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Control Engineering Practice 13 (2005) 559–566
CONTROL ENGINEERING PRACTICE
www.elsevier.com/locate/conengprac

Digital closed-loop nanopositioning using rectilinear flexure stage and laser interferometry

Hsien-Chi Yeh[a,b,*], Wei-Tou Ni[b], Sheau-shi Pan[c]

[a] *School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore*
[b] *Center for Gravitation and Cosmology, Department of Physics, National Tsing Hua University, 101 Kuang Fu Road, Section 2, Hsinchu, Taiwan 300, ROC*
[c] *Center for Measurement Standards, Industrial Technology Research Institute Building 16, 321 Kuang Fu Road, Section 2, Hsinchu, Taiwan 300, ROC*

Received 19 March 2003; accepted 26 April 2004

Available online 7 June 2004

Abstract

To enhance the accuracy of nanopositioning and the metrological capability of scanning probe microscopy, we construct a two-dimensional interferometric nanopositioning system consisting of rectilinear flexure stage, calibrated laser interferometer, and digital feedback control system. We implement a correlation matrix, determined by the piezoelectric constant and the crosstalk between two axes, into the closed-loop control algorithm to compensate the nonlinearity and the crosstalk of the PZT-driven stage. In the tests on nanopositioning, the 1-nm-step motion and the tracking along a 1-nm-radius circular target path are accomplished to verify the short-term repeatability and the subnanometer-level precision. Additionally, a scanning tunneling microscope equipped with the interferometric nanopositioning system is built up to demonstrate the metrological functions of scanning probe microscopy.

Keywords: Positioning system; Digital control; Feedback control; Crosstalk interference; Mechanism; Measuring elements

1. Introduction

The ultra-precision positioning and tracking techniques are essential to scanning probe microscopy (Fu, Young, & Vorburger, 1992; Jusko, Zhao, Wolff, & Wilkening, 1994; Xu, Smith, & Atherton, 1996; Meli, & Thalmann, 1998; Gonda et al., 1999a), nanometrology (Yoshida, 1992; Gonda, Kurosawa, & Tanimura, 1999b), advanced manufacturing processes and precision physical experiments (Nakayama, Tanaka, Shiota, & Kuroda, 1992; Ni et al., 1994, 1996, 1999). The state-of-art nanopositioning system typically consists of nano-drives, nano-guides, and nano-rulers. Furthermore, the closed-loop feedback control is necessary to reduce the nonlinearity, the hysteresis, and the measurement noises due to environmental fluctuations. To request for higher accuracy, the measuring element or used in the nanopositioning system must include the function of calibration and the traceability of measurement results. The heterodyne laser interferometer has the merits of subnanometer-level resolution, long dynamic range and traceability to the primary standard of length. Therefore it should be the suitable measuring tool especially for nanopositioning control with a long travel range.

In this paper, we present a two-dimensional interferometric nanopositioning system that consists of a two-dimensional flexure stage, a two-dimensional heterodyne interferometer, and a digital closed-loop feedback control system. A two-by-two matrix is implemented into the quasi-static closed-loop control algorithm to compensate the nonlinearity of the PZT-driven flexure stage. The subnanometer-level repeatability of positioning system is approved by testing on positioning and tracking along the target paths of straight line and circles. Meanwhile, a metrological scanning tunneling microscope is constructed by integrating the tunneling-current probe and the digital

*Corresponding author. School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore. Tel.: +65-679-069-06; fax: +65-679-118-59.

E-mail address: mhcyeh@ntu.edu.sg (H-C. Yeh).

0967-0661/$ - see front matter
doi:10.1016/j.conengprac.2004.04.019

interferometric nanopositioning system. This calibrated STM demonstrates the enhanced metrological functions of scanning probe microscopy that makes the measurement results of critical dimensions traceable to the primary standard of length.

2. Mechanism of flexure stage

The two-dimensional translation stage is composed of two up-down-stacked rectilinear flexure stages that have correspondingly the flexural mechanisms of double-compound leaf-spring and double leaf-spring. Both stages are manufactured from the same piece of hardened steel, and generate the rectilinear motion due to the symmetrical and parallel flexural mechanism (Smith & Chetwynd, 1994). The piezoactuator (PZT) is installed along the central line of stage to drive the movable platform through a steel-ball contact. Fig. 1 shows the mechanical layout of the flexural mechanism and the coupling between the PZT and the movable platform.

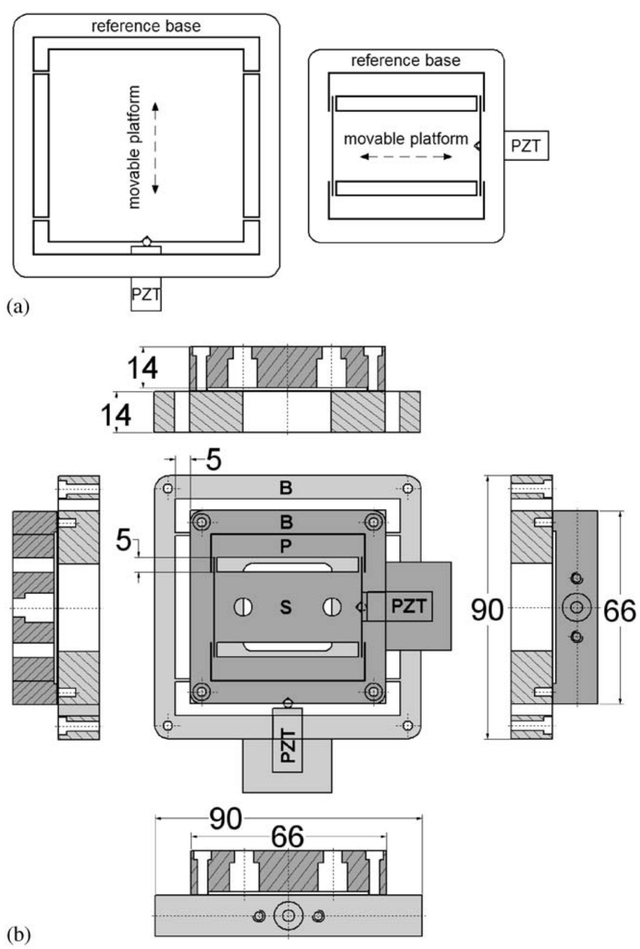

Fig. 1. Two-dimensional translation stage is composed of two stacked single-axis flexure stages. (a) The simplified drawing of two flexure stages. The bold lines shown in the figure are machined by using wire EDM (electric discharge machining), and the arrows represent the moving directions. (b) The detailed dimensions of the stacked flexure stage. The upper is the double compound leaf-spring flexure stage, and the bottom is the double leaf-spring flexure stage (B: Base, P: Primary stage, S: Secondary stage).

2.1. Stiffness of leaf spring

The leaf flexure of stage is a bracketed cantilever beam, not a simple cantilever. When the PZT drives the movable platform of stage, the flexural hinge is deformed with an anti-symmetrical deflected shape. Since the slopes of deflected beam at both ends are zero, a contraflexure point should exist at the center of the flexural hinge (Elmustafa & Lagally, 2001). As a result of the symmetric arrangement, these four identical leaf flexures share equally the driving force of the PZT, and generate the same deflections. According to the structural analysis, the total stiffness of the double leaf-spring stage is expressed as

$$k = \frac{4Ebd^3}{L^3}, \tag{1}$$

where E is Young's modulus, b is the width, d is the thickness and L is the length of leaf flexure. For a double leaf-spring flexure stage with the dimensions, $E = 2 \times 10^{-11}\,\mathrm{Nm}^{-2}$, $b = 14\,\mathrm{mm}$, $d = 1\,\mathrm{mm}$, $L = 5\,\mathrm{mm}$, the stiffness of stage is estimated to be $8.96 \times 10^7\,\mathrm{N/m}$.

The travel range of the flexure stage depends on the allowable deformation of the flexural hinge, the stiffness of the flexural hinge, and the maximum expansion of the PZT. Since the restoring force of the deflected flexural hinge would act back to the PZT as an external load that would reduce the expansion of the PZT. As a result, the travel range of the flexure stage would be shorter than the nominal value of the maximum expansion of the PZT. We use two PZTs (PhysikInstrumente, P830.10) with a full-range (0–100 V) expansion of 15 μm to drive the flexure stages, and find that the travel range of the double compound leaf-spring flexure stage is 12.4 μm, and the travel range of the double leaf-spring flexure stage is 5.5 μm. The different travel ranges of flexure stages are resulted from the different stiffness of the flexure stages.

2.2. Resonant frequency of flexure stage

The resonant frequency of flexure stage can be estimated simply by a Newtonian approach. First, we analyze the double compound leaf-spring stage equipped with a PZT. If the friction force and the mass of leaf spring are assumed to be negligible, the equations of motion describing the dynamic behavior of the