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A piezoelectric motor for precision positioning applications

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ABSTRACT

This study presents a novel precise piezoelectric motor capable of operating in either an AC drive mode or DC drive mode. In the AC drive mode, the motor acts as an ultrasonic motor which is driven by two orthogonal mechanical vibration modes to generate elliptical motion at the stator to push the slider into motion. In the DC drive mode, stick-slip friction between the stator and slider is used to drive the motor step-by-step. The experimental results show that the AC drive mode can drive the motor at a high moving speed, while the DC drive mode can simply drive the motor with a nanoscale resolution. In our experiments, a prototype motor is fabricated and its actions are measured. The results demonstrate that in the AC drive mode, the piezoelectric motor can achieve a 106 mm/s speed without a mechanical load and a 34 mm/s speed with 340 g of mechanical load when applying two sine waves with a drive of 11.3 V at 38.5 kHz. Meanwhile, in a DC driving mode, the motor is capable of performing precision positioning with a displacement resolution of 6 nm when driving at 100 Hz.

1. Introduction

With the rapid development of semiconductor processes, micro-electromechanical systems, nanotechnology and biotechnology, the demand for nanoscale ultra-precision positioning devices has been gradually increasing in various technical fields, and related applications have increased requirements for the performance of this type of product. Facing the continuous increase of functional requirements, many kinds of precision positioning devices are being actively developed. For miniature positioning devices several centimeters in size, the piezoelectric positioning device, designed in a piezoelectric structure, is usually the first choice, because the piezoelectric component has a high stiffness, large thrust and quick response, as well as nm-scale deformation displacement.

At present, the piezoelectric devices that are on the market for precision positioning applications are divided into three major types: a flexible hinge-based nanopositioner, an inchworm motor and an ultrasonic motor. In terms of a flexible hinge-based nanopositioner, the piezoelectric actuator is embedded in a flexible metal structure; nanoscale high accuracy positioning is implemented by the elastic deformation of the metal material. Yao et al. proposed an *XY* positioning platform for a parallel motion mechanism [1]. The mechanism consists of a parallel four-link, flexible hinge and a piezoelectric actuator. It has 20 nm positioning accuracy and an 87 μm stroke. Generally speaking, the maximum displacement of a multilayered piezoelectric actuator is only 0.1% of the total length of the actuator. For example, the maximum displacement of a 2 cm long multilayered piezoelectric actuator is only within 20 μm in the flexible structure design with displacement amplification characteristics and the stroke is approximately 200 μm. This type of device can meet the high precision requirement for nanoscale positioning, but its operational stroke of only about 200 μm often fails to meet the actual demand.

The operating principle of an inchworm motor imitates the motion mode of an inchworm crawling; its structure is formed of three piezoelectric actuators mounted in one flexible structure. The amount of continuous nanoscale movement is implemented by a series of cyclic deformation motions formed by three piezoelectric actuators. Salisbury et al. studied an inchworm motor; its moving velocity was 440 μm/s under a 12.5 N load [2]. The elongation indicator of a piezoelectric actuator determines the one-step displacement of an inchworm motor, so that nanoscale positioning accuracy can be reached, but the defect is that the moving velocity is not high, causing inconvenience.

An ultrasonic motor uses the converse piezoelectric effect of piezoelectric material. The stator formed in piezoelectric structures generates an ultrasonic vibration above 20 kHz. The friction motion can change the ultrasonic vibration of the stator into a rectilinear motion of the slider. In terms of characteristics, the ultrasonic motor has a high output torque, slow speed, high static confining force, no magnetic interference, a simple structure compared to an

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electromagnetic motor and it is noiseless. Kummel et al. researched a linear ultrasonic motor [3]. The stator structure was rectangular. The bending vibration mode and stretching vibration mode of the stator were driven when sine voltage was applied to the stator, and elliptical motion was generated on the contact surface of the stator. This elliptical motion pushed the slider to move under the friction. This type of motor could reach a maximum moving velocity of 120 mm/s under a 0.6 N load. Generally speaking, the ultrasonic motor can move at several centimeters per second, and the moving velocity of the motor is proportional to the elliptical motion of the stator. When the motor's moving velocity is higher than 100 mm/s, the elliptical motion of the stator is approximately several μm. If the ultrasonic motor is applied to the nanoscale precision positioning, the elliptical motion on the stator surface must be less than several nm, so that the positioning resolution may be about 10 nm. For a general ultrasonic motor, it is technically difficult to have a high moving velocity and positioning resolution of tens of nm at the same time.

In order to solve the technical difficulty in simultaneously high moving velocity and high positioning accuracy of an ultrasonic motor, Merry et al. developed a travel piezoelectric motor [4], hoping to control the motor's moving velocity at 10 nm/s–100 mm/s, so as to meet the nanoscale positioning requirement. The driving principle was that there were four piezoelectric actuators in the stator, and travel driving at a non-resonance frequency was adopted. The research indicated that the motor displacement error varied with the moving velocity. The motor moved within 0.1 mm when the moving velocity was lower than 100 nm/s; the error was only ±5 nm. However, when the motor's moving velocity increased, the displacement error increased accordingly.

The company, Physik Instrumente (PI), utilized two sets of piezoelectric actuators to develop piezoelectric drive mechanisms [5] which allowed a limited range analogue motion with nm resolution and a continuous step motion with a higher speed.

A single-phase signal-driven linear piezoelectric motor has been developed in a previous study by the authors of this paper [6], and the prototype has been completed. According to experimental measurements, the motor prototype reached about a 4.85 N static holding force in a static state. It reached a non-loaded maximum velocity of 88 mm/s when driven by an 11.3 V single-phase voltage at 36 kHz, and reached a velocity of 27.2 mm/s under a 200 g load. In addition, when it was driven by dual voltage, the two sine wave drive voltages had a 90° phase difference. It reached the non-loaded maximum velocity of 106 mm/s when the drive voltage was 11.3 V, and it reached a velocity of 34 mm/s under a 330 g load. This motor has good performance during fast movement, but in ultra-precision positioning applications, the positioning accuracy should be considered. Therefore, this study discusses extra accuracy for the driving means of the linear piezoelectric motor in our previous study in order to implement nanoscale positioning accuracy.

2. Structure and operational principle

2.1. Structure

Differing from general inchworm motors and ultrasonic motor structures, the piezoelectric motor discussed in this study has the following four characteristics: (1) the stator is designed to have a high stiffness; (2) two multilayered piezoelectric actuators drive the *XY*-direction two-dimensional quasi-static deformation motion of the stator; (3) two multilayered piezoelectric actuators drive the high frequency dynamic deformation motion of the stator above 20 kHz and (4) the maximum deformation of the stator occurs near the contact point during quasi-static deformation and high frequency dynamic deformation motion.

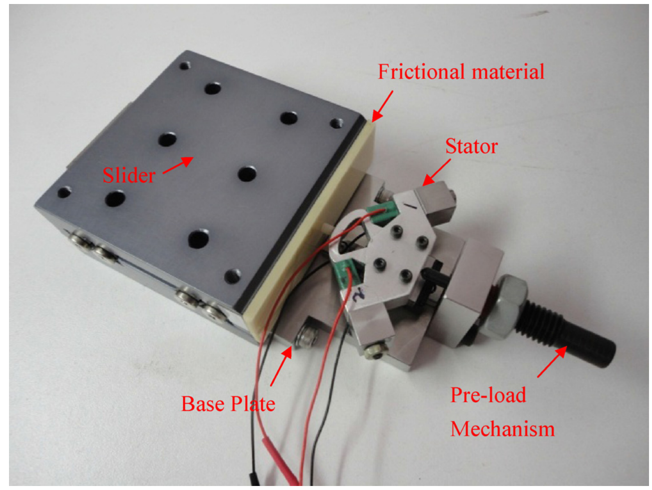

Fig. 1. Prototype of a linear piezoelectric motor.

The linear piezoelectric motor prototype discussed in this study is shown in Fig. 1. It consists of a slider, base plate, stator and pre-load mechanism. The detailing of the stator is shown in Fig. 2. Two multilayered piezoelectric actuators located at a 90° included angle are embedded in a metal elastic body. There is a semi-oval ring structure in the metal elastic body which deforms under the push of two piezoelectric actuators. The maximum deformation generally occurs in the center of the semi-oval ring, where a cylindrical frictional material is stuck as the contact point of the stator. In addition, there are four through, round holes in the bottom of the metal elastic body for fastening screws, and two added masses are fastened at both sides of the metal elastic body. The natural frequency of the stator can be adjusted by changing the mass size as required.

In order to drive the stator with two-phase alternating voltages, and to generate elliptical motion at the contact point of the stator, the stator is designed with two orthogonal vibration modes. In addition, in order to generate adequate deformation at the contact point when the stator is driven, the dimensions of the stator are adjusted during design, so that the deformation resulting from the push of the piezoelectric actuators occurs at the contact point of the semi-oval ring when possible. This detailed dimension design method can be referred to in literature [5]. Fig. 3(a) and (b) shows two high frequency, orthogonal vibration modes of the stator: the normal mode and the tangential mode. When the stator is driven, the normal mode is driven to generate a vertical displacement of the contact point in the *y*-direction, and the tangential mode is driven to generate a horizontal displacement of the contact point in the

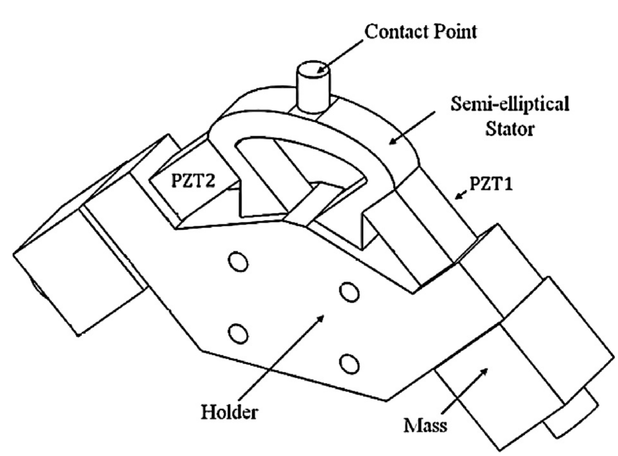

Fig. 2. Stator of the motor.