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Investigation of optical knife edge sensor for low-cost, large-range and dual-axis nanopositioning stages

ChaBum Lee [a,*], Seongkyul Jeon [a], Christopher K. Stepanick [a], Abolfazl Zolfaghari [a], Joshua A. Tarbutton [b]

[a] *Department of Mechanical Engineering, Tennessee Technological University, 1 William L Jones Dr., Cookeville, TN 38505, USA*
[b] *Department of Mechanical Engineering and Engineering Science, University of North Carolina, 9201 University City Blvd, Charlotte, NC 28223, USA*

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ABSTRACT

We analyzed the parameter effects of an optical knife-edge sensor (OKES) and the measurement uncertainty to achieve high linearity, long range, and high accuracy for nanopositioning stage applications. The OKES utilizes interference fringes produced from diffraction across the knife-edge. The total field at the detector was calculated from superposition of the incident field and the diffracted field at the knife-edge, and the edge diffraction effects on the sensor design parameters (distance between the knife-edge and detector, wavelength and beam diameter) were investigated by using a design of experiment (DOE), 3-Level L_9 matrix from the Taguchi Method. Multi-factor experiments were designed to determine the relationship between factors affecting the interferogram and the sensor linearity. It was found that a shorter knife edge-detector distance, shorter wavelength, and larger beam diameter show high signal-to-noise ratio for sensing linearity. The OKES was modeled by using the electromagnetic wave propagation principle, and it was experimentally verified by controlling the positioning of an XY nanopositioning stage by the OKES. The sensor noise level showed X 20.1 nm and Y 19.4 nm, and the fundamental sensing limits of the OKES were estimated to be X 0.19 nm/$\sqrt{\mathrm{Hz}}$ and Y 0.23 nm/$\sqrt{\mathrm{Hz}}$ for a ±1.0 mm working range. These results indicate that the OKES can be a good alternative to other precision metrology tools because of its large working range, positioning accuracy, resolution, linearity, and bandwidth, as well as its compact size and low cost.

1. Introduction

Nanopositioning systems are mechanical motion systems capable of nanometric dimensional precision for accuracy and resolution. Nanopositioning systems are the key to major breakthroughs in a variety of research areas and industrial applications including scanning probe microscopy [1–3], nanometrology [4–7], lithography [8–10], and semiconductor inspection [11]. Achieving large displacement range (>1 mm) along with nanometer level displacement accuracy (<50 nm), simultaneously, has been a key challenge in nanopositioning systems due to the physical limitations associated with integrating the driving mechanisms, actuators, and sensors. Currently, many commercially-available nanopositioning stages are restricted to a range of approximately a few hundred micrometers per axis. There is, however, a growing market need for multi-axis nanopositioning systems that can provide a millimeter range while maintaining nanometer level dimensional accuracy with a compact integration and low cost.

Most nanopositioning stages rely on flexure linkages to provide linear or rotational motions with no friction or backlash. Their monolithic configuration entirely eliminates friction and backlash, while also providing some additional advantages: nanometric precision and a maintenance free, potentially infinite, lifetime [12–14]. Along with its flexure design, a selection of proper sensors is key to fast and robust positioning control and high resolution measurement.

Many studies on flexure design have been introduced in the past decade [15], but compact and low cost sensors that can be simply integrated with nanopositioning systems have been rarely found. As illustrated in Fig. 1, non-contact sensors such as capacitive-type sensors (CS), laser interferometers, and laser encoders have been typically used due to their ability to perform dynamic motion characterization with a fast, high resolution measurement [16,17]. The CS is the most common because it can be integrated with the stage easily due to its compact size. However, the CS is limited to a working range of tens to hundreds of micrometers. Also, these systems include conductive targets and the attractive force between the target and the sensor probe should be considered for precision applications [18]. While miniature

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* Corresponding author.
E-mail address: clee@tntech.edu (C. Lee).

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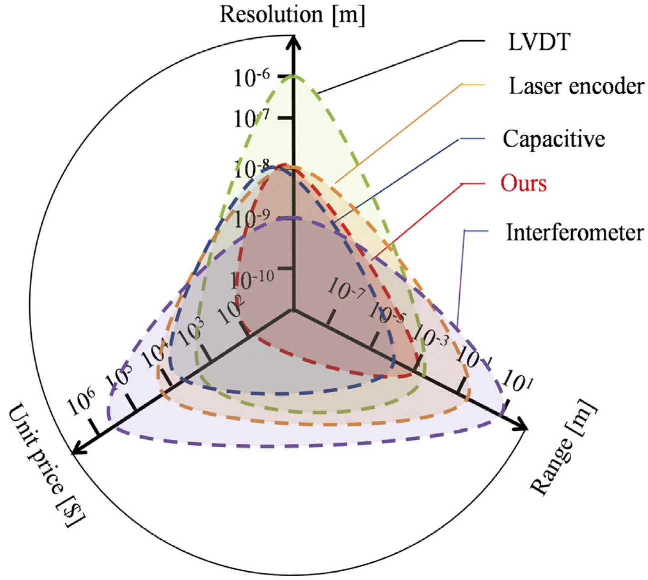

Fig. 1. Comparison of various displacement sensors.

versions using fiber-optic cables have become available recently, their integration within compact nanopositioning systems remains a challenge [19]. Strain gauges and piezoelectric sensors have also been used to measure displacement [20,21]. However, the noise level of strain gauges is too high to detect the displacement with sufficient bandwidth and nanometer resolution, and the piezoelectric sensors do not allow the measurement of low frequency or static displacement.

In general, knife-edges are used for characterizing optical spots as spatial filters and have been implemented in optical beam deflection based on in-plane displacement sensing [22,23]. Optical displacement sensors by means of knife-edges have been recently introduced. In particular, Braunsmann proposed an optical knife edge technique to detect and correct the nonlinear displacement in high speed atomic force microscopy [24]. Karabacak used a knife edge technique to measure sensitive in-plane displacement in nanomechanical beams [25]. Lockerbie proposed a displacement magnification method by using a knife-edge [26]. Strictly speaking, the research above only used knife-edges to partially block the transverse light, and the edge diffraction phenomenon has not been considered. Lee characterized the effect of the parameters of knife-edge diffraction sensing sensitivity based on an edge diffraction theory and showed that edge diffraction at the knife-edge can increase measurement sensitivity [27]. However, their measuring ranges are limited to a few tens of micrometers even though they achieved nanometer resolution because the detector was assumed to be a point. Also, Lee proposed a single axis flexure mechanism with a knife-edge based displacement sensor [16,17,28]. The lensed photodetectors were used to increase the measuring range, but it is limited to 500 µm and the resolution was 50 nm because of the lens effect.

In the previous section we outline the physical challenges associated with the displacement sensor to fulfill the requirements of nanopositioning systems: compact, multi-axis, high resolution, millimeter working range, easy system integration, and low cost. Our sensor utilizes optical knife edge (OKE) diffraction and provides non-contact displacement sensing. In the following sections we establish design principles for an optical knife edge sensor (OKES) which provide a millimeter working range and nanometer level accuracy for multi-axis nanopositioning. Furthermore, a mathematically derived theoretical model for an OKES is derived and experimentally verified by using an XY nanopositioning system. Additionally, in this article, the fundamental limits of the OKES are discussed in terms of resolution, linearity, bandwidth, and control effectiveness by using an XY nanopositioning system.

2. Theoretical model

2.1. Knife-edge diffraction

The measurement method of the OKES is illustrated in Fig. 2. The subscript i and j indicate a coordinate system and a paraxial beam propagating axis separated with a knife edge-detector distance L, k is the wavenumber, and A is the distance between the beam splitter (BS)/Prism and the optical knife-edge (OKE), and B is the distance between the OKE and detector. A laser diode (LD) light is separated by a 50:50 BS. The reflected beam at the BS is incident on the upper side of the OKE mounted on the stage and the transmitted beam at the BS reflects off the prism and is incident to the lower side of the OKE. Each incident beam is partially transmitted and blocked by an OKE position. In electromagnetic wave propagation, however, the OKE acts as a secondary light source, and creates a new wavefront that propagates into the geometric shadow area of the OKE. This is referred to as edge diffraction. Thus the partially transmitted beam and the diffracted beam created from the OKE are superimposed to generate interference fringes or so-called interferograms. The diffracted beam contributes to an increase in the peak power of the 1st fringe by more than 40% of the transmitted beam power [29,30]. The proposed OKES makes use of the optically amplified light signal. This amplification lends itself to producing a high sensor sensitivity. In addition, two signal outputs are differentially amplified and divided by the sum of the two signals. Consequently, the displacement along the traveling direction can be detected simultaneously by using two detectors (D_1, D_2).

Assuming that a Gaussian beam with a beam diameter α is incident on the OKE, the total field in front of the OKE is simply the incident field, and the beam propagates along the z axis, the incident field $\vec{E}_{0,j}$ can be defined as:

$$\vec{E}_{0,j}(x_{0,j}, y_{0,j}, z_j) = E_j e^{-\frac{x_{0,j}^2 + y_{0,j}^2}{(\alpha/2)^2}}, \tag{1}$$

where E_j is the constant electric field of LD and $\vec{E}_{i,j}$ is the field incident on the i coordinate system along j detector. The last term of Eq. (1) is for the aperture of the field. The incident field $\vec{E}_{0,j}$ becomes separated into two fields at the knife edge: the transmitted field, and the diffracted field. The superposition of the two fields creates constructive and destructive interference patterns at the detector. The superimposed wave can be derived by using a Fourier transform (FT), and the total field $\vec{E}_{d,j}$ (sum of transmitted and diffracted field) at j detector can be obtained by applying an inverse FT of the superimposed wave. The total field to be measured along the z axis can be defined from the inverse FT relation of the incident field as:

$$\vec{E}_{d,j}(x_d, y_d, z_i) = \iint_{k-space} \frac{1}{(2\pi)^2} \iint_{aperture} \vec{E}_{0,j} \cdot e^{ik \cdot r_{\{s\to 0\}}} e^{-ik \cdot r_{\{0 \to d\}}} dydxdkydkx, \tag{2}$$

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

Optical metrology systems can be extremely precise but are fundamentally limited by the surface quality of the optical components. As shown in Fig. 3, a model of a rough knife edge surface is presented and the phase difference between the transmitted and diffracted fields is related to the roughness under the assumption that the variation in heights of the knife edge exhibits a Gaussian distribution. Accordingly, the roughness on the knife edge bound-