LASER-CCD BASED SENSOR SYSTEM FOR REAL TIME DETECTION OF MOTION LINEARITY

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1. Introduction

The major goal of manufacturing science and technology is to achieve high productivity and high machining accuracy. In these days, while high productivity is being achieved, precision machining depends substantially on the reduction of motion errors induced by thermal and time dependent deformation. In order to minimize such an inaccurate machining results, the error compensation based on the in-process identification of the error cause is most effective.

Currently, there are two methods used in error detection. The first one is based on the utilization of laser interferometric instrument [1]. By this method, error detection usually cannot be performed in a real-time fashion during the machining process. The second method is based on the pre-established relationship between temperature distribution and thermal deformation errors, such as thermal error model [2]. Although this approach has found some application in machine tool industry, the enhancement of accuracy is limited, since the thermal behavior and deformation of machine tool systems are highly nonlinear in machine conditions [3] and this method can only detect thermal errors.

The purpose of this research is to propose and develop a novel Laser-CCD based 6 Degree-of -freedom motion Measuring System (LC6DMS) for real time, directly and simultaneously detection of motion linearity for machine error measurement and compensation.

2. A proposal of novel sensor system for real time detection of motion linearity

2.1 Conceptual design

Figure 1 shows a conceptual design of the proposed sensor, LC6DMS. This sensor is composed of two main modules in addition to computer system, which are a laser module and a CCD measuring module. The laser model is stationery on the global coordinate system and the CCD measuring module is rigidly mounted onto machine slider. The laser module produces two laser beams, B1 and B2, by using two splitters, BS1 and BS2, as two metrology bases for measurement. A laser beam B2 has inclination angle γ against B1 to measure the linear motion in Z-axis of the slider. The CCD measuring module consists of three CCD cameras, CCD1, CCD2 and CCD3, and two beam splitters, BS3 and BS4. The 6 degree-of-freedom (DOF) erroneous motions of machine slider, which are 3 linear motions $(\delta x, \delta y, d)$ and 3 angular motions (α, ϕ, θ), are measured as the relative motion between B1 and BS3 at the lowercase coordinate system o_{1B}-$x_{1B}y_{1B}z_{1B}$. During the measurement is being performed, the position of the laser beam is always captured by each CCD to measure the motion linearity of the machine slider.

2.2 Measurement principle

Figure 2 shows the coordinate system of the proposed sensor system, LC6DMS. O-XYZ is a world coordinate system attached at the center of BS1 and the others are moving coordinate systems attached at the center of BS3, BS4, CCD1, CCD2 and CCD3. W, H, L, L0 and γ are the geometric parameters of the sensor system and d is a distance of slider from the laser module.

The kinematics relationship between a six-dimensional motion of the slider, a three-dimensional translation $(\delta x, \delta y, d)$ and a composite rotation (α, ϕ, θ), and three laser positions $(y_{1C}, z_{1C}), (y_{2C}, z_{2C}), (x_{3C}, y_{3C})$ captured by three CCD cameras can be written in a following equation (1).

$$\begin{Bmatrix} y_{1C} \\ z_{1C} \\ y_{2C} \\ z_{2C} \\ x_{3C} \\ y_{3C} - \gamma(L+L0) \end{Bmatrix} = \begin{bmatrix} 0 & -1 & 0 & H & 0 & 0 \\ -1 & 0 & 0 & 0 & -H & 0 \\ 0 & -1 & 0 & H+L & 0 & 0 \\ -1 & 0 & 0 & 0 & -(H+L) & 0 \\ -1 & 0 & 0 & 0 & -(L+L0) & W \\ 0 & -1 & \gamma & L+L0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \delta x \\ \delta y \\ d \\ \alpha \\ \phi \\ \theta \end{Bmatrix} \tag{1}$$

The transformation equation from the three laser positions to a six-dimensional motion can be obtained by solving equation (1). Following equation (2) is the theoretical basis of LC6DMS for simultaneous measurement of 6 DOF machine slider motion. Once laser beam center coordinates are obtained from CCD image processing, the 6 DOF machine slide motion can be found immediately and simultaneously.

$$\begin{Bmatrix} \delta x \\ \delta y \\ d \\ \alpha \\ \phi \\ \theta \end{Bmatrix} = \begin{Bmatrix} -\frac{H+L}{L} z_{1C} + \frac{H}{L} z_{2C} \\ -\frac{H+L}{L} y_{1C} + \frac{H}{L} y_{2C} \\ \frac{L0-H}{\gamma L} y_{1C} - \frac{L+L0-H}{\gamma L} y_{2C} + \frac{1}{\gamma}\{y_{3C} - \gamma(L+L0)\} \\ -\frac{1}{L} y_{1C} + \frac{1}{L} y_{2C} \\ \frac{1}{L} z_{1C} - \frac{1}{L} Z_{2C} \\ \frac{L0-H}{LW} z_{1C} - \frac{L+L0-H}{LW} z_{2C} + \frac{1}{W} x_{3C} \end{Bmatrix} \tag{2}$$

3. Design and simulation study of LC6DMS

3.1 Optimization of structural parameters

In order to achieve highest measurement accuracy, the 5 structural parameters W, H, L, L0 and γ were optimized through simulation study. First, assuming a set of motion components,

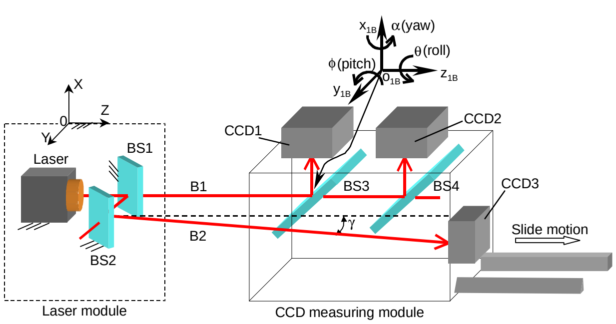

Figure 1: Conceptual design of LC6DMS

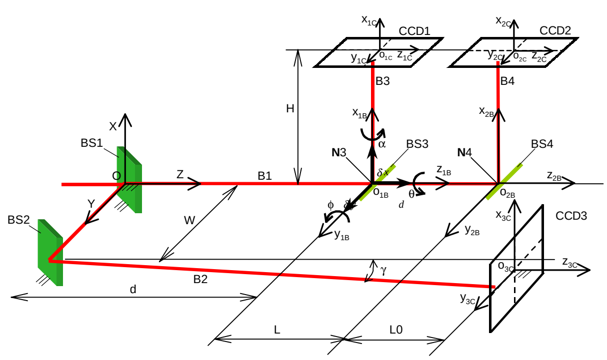

Figure 2: Coordinate system of LC6DMS

the theoretical beam center positions on each CCD are calculated by equation (1). Then, the beam center coordinate are obtained through calculation of intensity centroids of the beam images captured by each CCD in consideration of a diameter and divergence of a He-Ne laser beam and specifications of CCD cameras such as the count resolution and pixel size. Second, the 6 DOF erroneous motions are calculated by substituting the laser beam center coordinate obtained above into equation (2). The criteria of optimal design of the structural parameters are defined by following equation.

$$\delta x_{re} = \left|\frac{\delta x_o - \delta x_m}{\delta x_o}\right| \times 100\%,\ \ \delta y_{re} = \left|\frac{\delta y_o - \delta y_m}{\delta y_o}\right| \times 100\%,\ d_{re} = \left|\frac{d_o - d_m}{d_o}\right| \times 100\%$$
$$\alpha_{re} = \left|\frac{\alpha_o - \alpha_m}{\alpha_o}\right| \times 100\%,\ \phi_{re} = \left|\frac{\phi_o - \phi_m}{\varphi_o}\right| \times 100\%,\ \theta_{re} = \left|\frac{\theta_o - \theta_m}{\theta_o}\right| \times 100\% \quad (3)$$

where subscripts o and m shows the given motion error initially and the measurement results obtained from simulation respectively.

Figure 3 ~ Figure 6 shows the simulation results and its simulation parameters listed under the figures. The following structural parameters were designed based on these results and the overall module size requirement;

$$L = 60\text{mm},\ H = 54\text{mm},\ W = 46\text{mm},\ L0 = 28.5\text{mm},\ \gamma = 200\text{arcsec} \quad (4)$$

3.2 Theoretical measurement accuracy

The theoretical measurement accuracy of 6 DOF motion linearity was analyzed. Figure 7 and Figure 8 shows the theoretical measurement accuracy for linear motion. From Figure 7, it can be seen that the relative measurement errors for δx and δy are less than 0.09% over a range of 1~25 μm. Figure 8 shows that the relative error is less than 1.4% when the distance d is smaller than 2000 mm. The other theoretical measurement accuracy for three angular motions have achieved less than a 0.05% error over the range from 1 to 100 arecsec.

4. Conclusions

(1) A laser-CCD based novel sensor system for the direct and simultaneous detection of 6 DOF motion linearity was proposed.

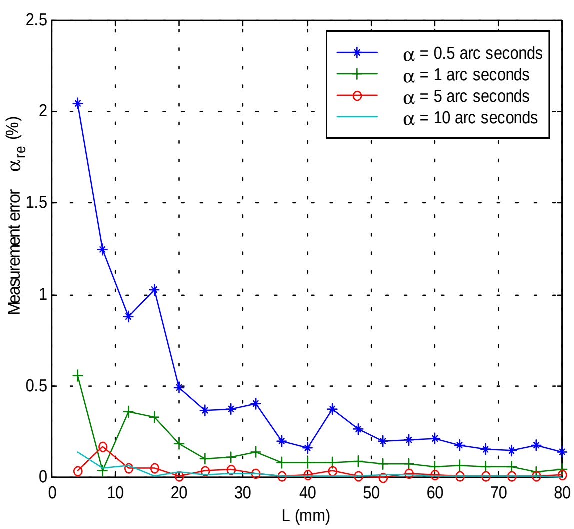

Figure 3: Relationship between L and α_{re}
(d=100mm,δx=5μm,δy=5μm,ϕ=10arcsec, θ=15arcsec,H=50mm)

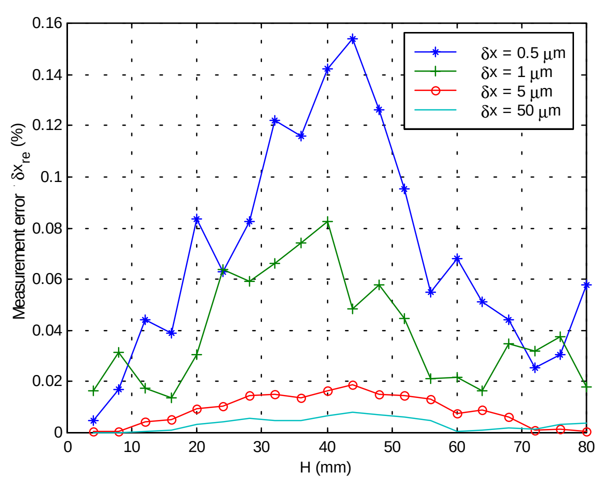

Figure 4: Relationship between H and δx_{re}
(d=100mm,δy=0.5μm,α=10arcsec,ϕ=10arcsec, θ=15arcsec,L=60mm)

(2) The theoretical bases of the proposed sensor system for simultaneous measurement of 6 DOF machine slider motions were established based on the kinematics relationships.
(3) In order to achieve highest measurement accuracy, the key structural parameters were designed through simulation.
(4) The theoretical measurement accuracy of the proposed sensor system was analyzed.

References

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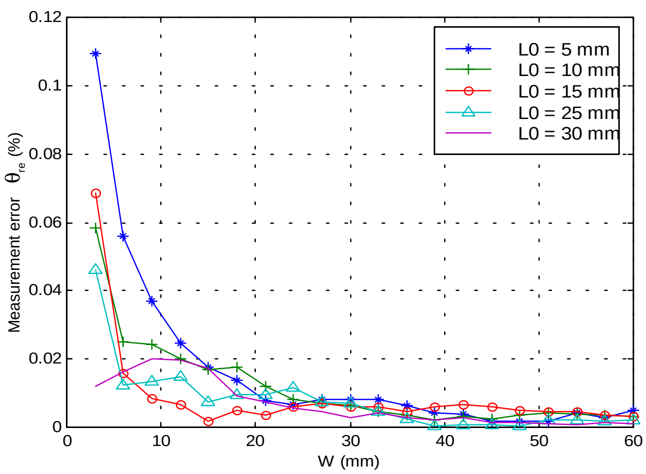

Figure 5: Relationship between θ_{re} and parameters W and L0
(d=100mm,δx=5μm,δy=0.5μm,α=10 arcsec, ϕ=10arcsec,θ=15arcsec,L=60mm,H=54mm)

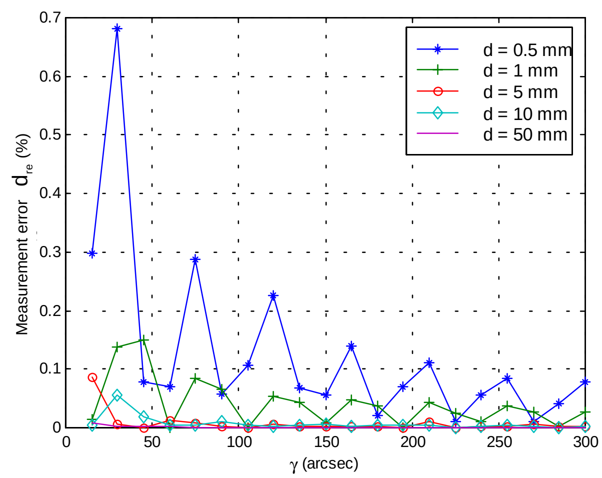

Figure 6: Relationship between d_{re} and beam inclination angle γ
(δx=0.5μm,δy=0.1μm,α=10arcsec,ϕ=10arcsec, θ=15arcsec,L = 60mm,H=54mm,W=46mm, L0=28.5mm)

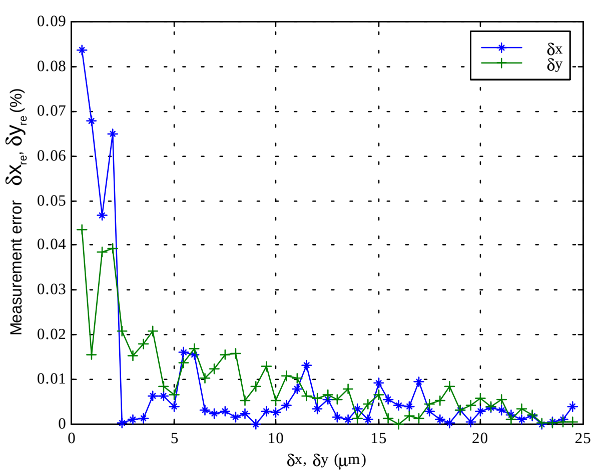

Figure 7: Theoretical measurement accuracy of δx and δy
(d=50mm, α=1arcsec, ϕ=5arcsec, θ=10arcsec)

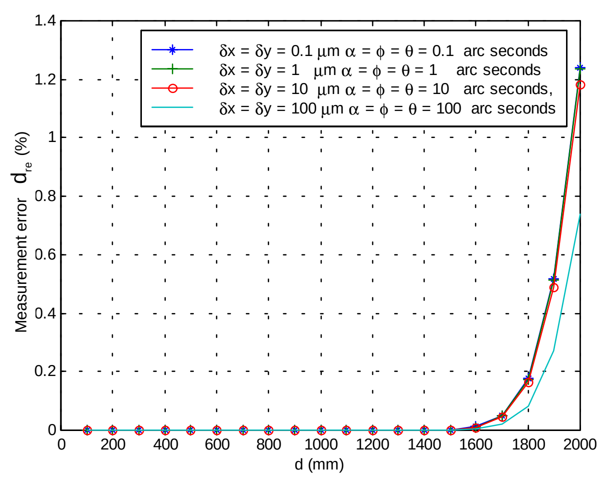

Figure 8: Theoretical measurement accuracy of d