A NEW SURFACE ENCODER FOR MULTI-AXIS POSITION DETECTION

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1. Introduction

Improvement of speed and precision of multi-axis stages for precision machine tools and photolithography steppers is strongly required. To fulfill this requirement, it is necessary to measure multi-degree-of-freedom (MDOF) translational and rotational motions of the stage precisely, and feedback the measurement results to the control system[1].

Conventional MDOF measurement systems consisting of multiple sensors (laser interferometers, linear/rotary encoders, autocollimators, etc.), however, are complicated and expensive. It is also difficult to integrate such sensors in the stage system.

The authors have proposed a new method for MDOF measurement named the surface encoder[2]. The surface encoder is composed of a two-dimensional (2D) optical angle sensor and a 2D angle grid. The angle sensor has the ability of detecting the 2D local slopes at a point on the angle grid surface, on which 2D sinusoidal angular patterns are generated. Since the angle profiles of the grid surface along X- and Y-axes are independent from each other, the X- and Y-outputs of the angle sensor provide the X- and Y-directional positions/displacements of the angle sensor relative to the angle grid, respectively. In other words, the 2D translational X- and Y- motion can be detected by a single surface encoder.

The authors have also proposed a modified surface encoder employing a scanning laser beam-type angle sensor. At each measurement position, the sensor scans a laser beam on the angle grid surface at a constant speed. In such a surface encoder, the lines along X- or Y-directions on the grid surface, at which the X- or Y-angles are zero, are used as the encoder graduations. The interpolations between the zero-lines (graduations) are carried out by counting the traveling time of the laser spot. Since only the zero-lines on the grid surface are used for position detection, the influence of the form error of the angle grid on the accuracy of position detection can be greatly reduced[3].

In this paper, the scanning laser beam-type surface encoder is improved to measure the three-directional rotational motions (pitch, roll, and yaw) in addition to the X- and Y-directional translational motions. Principle of the 5-degree-of-freedom (5-DOF) surface encoder and some experimental results are presented.

2. Principle of the 5-DOF surface encoder

Fig.1 shows a schematic principle of the 5-DOF surface encoder. The surface encoder system consists of a 2-D angle sensor and a 2-D angle grid. The profile height of the 2-D angle grid at the measurement position P(x,y) is represented as follows:

$$h(x,y)=A_X\sin\left(\frac{2\pi}{D_X}x\right)+A_Y\sin\left(\frac{2\pi}{D_Y}y\right) \quad (1)$$

Here, D_X, D_Y are the wavelengths of the angle grid in the X- and Y-directions, respectively. A_X, A_Y are the amplitudes. Assume that the position of the angle sensor is kept stationary and the angle grid moves in the

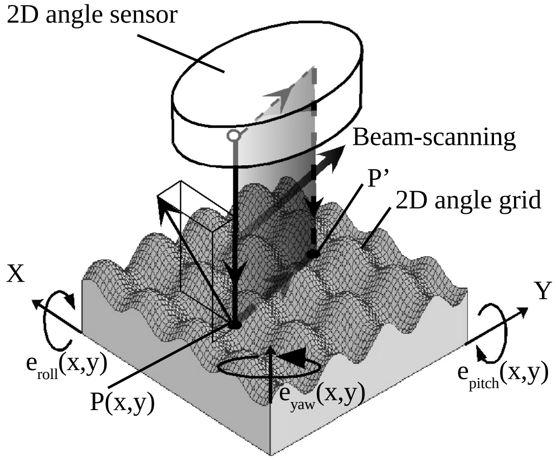

Fig.1 The surface encoder

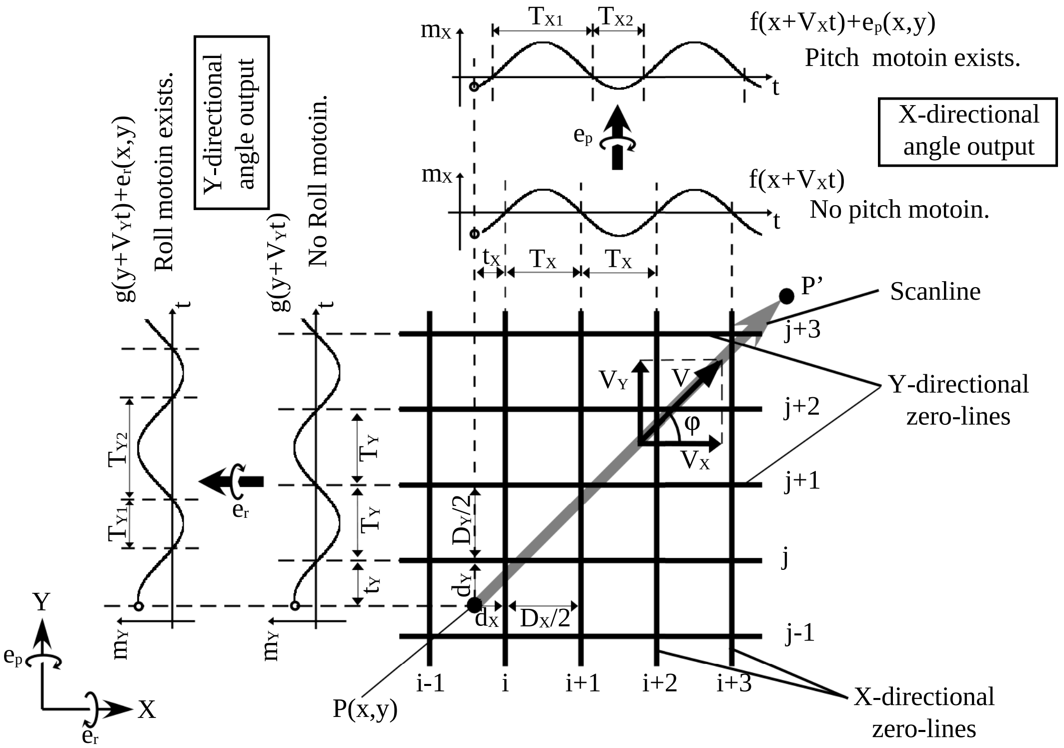

Fig.2 Measurement principle of 5DOF translational and rotational motions

XY plane, the X- and Y-directional outputs of the angle sensor ($m_X(x,y)$, $m_Y(x,y)$) at the measurement point P, which correspond to the X- and Y-directional local slopes of the grid surface, can be expressed as follows:

$$m_X(x,y)=\frac{\partial h}{\partial x}=\frac{2\pi A_X}{D_X}\cos\left(\frac{2\pi}{D_X}x\right)=f(x),\quad m_Y(x,y)=\frac{\partial h}{\partial y}=\frac{2\pi A_Y}{D_Y}\cos\left(\frac{2\pi}{D_Y}y\right)=g(y) \qquad (2)$$

Although it is possible to directly evaluate the position of the measurement point P from Eq.(2), the evaluation accuracy is influenced by the form error of the grid surface. To resolve this problem, we scan the laser beam of the angle sensor over the grid surface along a straight line at a constant speed V. Assume that the scan starts at the measurement point P and ends at a point of P'. The scanning length PP' is kept the same at all the measurement points. The angle between the scanline PP' and X-axis is let to be φ as shown in **Fig.2**. Also assume that the beam scanning speed is much faster than the movement speed of the angle grid so that the angle grid can be considered to be stationary during the scanning. In **Fig.2**, the X-directional and Y-directional zero-lines of the angle grid are numbered by i and j, respectively. The outputs of the angle sensor at time t after the scanning can be written as

$$m_X(x+V_Xt,y+V_Yt)=\frac{2\pi A_X}{D_X}\sin\left(2\pi\cdot\frac{x+V_Xt}{D_X}\right),\quad m_Y(x+V_Xt,y+V_Yt)=\frac{2\pi A_Y}{D_Y}\sin\left(2\pi\cdot\frac{y+V_Yt}{D_Y}\right) \qquad (3)$$

where V_X and V_Y are the X- and Y- directional components of V. Assume that the time distances for the spot to travel from the measurement P to lines i and j is t_X and t_Y, respectively. The position of the measurement point P relative to lines i and j can thus be evaluated from

$$dx=\frac{D_X}{T_X}\cdot t_X(x,y),\quad dy=\frac{D_Y}{T_Y}\cdot t_Y(x,y) \qquad (4)$$

where, T_X and T_Y are the time for the beam to travel between two adjacent zero-lines in the X- and Y- directions, respectively.

If rotational motions pitch e_p and roll e_r exist, the outputs of the angle grid become

$$m_X(x+V_Xt,y+V_Yt)=f(x+V_Xt)+e_p(x,y)=\frac{2\pi A_X}{D_X}\sin\left(2\pi\cdot\frac{x+V_Xt}{D_X}\right)+e_p(x,y) \tag{5}$$

$$m_Y(x+V_Xt,y+V_Yt)=g(y+V_Yt)+e_r(x,y)=\frac{2\pi A_Y}{D_Y}\sin\left(2\pi\cdot\frac{x+V_Yt}{D_Y}\right)+e_r(x,y) \tag{6}$$

As can be seen in **Fig.2**, when a pitch motion exists, the time distance between adjacent zero-points in the X-directional angle output will be different from T_X, and can be expressed as

$$T_{X1}(x,y)=\frac{D_X}{V_X}\left\{\frac{1}{2}\mp\frac{1}{\pi}\arcsin\left(-\frac{D_Xe_p}{2\pi A_X}\right)\right\},\ T_{X2}(x,y)=\frac{D_X}{V_X}\left\{\frac{1}{2}\pm\frac{1}{\pi}\arcsin\left(-\frac{D_Xe_p}{2\pi A_X}\right)\right\} \tag{7}$$

If e_p is small, combining T_{X1} and T_{X2} gives:

$$e_p(x,y)\approx\pm\frac{\pi^2A_X}{D_X}\cdot\frac{T_{X2}(x,y)-T_{X1}(x,y)}{T_{X2}(x,y)+T_{X1}(x,y)}=k\cdot\frac{T_{X2}(x,y)-T_{X1}(x,y)}{T_{X2}(x,y)+T_{X1}(x,y)}\quad\text{(k: const)} \tag{8}$$

Eq.(8) means that e_p can be detected by counting T_{X1} and T_{X2}. The same calculations can be applied to e_r (roll) through counting T_{Y1} and T_{Y2}.

On the other hand, when a yaw error e_{yaw} around Z-axis exists, the angle between the scanline and X-axis will change to $\varphi+e_{yaw}$, and e_{yaw} can be obtained from

$$e_{yaw}=\arcsin\frac{D_Y}{(T_{Y1}(x,y)+T_{Y2}(x,y))}-\varphi=\arccos\frac{D_X}{(T_{X1}(x,y)+T_{X2}(x,y))}-\varphi$$

$$=\arctan\frac{T_{X1}(x,y)+T_{X2}(x,y)}{T_{Y1}(x,y)+T_{Y2}(x,y)}\cdot\frac{D_Y}{D_X}-\varphi \tag{9}$$

As can be seen from above, 5-DOF motions (x, y, pitch, roll and yaw) at each measurement point P(x,y) can be measured by a single surface encoder.

3. Experiments

The experimental surface encoder designed and manufactured in this study is shown in **Fig.3**. The angle sensor is based on the principle of auto-collimation. By using an acousto-optical deflector (AOD), the beam from the light sources(LD) can be scanned at a constant and high speed on the angle grid. The wavelength and the amplitude of the angle grid were the same in X- and Y-axes, which were 300μm, 0.3μm, respectively.

Fig.4 shows the results of pitch detection. The scanning frequency of the beam, which was generated by the AOD, was 50Hz. The sampling number was 400 points at one-scanning. Pitch motions were applied to the angle grid. The horizontal axis

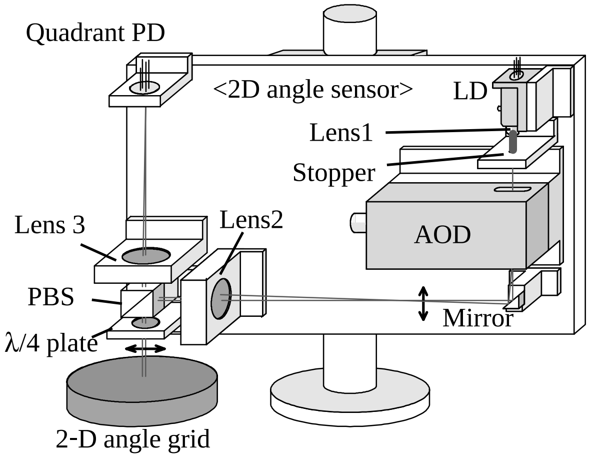

Fig. 3 The scanning optical 2-D angle sensor

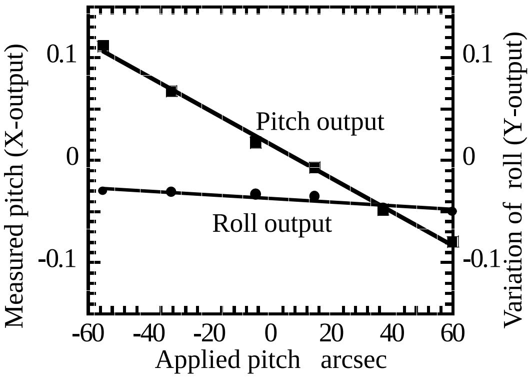

Fig. 4 Results of pitch measurement

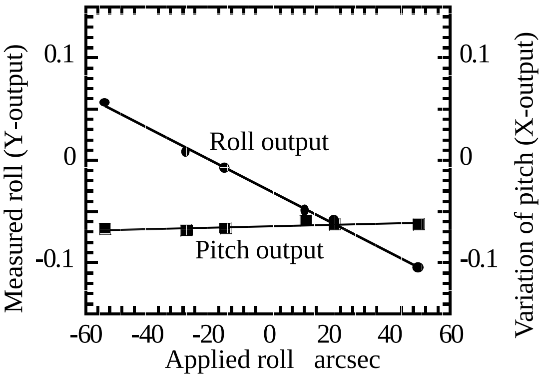

Fig. 5 Results of roll measurement

represents the result measured by an autocollimator placed outside the surface encoder. The vertical axis shows the pitch motion detected by the surface encoder. The corresponding roll output of the surface encoder, which should be constant if a pure pitch motion is applied to the angle grid, is also plotted in the figure. Three repeated measurements were made at the same location of the angle grid. Repeatability was about 5".

Fig.5 shows the results when roll motions were applied. The results shown in **fig.4 and 5** indicate that pitch and roll were detected separately.

Fig.6 shows the results of yaw detection. The horizontal axis represents the yaw motion of the angle grid applied by a rotary stage, and the vertical axis shows the corresponding change in the scanning time ($T_{Y1}+T_{Y2}$). The result indicates the possibility of yaw detection by the surface encoder.

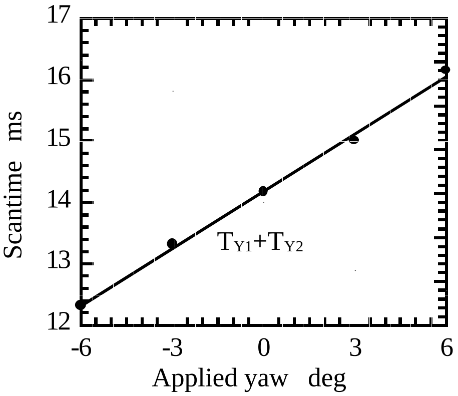

Fig. 6 Results of yaw measurement

5. Conclusions

1) A 5-degree-of-freedom surface encoder consisting of a scanning laser beam-type 2D angle sensor and a 2D angle grid has been developed. In addition to the X- and Y-translational motions, the rotational motions (pitch, roll and yaw) can also be simultaneously detected by such a surface encoder.
2) An experimental surface encoder has been constructed. The possibility of detecting 5-DOF motions has been verified.

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