Precision Engineering 40 (2015) 249–260

Contents lists available at ScienceDirect

Precision Engineering

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

A flexure-based electromagnetic nanopositioning actuator with predictable and re-configurable open-loop positioning resolution

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ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form 3 December 2014
Accepted 24 December 2014
Available online 7 January 2015

Keywords:
Flexure joints
Semi-analytic model
Lorentz-force actuation
Nanopositioning actuator
Thermal modeling
Lumped capacitance model
Flexure modeling

ABSTRACT

This paper presents a novel cylindrical-shaped Flexure-based Electromagnetic Linear Actuator (FELA) that exhibits predictable and re-configurable open-loop positioning resolution. By combining contactless Lorentz-force actuation and frictionless flexure-based supporting bearings, it produces high repeatable motion and sub-micron positioning resolution. In this paper, the design concept of this cylindrical-shaped FELA will be introduced. It focuses on the modeling of the flexure-based supporting bearings, the thermal modeling of the electromagnetic module, and the unique characteristics of FELA, i.e., predictable and re-configurable open-loop positioning resolution. A prototype was developed to evaluate the performance and demonstrate these unique characteristics of this new class of nanopositioning actuator.

1. Introduction

An actuator with nano-positioning capabilities has been the key technology in nano-/micro-scale manufacturing processes such as nano-imprint lithography, fibre optics alignment, MEMS assembly, nano-scale machining, etc. Among various types of nano-positioning actuators, the solid-state piezoelectric (PZT) actuators have been the most popular choice due to their large actuating force and high stiffness. However, PZT actuators have limited displacements that make them unsuitable to drive high-precision manipulators targeted for large traveling range [1]. Although some existing high-precision positioning actuators are able to eliminate such limitations, the displacement amplification techniques that are used within these actuators inherit other drawbacks. For example, PZT-driven actuators that use high-pitch screw actuating-shaft to achieve millimeters of displacement have poor repeatability due to backlash and Coulomb friction [2]. Others that use the magnetostrictive clamping technique [3], the inchworm clamping [4], and the impact-force method [5] to drive an internal shaft for displacement amplification purposes have low payload capacities. In addition, the slow response speed makes these actuators inefficient for high speed applications.

Electromagnetic driving scheme has the potential of delivering millimeters of traveling range with nanometers of positioning resolution. Actuators of such frictionless drive, i.e., voice-coil linear actuators and solenoid actuators, have also been employed in high-precision manipulation [6,7]. However, the voice-coil actuator produces relatively small output forces (or poor force sensitivity). Although the moving magnet actuator offers good dynamic behavior and good heat dissipation, the magnetic force attraction due to the external iron casing causes the output force to be inconstant throughout the entire displacement stroke [8]. A solenoid actuator offers good force sensitivity but is unable to achieve a constant output force throughout its allowable traveling range due to the nonlinearity between force and displacement [9]. Furthermore, magnetization on the ferromagnetic stator introduces nonlinear magnetic hysteresis that leads to inaccuracy in nanometric positioning tracking [10]. The drawbacks of existing nano-positioning actuators motivated the development of a Flexure-based Electromagnetic Linear Actuator (FELA) [11]. FELA is formed through a marriage between an electromagnetic (EM) driving scheme and the flexure joints to achieve a few millimeters of displacement, large continuous thrust force, and a direct-force control capability. From past literatures [12,11], FELA was able to deliver a positioning

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http://dx.doi.org/10.1016/j.precisioneng.2014.12.006
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accuracy of ±20 nm, a continuous output force of 60 N/A, an actuating speed of more than 100 mm/s throughout a large displacement stroke of 4 mm.

In our previous research efforts, the thermal management of FELA was not considered because its applications were mainly on automating embossing [13,14] and nano-imprinting processes [15,16] to replicate micro/nano-scale features. In these processes, large output force with direct precise force feedback is essential. Hence, high force generation and high motion repeatability were the key considerations during the design phase. In addition, the closed-loop feedback control implemented on the end-effector ensures any form of thermal expansion will not affect the positioning accuracy. Thus, the coils usually operate between 60 and 80 °C during those imprinting operations. However, recent challenges arisen from applications such as the optical fiber alignment and the bio-cell manipulation have demanded FELA to produce higher positioning and thermal stability over a few minutes of operation period with or without closed-loop feedback control. Thus, an improved version, which could meet such requirements, is required for those applications. In our recent research efforts, a model-based thermal compensation control was implemented to the existing FELA to compensate for the material expansion at the tip of the output shaft due to thermal induction from the energized coil [17]. This investigation shows that the effectiveness of thermal control largely depends on the amount of thermocouple sensors used to estimate the thermally induced position error. To reduce the complexity of the entire control system, a two-stage optimization method was explored to re-design the Electromagnetic (EM) module of the existing FELA [18]. These efforts led to the conclusion that by factoring the thermal effect in the initial design stage will be much effective over the thermal control or thermal management approach in the later stages.

This paper presents a novel cylindrical-shaped FELA that achieves lower heat generation as compared to the existing rectangular-shaped FELA. It consists of a new Lorentz-force Electromagnetic (EM) module and flexure-based membrane supporting bearings. In this work, the cylindrical-shaped FELA has targeted specifications of ±10 nm positioning accuracy and ±0.15 °C thermal stability over a stroke length of 2 mm at the end-effector. To achieve the desired thermal characteristic, an accurate thermal modeling of the EM module will be presented. To synthesize the desired stiffness characteristic that facilitate the EM module in achieving the targeted thermal stability, the stiffness modeling of the flexure-based membrane bearings was conducted using a novel semi-analytic modeling approach [19] and will also be presented in this paper. Most importantly, this paper also presents a unique characteristic of the FELA, i.e., predictable and re-configurable open-loop positioning resolution. Such characteristic cannot be found in existing nanopositioning actuators. All theoretical modeling and the unique characteristics of FELA will be evaluated and demonstrated.

2. Design concept of the novel cylindrical-shaped FELA

The cylindrical-shape FELA comprises of a new Lorentz-force EM module and a pair of flexure-based membrane support bearings as shown in Fig. 1. Termed as an Electromagnetic Driving Module (EDM), the Lorentz-force EM module is formed by a PM-based magnetic circuit with the moving air-core coil while while the flexure-based membrane bearings are used to support both ends of the moving air-core coil in order to retain the contactless nature of the EM driving scheme. Consequently, the frictionless characteristic of both driving and supporting elements ensure high motion repeatability.

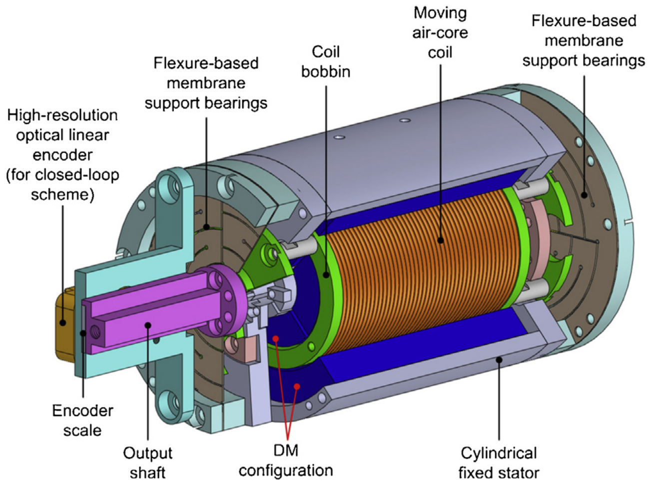

Fig. 1. A detailed breakdown on the cylindrical-shaped FELA.

2.1. A segmented dual-magnet configuration

In the previous EDM design [11], 50% of the moving air-core coil does not operate within the magnetic field regions. Assuming that this portion of coil could operate within the magnetic field regions, the overall force generation could be enhanced by up to 50% with the same amount of input current. In other words, only 50% of the input current would be needed to generate the equivalent amount of force that the previous EDM design is producing. Consequently, heat generation could be reduced by half. In this paper, a segmented Dual-Magnet (DM) configuration was proposed to ensure that the entire air-core coil is operating within the magnetic field regions as shown in Fig. 2a. Instead of a complete stator casing, the new cylindrical-shaped EDM was constructed by a group of segments whereby each segment was formed via a DM configuration as shown in Fig. 2b.

Based on a segmented architecture, the magnetic field travels from outer PM to the inner PM within the designated closed-loop ferrous path to reduce magnetic leakages. (Note: the magnetization direction of the outer and inner PMs are similar.) Thus, most of the magnetic field could be extracted from both PMs to enhance the magnetic flux density within the effective air gap, in which the moving air-core coil operates. The segmented concept also prevents demagnetization between two inner PMs or two outer PMs when packed closely together because of the designated closed-loop ferrous path from each segment. Such a concept also reduces the assembly time significantly since the PMs can be glued in each segment concurrently before assembling all the segments together. Lastly, the cylindrical DM configuration forms an encasement for the magnetic field and prevents magnetic field leakage to the environment. Hence, FELA can be used in certain applications and environment that are sensitive to EM or magnetic field disturbance.

Unlike conventional magnetic circuits [20,21] that deliver inconsistent and non-uniform magnetic flux density within the effective air gaps, the DM configuration delivers constant and evenly distributed magnetic flux density within a large effective air gap [22], i.e., 10 mm gap between the outer and inner PMs. By restricting the moving air-core coil to operate within the effective air gap as shown in Fig. 3, the new cylindrical-shaped EDM produces a constant current–force sensitivity (N/A) throughout the entire traveling range of the moving coil. Governed by the Lorentz-force principle and assuming that the magnetic flux density, B_{ext}, is perpendicular to the direction of input current, i, the output force, F, is expressed as

$$F \equiv iLB_{ext} \qquad (1)$$