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A simple optical system for miniature spindle runout monitoring

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ABSTRACT

We proposed a novel optical technique to monitor miniature spindle runout in a simple manner. Miniature spindles are commonly used in many machining applications, for example: micro-milling and micro-grinding. However, the capacitive sensors (CS) or eddy current sensors typically used for spindle runout measurements cannot be used for miniature spindle systems. This is due to the nonlinearity of the charge between a curved surface and a flat plate (sensing area) and a curved surface (measuring target area) and the effective sensing area being larger than the measuring target area. The proposed sensor utilizes curved-edge diffraction (CED), which uses the effect of the cylindrical surface curvature on the diffraction phenomenon in the transition regions adjacent to shadow, transmission, and reflection boundaries. The laser beam is incident to the spindle shaft edges along the Y and Z axes, four photodetectors then collect the total fields produced by the interference created by the waves due to CED around the spindle shaft edges. Two CS were used as a baseline comparison with the proposed sensor's performance. A spindle with a shaft diameter of ϕ 5.0 mm (same as CS effective sensing area) was selected to compare the results of the curved-edge sensor (CES) with the results of the CS. The spindle runout was measured and the following results were found: CES-CS calibration nonlinearity (Z 0.35% and Y 0.40%) and resolution (Z 20.1 nm and Y 26.0 nm for CS and Z 20.3 nm and Y 15.9 nm for CES). The fundamental sensing limit of CES was estimated to be: Z 0.52 nm/$\sqrt{\mathrm{Hz}}$ and Y 0.41 nm/$\sqrt{\mathrm{Hz}}$ for a working range of approximately 100 μm, respectively.

1. Introduction

Spindle runout is a rotation inaccuracy which occurs when the cutting tool is no longer aligned with the rotational axis, and can be classified as axial runout and radial runout. The former occurs when the cutting tool is rotating at an angle to the axis [1–6], and the latter occurs when the cutting tool is rotating off center to the rotational axis. Spindle runout in computer numerical control (CNC) machine tools can decrease tool life and leads to the machining of defective parts, for example, in drilling applications, spindle runout can result in a bore diameter that is actually larger than the drill's nominal diameter [6–8]. A spindle can be measured either dynamically or statically by various contact or non-contact sensing systems. The static measurement is significantly cheaper and easier, yet somewhat less accurate than dynamic measurement because it is unable to account for heat, vibration, and centrifugal forces acting on the spindle system.

Capacitive sensors (CS) or eddy current sensors (ECS) are particularly well suited for measuring the performance of high speed precision spindles and other rotating shafts [6,8]. Since CS and ECS provide high measurement bandwidth and fast response, they are capable of gathering data even as the spindle or shaft sweeps through its entire speed range. However, it is standard practice for commercial CS and ECS to be factory calibrated with flat target surfaces and not curved target surfaces. As a general rule, the measuring target should also be 30–50% larger than the CS in use (manufactures' recommendation) [9–11]. If the measuring target is not large enough to support the electric field it will tend to wrap around the target edge and enter normal to the target side. This electric field distortion will create measurement errors by degrading the sensor linearity and changing its sensitivity and measuring range. Due to the different behavior of the electric field between two interfacing surfaces when measuring a curved target surface, the error in sensitivity may be as much as 150%. Furthermore, the nonlinearity may prevent accurate measurements with small diameter targets [12,13]. Measuring targets that are too small to support the electric field can also provide false displacement signals from lateral motions. Additionally, if a tilted or curved target is being measured the electric field will be distorted and the accuracy will be compromised because the CS or ECS will measure the average distance to the target under the area of the sensor and the

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measuring target surface will prevent the CS and CES from full target contact. Thus, there is no proper measuring devices for the high precision displacement measurement of curved, relatively small (smaller than the effective sensing area of CS) target surfaces.

Since these effects lead to critical measurement error in precision metrology for manufacturing applications requiring the highest accuracy, to fill the technology gap, it is urgent that a new rigorous sensing methodology for precision dimensional metrology of curved target surfaces be investigated. Lee recently introduced a displacement sensing technique utilizing curved edge diffraction (CED) for the first time [13]. However, only the experimental approach was considered because the theoretical approach requires complex mathematical and computational work to model. In this article, a novel optical sensing method that can overcome the current issues with CS and ECS for the miniature spindle metrology has been discussed using theoretical and experimental approaches.

2. Measurement principle

The knife-edge sensing techniques for dimensional measurement applications have been recently introduced [14–17]. In particular, Lee proposed a new linear displacement sensing method utilizing knife-edge diffraction (KED) [16,17]. An electromagnetic (EM) wave incident on the knife-edge gives rise to two waves, a transmitted wave and an edge-diffracted wave. The total electric field represented by a sum of the two waves creates an interferogram at the detector plane. A high sensor sensitivity can be observed near the center of a Gaussian laser beam. The convenient and efficient computational method for KED problems in the transition region adjacent to the shadow boundary was introduced. However, unlike KED, an analytical approach to CED is difficult because CED can be understood from the asymptotic solution of several canonical problems, which involve the illumination of the edge by diffraction wavefronts [18]. In this work, CED solutions were formulated in a compact, accurate form using the diffraction characteristics valid in the transition region adjacent to the shadow and reflection boundaries. As shown in Fig. 1, an electromagnetic EM wave incident on the curved edge, with radius of curvature: R, gives rise to an incident wave, diffracted wave, and reflected wave, which propagates along a surface ray. RB, SB and DSB represent reflection boundary, shadow boundary, and deep shadow boundary, respectively. Such surface ray fields may also be excited at the transition region and can be separated into three different regions similar to KED. The total electric field may be represented by a sum of three waves, and can be observed at the detector plane. This sum predicts the scattering of the optical large platform that involves the use of spatial domain Fresnel integrals for the diffracted fields. Assuming that the light source with a Gaussian intensity profile is not diverging, the detector size is relatively small compared to the distance L_2 between the curved edge and the detector, and the detector is placed along the light propagation axis, only the transmitted wave and edge-diffracted wave can be considered. Two waves are superimposed to generate an interference fringe at the detector plane, this contributes to an increase in the peak power of the 1st fringe. The steep slope of this signal plays a role in increasing the sensor sensitivity up to approximately 40% due to the edge diffraction principle [16,19,20].

The incident field $\vec{E}_s$ with a Gaussian aperture distribution can be defined as [21,22]

$$\vec{E}_s(x_s, y_s, z_s) = E_0 e^{-jk_0 z_s} e^{-\frac{x_s^2+y_s^2}{\alpha^2}} \tag{1}$$

where E_0 is the amplitude of the incident field, k_0 is the wavenumber in air, and α is the beam width. The incident field $\vec{E}_s$ creates constructive and destructive interferences with the diffracted field created by a phase change at the knife-edge. The superimposed wave can be obtained by applying a Fourier transform (FT), and the total field $\vec{E}_d$ (sum of incident and diffracted fields) at the detector, can be obtained by taking the inverse FT of the superimposed wave [16,19,20]. The total field measured along the z axis can be expressed as

$$\vec{E}_d(x_d, y_d, z_d) = \frac{1}{(2\pi)^2} \iint_{k-space} e^{-j\vec{k}\cdot\vec{r}_{o\to d}} \left[\iint_{aperture} \vec{E}_s e^{j\vec{k}\cdot\vec{r}_{s\to o}} dxdy \right] dk_x dk_y \tag{2}$$

where $\vec{r}_{i\to j}$ is a position vector from i to j in the coordinate system.

Finally, the power of the combined fields at a detector can be calculated as

$$P_j(y_o) = \iint_{m\times m} \vec{E}_d(x_d, y_d, z_i = L_2) \cdot \langle \vec{E}_d^*(x_d, y_d, z_i = L_2) \rangle^* dxdy. \tag{3}$$

where $\langle\ \rangle^*$ denotes a complex conjugate of $\vec{E}_d(x_d, y_d, z_i = L_2)$, and the total power P_j induced by CED at the detector will be calculated by multiplying the total field and the conjugated total field at each detector plane and integrating over the detector size ($m \times m$). The edge diffraction patterns can be obtained from Eq. (3).

As shown in Fig. 2, the edge diffraction fringe is clearly observed under the conditions: $L_2 = 100$ mm, $\lambda = 633$ nm, $\alpha = 0.5$ mm, $m = 0$ mm (point source), while the fringe is not clearly seen in the case of $m = 0.5$ mm. This result indicates that the detector size has a significant influence on the CED fringe pattern, especially the first peak. In addition to the detector size effect, the surface roughness of the spindle may also have an effect on the CED fringe pattern, and some portion of the scattering field exists because of the surface roughness because the diffracted field becomes incoherent and the interference fringe becomes weak when the light is incident on the rough surface. In this work, the surface roughness effect has not been considered, and dimensional sensing characteristics from the spindle shaft surface has been the focus.

3. Experiments

In the experiment, as illustrated in Fig. 3, the laser beam (λ 633 nm, power 2.3 mW, α 0.5 mm) is split into four by using beam

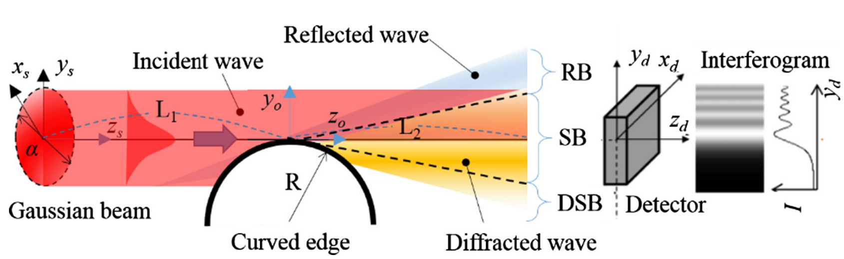

Fig. 1. Measurement principle of CES: x_i and y_i is an i coordinate (source, spindle, or detector denoted as s, o, and d, respectively) system at $z = z_i$, respectively.