Precision Engineering 52 (2018) 308–322

Contents lists available at ScienceDirect

Precision Engineering

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

Mechatronic design, actuator optimization, and control of a long stroke linear nano-positioner

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ARTICLE INFO

Keywords:
Voice coil actuator
Topology optimization
Dynamic Error Budgeting
Air bearing
Nano-positioning
Optical encoder
Encoder quadrature detection errors
Eddy currents

ABSTRACT

In this paper, mechatronic design, actuator optimization and controls of a long-stroke (20 mm) linear nano-positioner are presented. The mechatronic design is described in terms of the stage's most prominent features regarding mechanical design, assembly, actuator configuration, and power supply. A novel air-bearing/bushing arrangement has been used in which the commonly employed double shaft arrangement is replaced with a single shaft supported by an air bearing from the bottom to constrain the roll motion. The assembly is greatly simplified by exploiting the self-aligning property of the air-bushings which are held in the housings by O-rings. Also, the footprint of the stage is reduced. Voice coil actuators (VCA) in moving magnet mode have been used in complementary double configuration for uniformity of force response. The performance objectives of previously optimized VCA's as standalone actuators are re-evaluated in this configuration. It is observed that while the performance objectives decrease a bit, the desirability of the design point is still retained. Controller design has been made for the current control and position control loops. Heydemann's method for the compensation of encoder quadrature detection errors is implemented. The positioning resolution of the stage as measured from the sensor output is experimentally determined to be $+/-5$ nm. Dynamic Error Budgeting (DEB) method has been used to analyze the contributing factors to the positioning error, and sensor broadband noise is determined to be the major contributor. The actual positioning accuracy of the stage is estimated by DEB to be 0.682 nm root-mean-square (RMS). The trajectory following accuracy is determined to be $+/-15$ nm. It is expected that trajectory following accuracy can substantially improve if more advanced compensation methods for encoder quadrature errors are implemented.

1. Introduction

Precision motion systems find a broad range of application in micro/nano machining tools, lithography scanners, testing and metrology machines, micro-assembly, biotechnology, optics manufacturing, magnetic data-storage, optical disk drives, and so on [1–3]. Various technologies for the actuation, bearing system, and position sensing of such systems have been employed depending on the desired number of motion axes, motion range, and positioning resolution.

The number of motion axes among ultraprecision motion stages range from single – axis/linear to 6 degrees of freedom (DOF). The number of motion axes has a profound effect on the choice of bearing technology. As expected, most 6 – DOF stages [4–7] employ magnetic levitation (maglev) to avoid bearing contact. One shortcoming of this method is the necessity to constantly power the coils which provide the levitation force. Alternatively, Shamoto et al. [8] have proposed a 6-DOF stage using a 'walking drive', in which nine pairs of piezoelectric actuators provide actuation in all 6 axes through a series of strokes. In the case of XYθ stages (i.e., planar stages with rotation capability), the stages can be supported from the bottom with air bearings [9–11] or flexures [12,13]. Both air bearings and flexures are virtually free from friction and provide theoretically infinite motion resolution. Air bearings typically have lower bearing stiffness and require tight tolerances in the manufacturing of the mating components. On the other hand, flexures require actuators to be powered during position holding. Also, they need to be proportionally larger for higher stroke lengths to limit their stiffness.

Among different actuator alternatives, voice coil actuators (VCA) based on Lorentz forces have been researched extensively [4,5,9,10,14–17], possibly due to their non-contact, continuous operation which is free from hysteresis, force/torque ripple, and backlash [18,19]. In stages supported by magnetic levitation [4,5], VCA's are used for both bearing forces and maneuvering. In some other cases, linear motors employing Halbach magnet arrays are used to generate actuation and levitation forces at the same time [6,7,20]. In [6], stator windings with different orientations are overlaid on top of each other in

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https://doi.org/10.1016/j.precisioneng.2018.01.007
Received 28 September 2017; Received in revised form 17 January 2018; Accepted 22 January 2018
Available online 13 February 2018
0141-6359/

a compact printed circuit board (PCB) structure, making the design more feasible for large motion ranges. The PCB stator was also employed in [7] for a 6 DOF rotary table. In [21] a rotary VCA is combined with a translational tubular VCA in a single shaft design supported by air bushings, to achieve rotary-linear motion. A close alternative to VCA is the usage of reluctance actuators [12] which provide higher force density, maximum forces, and power efficiency. The inherent nonlinearity in such systems can sometimes be remedied using a special design to linearize the response, as [22] proposed for a fast tool servo (FTS).

Numerous single axis ultraprecision stages have also been proposed [14,15,17,23–29]. Using VCA's with optical encoders [14,15,17], several millimeters of motion range with nanometer level resolution could be achieved. For smaller motion ranges less than 0.5 mm, capacitance sensors could be used [24,29]. Stacked designs combining multiple actuation and bearing technologies have also been proposed [25–27], where the fine positioning resolution is preserved over extended motion ranges (> 50 mm).

In this paper, mechatronic design, actuator optimization, and control of a long stroke (20 mm) linear nano-positioner is presented. The nano-positioner employs a novel air-bushing/bearing arrangement in which the moving body consists of plates attached to a single shaft engaging to air bushings. Instead of the commonly utilized double shaft arrangement, the roll resistance is provided by an air bearing placed underneath the moving body. This way, the self-aligning property of the air bushings which are held in the housings by O-rings is exploited to a high degree, the assembly is greatly simplified, and the footprint of the stage is reduced. The nano-positioner is actuated by voice coil actuators (VCA) in complementary double configuration for uniformity of force response along the stroke length. In our earlier research, performance of a single standalone VCA was optimized based on the acceleration per current density and the motor constant, which is a measure of force produced per power dissipated [30]. In this paper, performance optimality for the application of two VCA's arranged in a complementary double configuration is verified. The nano-positioner can achieve +/−5 nm positioning accuracy, and +/−15 nm trajectory following accuracy. The positioning accuracy is analyzed using the Dynamic Error Budgeting (DEB) method, and the contributions of various disturbances to the positioning error are determined.

This paper is organized as follows: The mechatronic design is detailed in Section 2 with emphasis on the most prominent design features. A brief summary of VCA design and the re-calculation of performance objectives for the complementary double configuration are presented in Section 3. System identification and controller design for the current and position control loops, including the analysis of eddy current effects, experimental verification of the positioning and trajectory following accuracies, as well as DEB analysis of the positioning resolution are presented in Section 4. The concluding remarks are provided in Section 5.

2. Mechatronic design

In this section, first a conceptual design of a low-cost desktop micro-milling machine is presented, which places the nano-positioner in context in terms of design goals. Following that, a list and explanations of the most prominent design features of the nano-positioner are presented.

2.1. Conceptual design for a low-cost desktop micro-milling machine

Front and back views for the conceptual design of a low-cost desktop micro-milling machine are presented in Fig. 1. The proposed design utilizes air bushings/bearings for high positioning resolution. Voice coil actuators working in moving magnet mode are preferred for non-contact and continuous actuation. With the design, workpiece dimensions of 20 mm × 20 mm × 20 mm are targeted. Servo accuracy is intended to be in the order of nanometers, and part accuracy to be a few microns. A pneumatic counter-balance is built-in to cancel out the effect of gravity; hence, running a constant current on the vertically oriented actuator is avoided. This way, excessive heating of actuator coils is prevented. The linear nano-positioner described in this paper corresponds to a prototype version of the X positioning axis of the micro-milling machine. Its design is further detailed in the following.

2.2. Mechatronic design of the nano-positioner

The exploded view and photograph of the long-stroke linear nano-positioner is presented in Fig. 2. The most prominent design features of the stage can be outlined as follows:

i An air-bearing/bushing arrangement has been used in which the commonly employed double shaft arrangement (like the ones used in the Y and Z motion axes of the micro-milling machine in Fig. 1) is replaced by a single shaft supported by an air bearing from the bottom to constrain the roll motion. This way, manufacturing and assembly are greatly simplified by exploiting the self-aligning property of the air-bushings, which are held in the housings by O-rings. The necessity of complex fabrication procedures and specialized fixtures is eliminated. Also, the footprint of the stage is roughly reduced by half, which is important for suitability in desktop applications and in multiple arrangements in a work center. After the guideways are self-aligned, under pneumatic pressure, an epoxy material can be injected into the cavity between the air bushings and the housings to achieve further stiffness in the radial direction [31,32].

ii VCA's are used in moving magnet (MM) mode. Although this increases the overall moving mass, it is considered a good trade-off from the moving coil configuration, by eliminating possible parasitic forces due to lead cables. Such forces degrade both the positioning accuracy under no-load conditions and the repeatability, by acting as an uncertain disturbance force. VCA's have been preferred over linear motors due to the small motion range required in this application, as well as their ripple-free, continuous force output. Also, in contrast to the linear motors which require a three-phase power source and a more complicated current controller design, VCA's have been powered using single-phase, linear amplifiers.

iii The complementary double VCA configuration has been used to provide near uniform force response per supply current over the whole stroke. Actuator force factor (K_f) is simulated using COMSOL® finite element analysis (FEA) as shown in Fig. 3. It is observed that the combined force response is mostly uniform, allowing better linearization of the overall positioning system, and higher bandwidth control to be achieved without compromising stability margins or requiring explicit gain scheduling.

iv The shaft, top and bottom plates are made of Aluminum 6061 for reduced mass, corrosion resistance, and the prevention of electromagnetic attraction. Support structures are also made of the same material. The shaft is precision ground to achieve the tight tolerances (g6) and the surface quality (Rq16) required by the air bushings [31,33].

v To minimize unwanted moment generation during actuation, the top and bottom plates are sized to align the axis of actuation with the center of mass, using CAD program calculations.

vi The discharge of compressed air from the air bushings and bearings helps to remove heat which is mainly produced by the actuator coils, by acting like a heat sink. Although the convective coefficient of heat transfer is relatively high in the air-bushing/shaft interface, due to the limited mass flow rate, the heat removal is only partially effective in isolating the payload from thermal disturbances.

vii VCA cores are mounted at the two ends of the shaft using the method detailed in Fig. 4 to prevent variations due to screw thread. The mating extension of the shaft and the hole on the VCA core are