Optics Communications 366 (2016) 168–173

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Measurement of four-degree-of-freedom error motions based on non-diffracting beam

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ARTICLE INFO

Article history:
Received 19 September 2015
Received in revised form
14 December 2015
Accepted 20 December 2015
Available online 29 December 2015

Keywords:
Linear stage
Motions Error
Multi-degree-of-freedom
Non-diffracting beam

ABSTRACT

A measuring method for the determination of error motions of linear stages based on non-diffracting beams (NDB) is presented. A right-angle prism and a beam splitter are adopted as the measuring head, which is fixed on the moving stage in order to sense the straightness and angular errors. Two CCDs are used to capture the NDB patterns that are carrying the errors. Four different types error~~s~~, the vertical straightness error and three rotational errors (the pitch, roll and yaw errors), can be separated and distinguished through theoretical analysis of the shift in the centre positions in the two cameras. Simulation results show that the proposed method using NDB can measure four-degrees-of-freedom errors for the linear stage.

1. Introduction

Linear stages are widely used in scanning-type measuring instruments, precision machines and manufacturing [1,2]. In some demanding applications, the control systems need to regulate stages' 6-DOF attitude in real time in order to ensure stages' position and pose accurate. However, error motions of a linear stage directly influence the performance of the precision positioning system in which the stage is used. Therefore, it is a critical task to measure the error motions.

The adoption of a multi-degree-of-freedom measuring method in order to correct the geometrical error of linear stages has been studied worldwide [3–4]. Many researchers present different methods to compute the error motions [5–8]. Kuang put forward a four-degree-of-freedom laser measurement system adopting a cube corner retro-reflector and a beam splitter as the measuring head [5]. Gao et al. set up two 6-DOF measurement systems for precision linear air-bearing stages, which consisted of interferometers, autocollimators and capacitance probes [7]. Gao proposed a 6-degree-of-freedom measurement method of X–Y stages based on nine interferometers' additional information [8].

Non-diffracting beams have many advantages in that the size and shape of the central spot remains constant if it is illuminated by parallel beams [9], and that two non-diffracting beams can generate moiré fringes which ~~is~~ are sensitive to changes in the distance between the two beams [10]. In this paper, we present a four-degree-of-freedom measurement method based on non-diffracting beams. A right-angle prism and a beam splitter were fixed on a moving stage in order to sense the straightness and angular errors. The method can measure the vertical straightness error and three rotational errors (the pitch, roll and yaw errors).

2. Theory

2.1. Measuring principle

There are six error motions for a linear stage, three translational errors (the positioning error, horizontal straightness error and vertical straightness error) and three rotational errors (the pitch error, roll error and yaw error). The schematic diagram for measuring the four-degree-of-freedom error motions with non-diffracting beams is shown in Fig. 1, which consists of a moving unit and some fixed optical elements. The moving unit, including a beam splitter (BS4) and a right-angle prism (RA), is taken as the error motion sensor that moves with the linear stage. The laser passes through a beam expander, and after reflection on mirror 1,

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http://dx.doi.org/10.1016/j.optcom.2015.12.051
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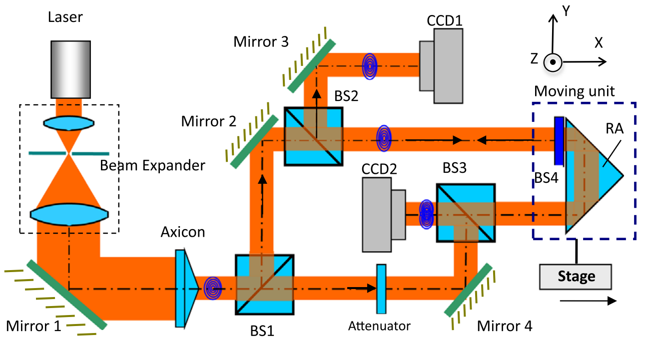

Fig. 1. Schematic diagram of multi-DOF error motions with non-diffracting beams.

illuminates an axicon lens. The collimated beam, after omitting the axicon lens, forms non-diffracting beams, which have the form of a zero-order Bessel function.

A beam splitter prism (BS1), placed after the axicon lens, splits the non-diffracting beam into two beams, the transmitted beam and the reflection beam. The reflected non-diffracting beam, after reflection by mirror 2, travels through BS2, is reflected by BS4, BS2 and mirror 3, and reaches CCD1. The image of the NDB captured by CCD1 is shown in Fig. 2(a). The other beam transmits from BS4, after traveled through RA, BS3, arrives CCD2. The transmitted non-diffracting beam exiting BS1, passes through an attenuator and is reflected by mirror 4, from where it meets the beam from the moving unit. These two non-diffracting beams generate non-diffracting moiré fringes, which are captured by CCD2, as shown in Fig. 2(b).

The moving unit is fixed on the linear stage and is sensitive the error motions of the stage. When the stage moves, the position of the central points of the non-diffracting beams (as received by CCD 1) and the forms of moiré fringes (obtained by CCD 2) will change in relation to different errors. By analyzing the position of these centre points, we can measure the four-DOF errors, which are straightness, yaw, pitch and roll. Obviously, one of central points in CCD2 will be unchanged whilst the other one will changes according to different motion errors of stage.

2.2. Error motions analysis

The setup system as shown in Fig. 1 can measure four-degree-of-freedom error motions: vertical straightness error, the pitch error, roll error and yaw error. The NDB arriving at CCD1 is sensitive to the pitch and yaw error whilst the moiré fringes received at CCD2 vary with any error within the four-degrees-of-freedom. According to the patterns captured by the different cameras, the error motions can be analyzed separately. These principles are presented individually in the following sections.

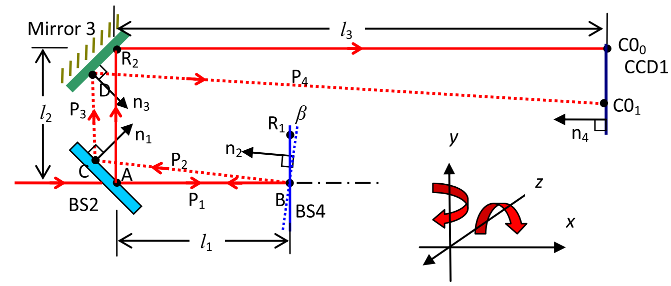

Fig. 3. Diagram of the measuring principle of yaw and pitch error with the NDB received by CCD 1.

a) **The error motion analysis due to the NDB received by CCD1**

The NDB received by CCD1 is the reflection beam coming from the BS4 (one component of the moving unit) and the centre position of the NDB will be changed when the moving unit has pitch error and yaw errors. The position of central point does not change when the stage only has a straightness error or a roll error. Fig. 3 shows the schematic diagram of the yaw error measurement principle. Some reference points and the positional relationships of the components are also shown in Fig. 3. When the BS4 is in the original position without any error motion, the beam passes through the points **A**, **B**, $\mathbf{R}_2$, $\mathbf{CO}_0$, whilst when the BS4 exhibits pitch error or yaw error, the optical path is follows the dashed path shown in Fig. 3.

In order to analyze the errors simply, a space vector principle is used. In Fig. 3, assuming **A**, **B**, **C**, **D** and **C**00 are critical vector points, and supposing the coordinates of **A** (which is the point on the BS2 illuminated by the incidence beam), are (0, 0, 0), then the coordinates of **B**, $\mathbf{R}_2$ and $\mathbf{CO}_0$ are (l_1, 0, 0), (0, l_2, 0), and (l_3, l_2, 0), respectively. Assuming **P**1, **P**2, **P**3 and **P**4 are direction vectors, **n**1, **n**2, **n**3 and **n**4 are normal vectors of each component. According to the space vector relationship of the reflected beam, the vector points and direction of each beam have the following relationship:

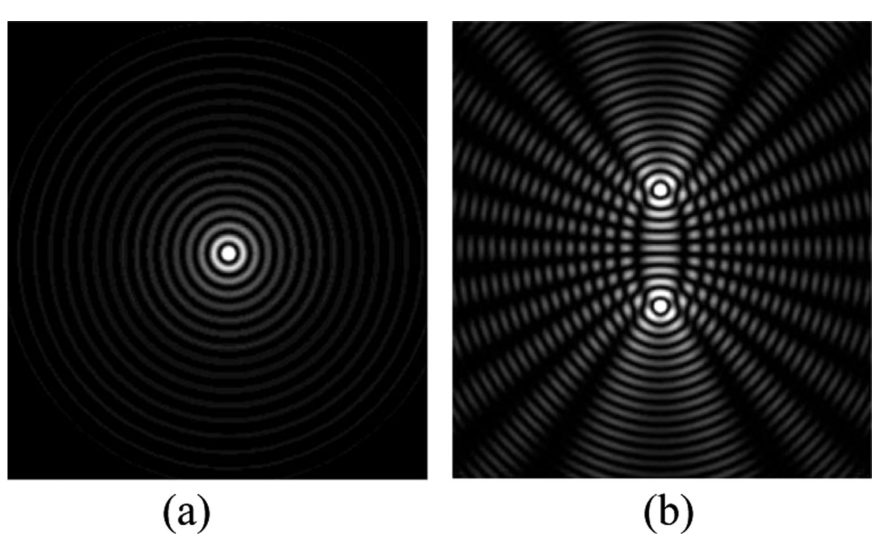

Fig. 2. The images received by the CCDs. (a) a single NDB, (b) non-diffracting moiré fringes formed by two NDBs.