Sensors and Actuators A 278 (2018) 60–66

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Design and evaluation of a micro linear ultrasonic motor

Shunsuke Izuhara, Tomoaki Mashimo*

Toyohashi University of Technology, 1-1 Hibarigaoka Tenpakucho, Toyohashi, Aichi 441-8580, Japan

ARTICLE INFO

Article history:
Received 10 January 2018
Received in revised form 1 May 2018
Accepted 12 May 2018
Available online 18 May 2018

Keywords:
Microactuators
Piezoelectric actuators
Ferroelectrics
Micro-robotics

ABSTRACT

We propose a micro linear ultrasonic motor, which is one of the smallest linear actuators that can generate practical force. Such a small actuation mechanism can be used for a wide range of applications, such as auto-focus systems used in thinner cell phones and smaller endoscopes. In this paper, we design the micro linear ultrasonic motor and evaluate the performance of the prototype motor. The size of the prototype stator with piezoelectric elements measures 2.6 mm in height, 2.6 mm in width, and 2.2 mm in depth (the length in slider travel direction). There is a hole of 1.4 mm in diameter at the stator center, and the slider inserted into the hole moves back and forth when voltages are applied to the piezoelectric elements. By optimizing the preload between the stator and slider experimentally, the motor thrust force has been improved to over 10 mN, which is a practical force for moving small objects. Experiments clarify the output characteristics in response to the input voltages. Finally, a maximum thrust force of 20 mN has been obtained at applied voltages with an amplitude of 150 V_{p-p}.

1. Introduction

Micro actuators are required for a variety of future devices ranging from mobile devices to minimally invasive medicines. Much of the existing micro actuators are rotary ones, but micro linear actuators also have a strong demand from industry. A typical application of micro linear actuators might be the auto-focus mechanisms employed in a wide range of camera devices such as cell phones and endoscopes. Micro linear actuators control the lens position linearly and accurately to obtain clearer images. For thinner and smaller applications, the further miniaturization of auto-focus mechanisms are expected. One of the key technologies is linear actuators, but existing linear actuators have not satisfied the specifications required for the miniature devices, such as dimensions and thrust force.

In the past two decades, micro linear motors have been proposed using several driving principles [1]. Electromagnetically voice coil motors are used for cell phone camera lenses (the typical size of the motor units measures approximately 10 mm × 10 mm × 5 mm), but the electromagnetic force of the smaller voice coil motors are too low to be implemented into thinner devices. Other driving principles have been attempted for micro linear motors, such as electrostatic force [2], electrochemical reaction [3], and shape memory effect [4], but the low force density of these actuators limits further deployment.

Piezoelectric ultrasonic motors have the potential to become micro rotary motors because of their simple structure and high torque density [5–8]. They are expected to become micro linear motors as well [9]. In fact, miniature linear ultrasonic motors have been implemented to cameras, such as Konica Minolta's *Smooth impact drive mechanism* [10] and Canon's *Nano motor* [11]. In addition, there is a commercially available linear ultrasonic motor for multiple purposes, such as New Scale Technologies' *Squiggle motor* [12]. Seeing linear ultrasonic motors under development, several researchers have studied driving principles, such as simultaneous excitation of two vibration modes [13–15] and resonant impact drive mechanism [16–18]. All of the miniature linear ultrasonic motors showed a relatively high force density, but their stators are still long or large for the thinner and small applications. The smallest linear motor, which uses the vibration of two beams as the driving principle, generates approximately 10 mN from a stator with about 3 mm length [19]. It satisfies the required size and force, but complicated fabrication strategies are necessary.

In this paper, we propose a micro linear ultrasonic motor, which is one of the smallest linear motors reported to date. The stator comprises of a metallic cuboid with a side length of approximately 2 mm and piezoelectric elements with a thickness of 0.3 mm bonded to its four sides. The size of the prototype stator with piezoelectric elements measures 2.6 mm in height, 2.6 mm in width, and 2.2 mm in depth (length in slider travel direction). There is a hole of 1.4 mm at the stator center, and the slider inserted into the hole moves linearly. This hollow design is similar to the voice coil motor and is suited as linear actuators for miniature auto-focus mechanisms. As the driving principle, it uses the simultaneous excitation of two

---

* Corresponding author.
E-mail address: mashimo@eiiris.tut.ac.jp (T. Mashimo).

https://doi.org/10.1016/j.sna.2018.05.022
0924-4247/

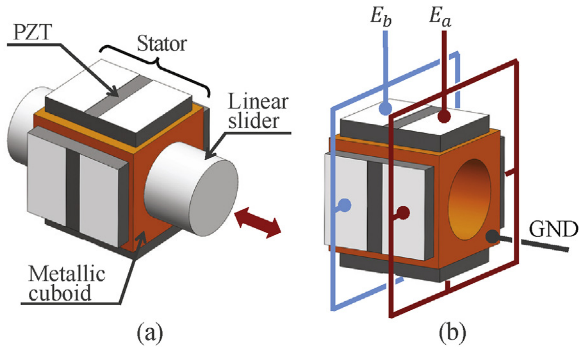

Fig. 1. (a) Schematic of the micro linear ultrasonic motor and (b) voltages applied to the micro linear ultrasonic motor.

vibration modes generated by the cuboid stator. This driving principle has been verified by much larger stators [20,21], but further details have not been studied, such as how to miniaturize the stator and how to optimize the motor output.

In the rest of this paper, we briefly describe the driving principle of the micro linear ultrasonic motor in Section 2. Section 3 shows how to design and build the micro linear ultrasonic motor. In Section 4, the characteristics of the micro linear ultrasonic motor are evaluated by experiments.

2. Micro linear ultrasonic motor

2.1. Driving principle

Fig. 1(a) shows the schematic of the micro linear ultrasonic motor. The stator is composed of a single metallic cuboid with a through-hole and four piezoelectric elements adhered on its four sides. The linear slider, a cylindrical shaft with a slightly smaller diameter than the stator hole, is inserted into the stator hole. To drive the slider linearly, two vibration modes are simultaneously excited by the piezoelectric elements. We define these two vibration modes as first extension mode and second extension mode shown in Fig. 2(a) and (b), respectively. When the stator is sufficiently long in the slider movement direction, the behavior of the two vibration modes is very similar to that of extension modes introduced in vibration engineering. This is the reason that we call them first and second extension modes. Basically, the first and second extension modes have individual natural frequencies, so the natural frequencies are separated at a long stator. However, when the stator is in the neighborhood of a cubic shape, the natural frequency of both modes can take the same value. This agreement enables the simultaneous excitation of the two vibration modes at the same frequency.

To excite the first and second extension modes, two voltages are applied to the piezoelectric elements as shown in Fig. 1(b). We denote the voltages applied to the four electrodes on the right side as E_a and the voltages to the left side as E_b. They are expressed as

$$E_a = A_E \sin(2\pi f_E t), \tag{1}$$

and

$$E_b = A_E \sin(2\pi f_E t + \phi), \tag{2}$$

where A_E and f_E are the amplitude and the frequency of the applied voltages, respectively, and ϕ is the phase difference between E_a and E_b. The frequency f_E is adjusted to be equal to the natural frequency of both the first and second extension modes. To excite the first extension mode, the same voltages ($E_a = E_b$ when $\phi = 0$) are applied. The piezoelectric elements repeat to expand and shrink, and this repetition excites the first extension mode (Fig. 2(a)). On the other hand, when E_a and E_b have a reversed phase ($\phi = \pi$), they shrink the left side and expand the right side or vice versa. This repetition excites the second extension mode (Fig. 2(b)).

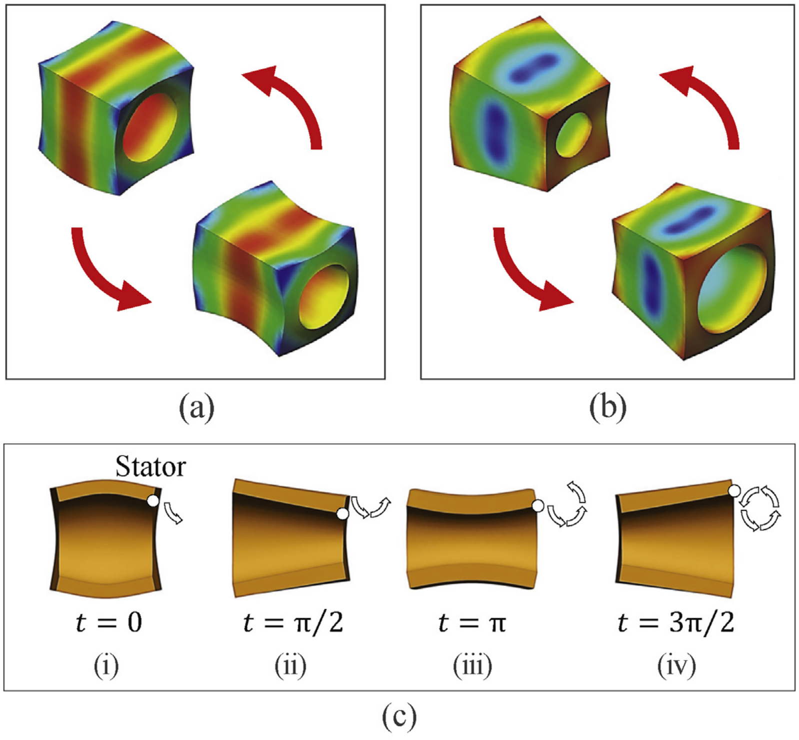

Fig. 2. The driving principle of the micro linear ultrasonic motor. (a) The first extension mode, (b) second extension mode, and (c) the combination of the first and second extension modes where the first extension mode repeats (i) and (iii) and the second extension mode repeats (ii) and (iv). When a temporal difference of $\pi/2$ is given between the first and second extension modes, the stator edge generates an elliptical motion.