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Measurement of the thermal elongation of high speed spindles in real time using a cat's eye reflector based optical sensor

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ABSTRACT

This paper describes an optical sensor for the real-time measurement of axial thermal elongation of a machine tool high-speed spindle. A cat's eye optical reflector embedded in the spindle reflects the image of a laser diode beam onto a quadrant photodiode detector. Changes in the position of the reflected laser spot on the photodiode in a detection module allows determination of changes in length of the spindle. The resolution is 50 nm for the low frequency range. The accuracy of this optical sensor is better than 1 μm within the measuring range of ±100 μm and the triple standard deviation is 0.03 μm. The experimental results showed that thermal elongation can be measured and controlled to within 2 μm of elongation and shortening variation within the stated range using an oil cooling system.

1. Introduction

The accuracy of machined parts and components is limited by the accuracy of the machine tool used for their production. Conversely, the working accuracy of a machine tool is reflected in the conformity of final machined parts and components to predefined specifications in both size and geometric shape. This makes maintenance and improvement of the accuracy of machine tools an important issue. In general, the error factors that influence the accuracy of machine tools can be either quasi-static or dynamic [1]. Quasi-static errors are deviations in the size or shape of machined components that result from changes in the relative position of cutter and workpiece. This may be a thermal effect that causes expansion of the structure of the machine tool, or the weight of the loaded workpiece may result in deformation of the body. Dynamic errors are derived from spindle motion, vibration, electromechanical and control systems. Quasi-static errors account for 70% of overall machine tool errors and are derived from (1) geometric and kinematic errors; (2) thermal errors; and (3) cutting-force induced errors. From 40% to 70% of errors do not involve temperature and can be reduced by machine design and structural improvements such as of static and dynamic stiffness [2]. The effect of machine tool heat source distribution is also a topical subject [3] as machine tools are influenced by internal and external thermal sources during cutting operations [4,5]. The main source of heat during machining arising from the high operation speed of the spindle. In 1993, Chen et al. used 18 thermocouples and a laser interferometer to measure temperatures of a horizontal milling machine, the room temperature, and the thermal deformation displacement of the machine spindle [6]. This arrangement resulted in the actual cutting dimensional errors being reduced from 92.4 μm to 18.9 μm, and the milling depth error from 196 μm to 8 μm. However, a laser interferometer based measuring system is difficult to use in practice and is also very large. In 1996, Srinivasa et al. used a laser ball bar (LBB) to test the geometric positional errors of spindle space and spindle thermal deformation displacement simultaneously [7]. As this method involved contact, the measurement of spindle displacement was limited. In 1997, Li et al. mounted a probe and one-dimensional ball plate on the table of a CNC machine to measure spindle thermal deformation error using auto-regression to build a thermal deformation displacement prediction model [8]. Although, they were able to reduce the thermal deformation displacement from 7 μm to 2 μm, the system could not be used for on-line real time measurement. In 2003, Ko et al. gripped a 150 mm precision cylindrical rod on the machine tool spindle and used three capacitive probes to measure the thermal deformation displacement in the Y and Z directions [9] and also used linear regression to predict the spindle thermal deformation error. However, this method could not be used in real time either. In 2008, Rui et al. used the finite element method to analyze the

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thermal expansion and hot bending module elements of spindle structure to determine the spindle-induced thermal source and the position of thermal coupling [10]. A thermal error prediction model was built using temperature and thermal deformation displacement data that could be used to reduce thermal deformation by 75%. However, there are so many factors that affect the thermal deformation of the spindle during the cutting process, that simulation and response using the finite element method is very difficult to achieve. In earlier work we developed an optical system that was mounted on the cutter holder side to measure spindle operation round-out and tilt errors directly [11,12]. In this type of measurement system a light source, or light reflection component, was mounted on the spindle and the error was measured using geometric optical principles. However, because the detection component was mounted on the cutter clamping head, on-line real-time measurement could not be implemented. In other words changes in the spindle resulting from heating during machining could not be known.

There are four methods that can be used to reduce thermal elongation of the spindle: (1) changing the spindle structure; (2) controlling the ambient temperature; (3) using statistics and neural network analysis to build a mathematical model of thermal error relationship; this involves detecting machine temperature rise off-line and estimating thermal elongation; (4) using a displacement meter to measure the elongation of a reference surface of the spindle for compensation, the working distance for this mode is very short and installation is difficult.

This study proposes a novel cat's eye based optical sensor which can be embedded in the spindle and will measure its axial thermal elongation at speeds in excess of 6000 rpm. The advantages of this optical sensor are (1) The optical characteristic of the cat's eye reflector makes installation of the system easy and allows a longer working distance; (2) The cat's eye is embedded in the shaft and the axial thermal elongation of the spindle can be measured directly. (3) Real-time measurement of axial thermal elongation is possible while the spindle is rotating. (4) The influence of large current noise from the spindle motor is minimized using optical technique rather than using eddy current or capacitance based displacement sensor. (5) It is unnecessary to build a mathematical model of the thermal error relationship. (6) Resolution of about 50 nm is possible. (7) The signal processing circuit is simple, easy to build and costs little. (8) The sensor is not expensive either. The device is competitive and can replace recent commercially available products used for spindle thermal elongation measurement.

2. On-line real-time cat's eye based optical sensor

The optical sensor developed for this study consists of a laser spot position detection module and a cat's eye reflector. The reflector is embedded in the spindle and when it rotates and there is axial thermal elongation, the reflector is displaced and this movement can be measured by the laser spot detection module. These two components are the keys to this system for on-line real-time measurement of the axial thermal elongation of a high-speed spindle.

2.1. Cat's eye reflector

The cat's eye reflector is a ball lens with refractivity $n'=2$ and 1/3 of the surface is coated with a layer of reflective aluminum. Fig. 1 shows the characteristic of the laser beam path in the ball lens. When the cat's eye reflector is shifted horizontally ε_y in the y-direction, the reflected laser beam will also be horizontally shifted $2\varepsilon_y$. This type of reflector is not very sensitive to tilt error and elongation measurements can be made without taking the tilt effect of the spindle into consideration. The lens equation of the cat's eye can be derived by using an ABCD matrix and the Lensmaker's equation, as below:

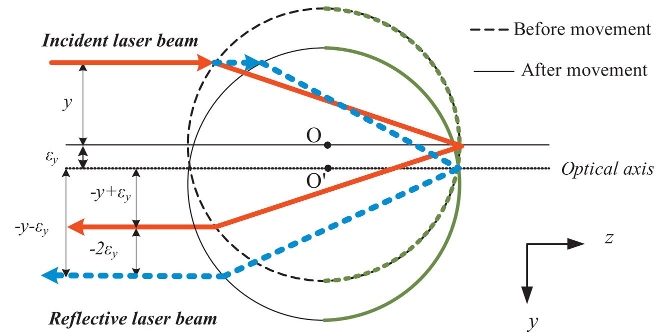

Fig. 1. Principle of cat's eye reflector.

$$\begin{bmatrix} y' \\ u' \end{bmatrix} = \begin{bmatrix} 1-\frac{(n'-n)d}{n'R_1} & \frac{d}{n'} \\ (n'-n)\left(\frac{1}{R_2}-\frac{1}{R_1}\right)-\frac{(n'-n)^2 d}{n'R_1R_2} & 1+\frac{(n'-n)d}{n'R_2} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{R_2} & 1 \end{bmatrix} \begin{bmatrix} 1-\frac{(n'-n)d}{n'R_1} & \frac{d}{n'} \\ (n'-n)\left(\frac{1}{R_2}-\frac{1}{R_1}\right)-\frac{(n'-n)^2 d}{n'R_1R_2} & 1+\frac{(n'-n)d}{n'R_2} \end{bmatrix} \begin{bmatrix} y \\ u \end{bmatrix} \quad (1)$$

When the cat's eye reflector shifts ε_y downwards, the distance between the incident point and the new optical axis is $y+\varepsilon_y$. Then by means of Eq. (1),

$$\begin{bmatrix} y' \\ u' \end{bmatrix} = \begin{bmatrix} 0 & 4 \\ -0.25 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -0.5 & 1 \end{bmatrix} \begin{bmatrix} 0 & 4 \\ -0.25 & 0 \end{bmatrix} \begin{bmatrix} y+\varepsilon_y \\ 0 \end{bmatrix} = \begin{bmatrix} -y-\varepsilon_y \\ 0 \end{bmatrix} \quad (2)$$

where $n=1$ is the refractive index of air and $n'=2$ is the refractive index of the cat's eye reflector and the diameter d of the cat's eye is 8 mm. In other words, the displacement of cat's eye ball reflector is twice as big as the bias shift given by the equations.

2.2. Laser spot position detection module

The laser spot position detection module is shown in Fig. 2. The collimated laser light emitted by the laser diode, is polarized by the PBS and split into penetrating horizontally polarized light (p-Wave) and reflected vertically polarized light (s-Wave). It should be noted that this system uses the vertically polarized light for measurements. When the vertically polarized light passes through the λ/4

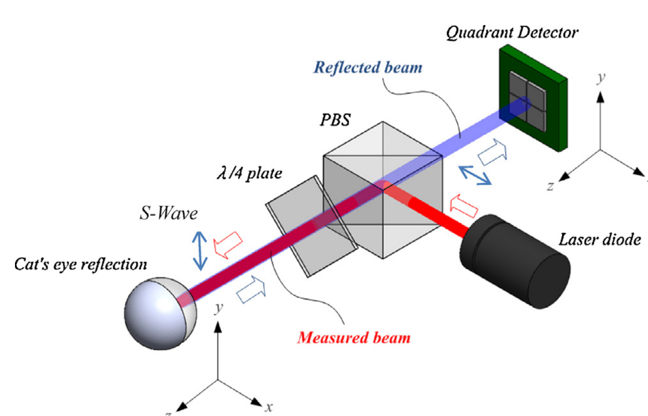

Fig. 2. Schematic diagram of the optical sensor module architecture.