure 2 Conceptual Design of LCSEMS

4. Measurement Principles

In Figure 2(b), $X-Y-Z$ is the moving coordinate system attached at the center of BS1. There are three global coordinate systems: $x_1-y_1-z_1$, $x_2-y_2-z_2$ and $x_3-y_3-z_3$. $x_2-y_2-z_2$ and $x_3-y_3-z_3$ are attached to the center of BS2 and BS3 respectively $x_1-y_1-z_1$ is attached to the ideal center of BS1. In Figure 2(b), $X-Y-Z$ and $x_1-y_1-z_1$ coincide each other.

4.1 Inclination

The coordinate system X - Y - Z moves with respect to the global coordinate system x_1 - y_1 - z_1 . Because BS1 is fixed on and rotates with the spindle, laser beam b2 is always perpendicular to the axis of the laser. The three centers of CCD1, CCD1a and CCD1b form a triangle on the plane of x_1 and y_1 . Since we are measuring the orientation of the spindle at rest, we can manually rotate the spindle so that laser beam b2 is pointed towards each of the three CCDs and collect the beam position on each CCD. The three positions of laser beam image on CCDs form a plane, in which we have the coordinate information needed to determine the spatial relation of the spindle with respect to the global reference frame x_1 - y_1 - z_1 (as shown in Figure 3).

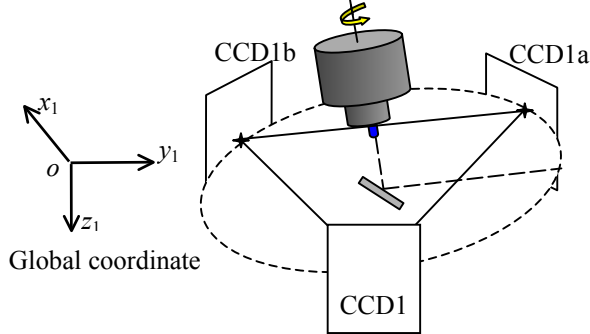


Figure 3 Measurement principle of inclination

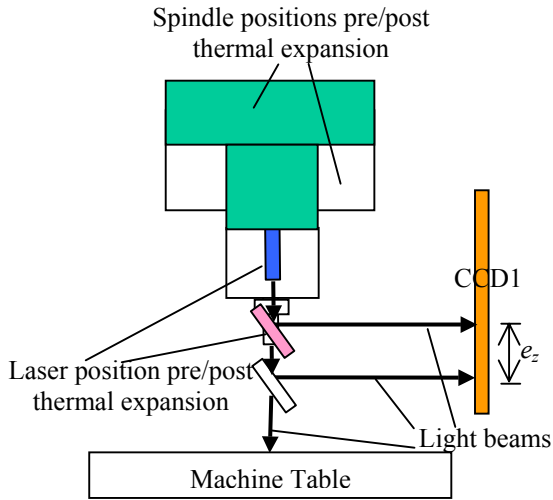


Figure 4 Measurement principle of thermal expansion

4.2 Thermal expansion

In order to detect the thermal expansion effect on a spindle, we need to measure the spindle tip position over time. The position of laser beam b2 is first measured on CCD1 while the spindle is at rest and room temperature. To inspect the thermal expansion effect on a spindle in a given time and a given RPM, the spindle is then turned on for the given time period at the given speed. A second beam position is then taken. The displacement of beam position between the two

beam positions is the result of thermal expansion for the given time and speed as shown in Figure 4).

4.3 Four-degree-of-freedom radial motion error

Radial error motion has six components. Three translational components: δx , δy and δz , and three rotational components: α , ϕ , and θ . The six components result in a six degree of freedom erroneous motion when rotating the spindle. From the past research [7], δz cannot be measured with good resolution. Therefore, it will not be considered in this research. Also, θ does not affect workpiece accuracy due to the symmetrical geometry of spindles. Therefore, it will not be considered, either. As a result, only four-degree-of-freedom motion errors will be measured in this research.

Based on the conceptual system design, the spatial correlation between the spindle tip and the positions of the laser beam image on CCD2 and CCD3 was derived by vector analysis as follows

$$\begin{bmatrix} y_2 \\ z_2 \\ y_3 \\ z_3 \end{bmatrix} = \begin{bmatrix} 0 & -1 & H & 0 \\ -1 & 0 & 0 & -H \\ 0 & -1 & H+L & 0 \\ -1 & 0 & 0 & -(H+L) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \alpha \\ \phi \end{bmatrix} \quad (1)$$

From the inversion (Equation (2)) of this equation, we can obtain the four erroneous components.

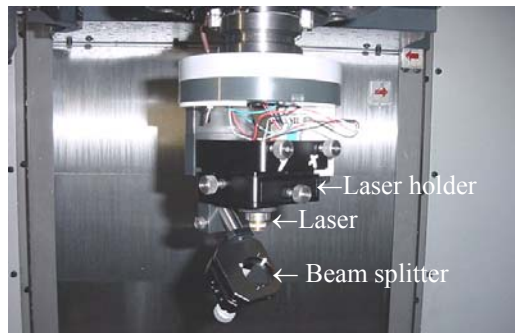
$$\begin{bmatrix} \delta x \\ \delta y \\ \alpha \\ \phi \end{bmatrix} = \begin{bmatrix} -\frac{H+L}{L}z_2 + \frac{H}{L}z_3 \\ -\frac{H+L}{L}y_2 + \frac{H}{L}y_3 \\ -\frac{1}{L}y_2 + \frac{1}{L}y_3 \\ \frac{1}{L}z_2 - \frac{1}{L}z_3 \end{bmatrix} \quad (2)$$

When the spindle rotates, the coordinate system X - Y - Z moves with respect to the global coordinate systems x_2 - y_2 - z_2 and x_3 - y_3 - z_3 . The relative motion can be decomposed into two parts: a two-dimensional translation of δx and δy and a composite rotation α and ϕ . Once beam center position (y_2, z_2) and (y_3, z_3) on the two CCDs are captured, the four-degree-of-freedom machine motion error components $(\delta x, \delta y, \alpha, \phi)$ can be found from Equation (2). The coordinate (y_2, z_2) and (y_3, z_3) are the beam positions on CCD2 and CCD3 respectively. L and H are the structural parameters defined in Figure 2.

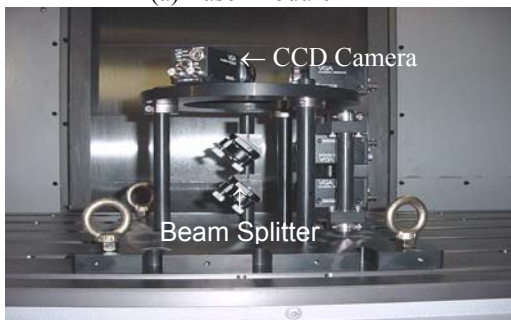
5. Prototype Evaluation of LCSEMS

Based on the above analysis, a prototype of this system has been built. As aforementioned, the system includes

two module. Figures 5(a) and (b) show the pictures for these two modules.



(a) Laser module



(b) CCD module

Figure 5 Picture of system prototype

5.1 Laser module

One of the major requirements for the laser module is to have stable beam generation. This is because the accuracy of the system depends on the laser beam to provide an accurate reference point. Therefore, checking the laser beam stability becomes an important priority for system evaluation. Environmental vibration, temperature change and even stability of laser power supply will influence the laser stability. Steps taken to test laser beam stability include beam profile detection, beam drift calculation and beam processing. To numerically increase laser beam stability, a process called “frame-averaging” is used. This process adds a certain number of beam images together before dividing the image by the number to take the average beam intensity distribution. Then the beam center is calculated using the Centroid method. For final measurement, average of a certain number of beam center point will be used to increase the accuracy of measurement. Figure 6 shows the result of averaging every 100 points out of 1500 beam center points. The variation for the 15 resulted center points is about 0.3 μm , which meets the 1 μm accuracy requirement.

5.2 CCD module

CCD camera has noise known as “dark current”. To minimize the effect of this noise, dark current’s highest level is measured and then subtracted from the data collected.

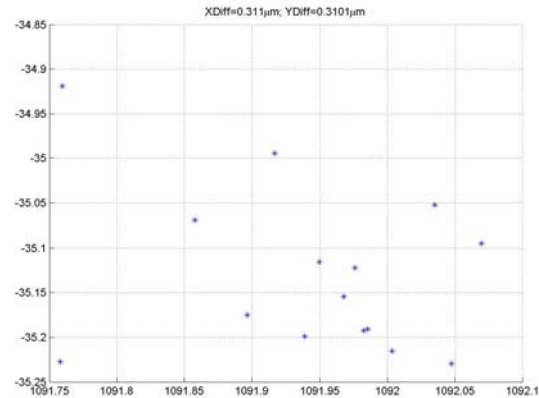


Figure 6 Averaged center point

6. Conclusions and Future Work

A system called Laser-CCD Spindle Error Measurement System (LCSEMS) has been proposed to measure four types of spindle positioning errors. The measurement principles have been discussed in detail. A prototype has been built and major problems associated with measurement accuracy have been identified. Initial evaluation indicates that the system can meet the 1 μm accuracy requirement.

Future work is to improve the stability of laser and therefore to maintain the measurement accuracy of the system, and finalize the prototype.

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