Sensors and Actuators A 213 (2014) 102–107

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Micro ultrasonic motor using a one cubic millimeter stator

Tomoaki Mashimo*

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

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form 1 February 2014
Accepted 14 March 2014
Available online 3 April 2014

Keywords:
Piezoelectric actuators
Ultrasonic motors
Micro motors

ABSTRACT

Ultrasonic motors are expected to be used as micro-actuators, and the miniaturization of these devices is an interesting subject. We present a micro ultrasonic motor using a stator with a volume of approximately 1 mm^3, which is one of the smallest ultrasonic motors. The stator consists of a metallic cube with a through-hole and piezoelectric elements adhered to its sides; the simplicity of the stator allows it to be miniaturized without special machining processes. The vibration mode that the stator generates for rotation is three waves around the circumference of the hole. This vibration mode can generate certain vibration amplitudes and driving torques even when the stator is miniaturized. In this paper, we build a prototype micro ultrasonic motor and examine its basic characteristics, including impedances and vibration amplitudes. The basic motor performance, such as its torque and rotational speed, is demonstrated experimentally.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Minimally invasive diagnoses and treatments, such as those using endoscopes and catheters, require micro-motors with volumes of less than 1 mm^3 for further development. For example, a robotic catheter using micro-motors can quickly select a branch of blood vessels at a bifurcation and spin an ultrasonic or optical sensor to screen for the presence or absence of thrombi inside the vessels. Many driving principles have been proposed to actuate micro-motors, including electromagnetic, electrostatic, piezoelectric, thermal, and electro-conjugate fluid (ECF) principles. Among these methods, ultrasonic motors based on piezoelectric effects in particular are expected to be the most prominent micro-motors for generation of practical torques in small structures [1–3].

Ultrasonic motors have two advantages that are appropriate for miniaturization. First, ultrasonic motors have high energy densities and can drive with high torques at low speeds without using a reduction gear. Second, ultrasonic motors have simple structures using few components. A good example of a practical application is their use in watches; an ultrasonic motor with a diameter of 4.5 mm and height of 2.5 mm can be mounted to rotate calendar rings [4]. The authors have noted that the torque produced by the miniature ultrasonic motor is approximately 50 times larger than that of similarly-sized electromagnetic stepping motors [5].

Over the last decade, several researchers have built prototype millimeter-scale ultrasonic motors. Many of the existing millimeter-scale ultrasonic motors use a bending vibration mode of a hollow cylinder as their driving principle; the cylinders are approximately 1.5 mm in diameter and 5 mm in length [6–9]. The bending vibration mode can generate larger vibration amplitudes and higher outputs than other vibration modes, but the amplitude decreases severely when the cylinder length is shorter. Another interesting driving principle involves coupling of the axial and torsional vibration modes of the stator [10,11]. This type of motor is simply excited using a piezoelectric element, but the rotation can only be produced in one direction. One of the smallest ultrasonic motors in the literature also uses this coupling [12]: a metallic tube with diameter of 0.25 mm and length of 1 mm, which is excited using a piezoelectric element, spins a sphere. However, the total size of the motor, including a preload mechanism, is as much as a few millimeters.

We have proposed an ultrasonic motor that can generate rotation using a single cubic stator [13,14]. One advantage of this motor for miniaturization is the use of a vibration mode that generates three waves along the circumference of a hole in the stator (three-wave mode). This three-wave mode is also well known as the mode shape that is generated in a ring in vibration engineering [15]. Unlike the bending vibration mode, the three-wave mode is independent of the length of the stator. The motor can generate a certain vibration amplitude, regardless of the stator length, even when that length is reduced to as little as 1 mm. Another advantage for miniaturization is the simple motor construction. The stator consists of a metallic cube with a through-hole and plate piezoelectric

---

* Tel.: +81 532 81 5139; fax: +81 532 81 5141.
E-mail address: mashimo@eiiris.tut.ac.jp

http://dx.doi.org/10.1016/j.sna.2014.03.018
0924-4247/© 2014 Elsevier B.V. All rights reserved.

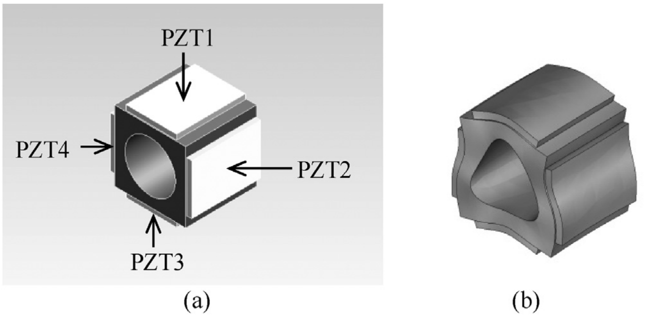

Fig. 1. (a) Schematic diagram of the stator, and (b) the vibration mode that generates three waves around the hole (three-wave mode).

elements adhered to its sides. The proposed ultrasonic motor is built without using any special machining or assembly methods. In this study, we build a prototype and demonstrate the performance of our micro ultrasonic motor, consisting of a cubic stator with a volume of approximately 1 mm^3, which is one of the smallest reported ultrasonic motors.

2. Driving principle

Fig. 1(a) shows a schematic diagram of the stator. The metallic part of the stator is a single metallic cube with a through-hole, and four piezoelectric elements, PZT1–PZT4, are adhered to the four sides of the stator. When a voltage is applied to one of the piezoelectric elements, the stator generates a vibration mode that excites three waves around the circumference of the through-hole (three-wave mode), as shown in Fig. 1(b).

The micro ultrasonic motor uses a combination of two identical three-wave modes for generation of the rotation as its driving principle. In the motor, the voltage E_1, which is applied to the piezoelectric element PZT1, is expressed as

$$E_1 = A_E \sin(2\pi f_E t), \tag{1}$$

where A_E and f_E are the amplitude and the frequency of the voltage, respectively. When f_E is equal to the natural frequency of the three-wave mode, the vibration mode is excited by the piezoelectric element. When the voltage E_1 is applied to the piezoelectric element PZT1, a three-wave mode is generated as shown in Fig. 2(a). The second voltage E_2, which is applied to the next piezoelectric element PZT2 is expressed as

$$E_2 = A_E \sin(2\pi f_E t + \phi), \tag{2}$$

where ϕ is the phase difference between E_1 and E_2. Additionally, when E_2 is applied to piezoelectric element PZT2, a second three-wave mode is generated, as shown in Fig. 2(b). These two three-wave modes have an angular difference of $\pi/2$ between them in the circumferential direction. When the phase difference $\phi = \pi/2$ applies to the voltage E_2, the stator produces a traveling wave in the through-hole circumferentially by combining the two three-wave modes. During that time, a point on the surface of this traveling wave generates an elliptical motion. This elliptical motion transfers its driving force via friction to the rotor that is inserted into the hole, and the rotor then spins. The production of the traveling wave is detailed in [13]. Consequently, the driving principle of the micro ultrasonic motor proposed here is almost the same as that of the traveling wave ultrasonic motor [16].

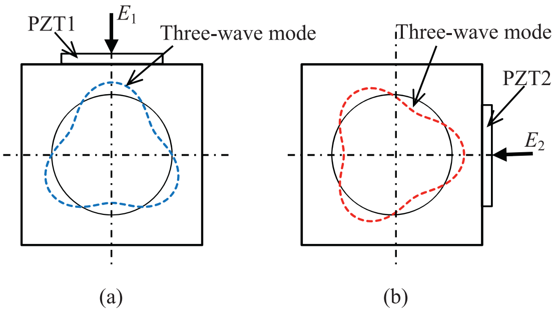

Fig. 2. Three-wave mode generated by (a) voltage E_1, and (b) voltage E_2.

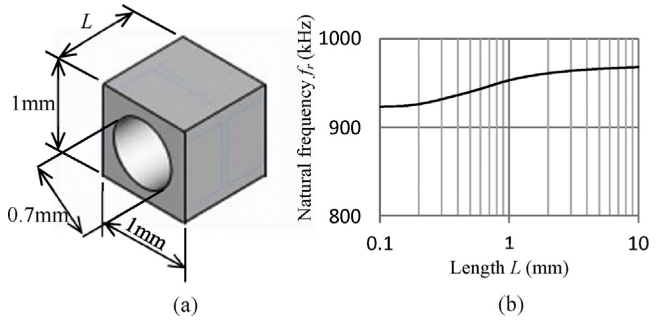

Fig. 3. (a) Dimensions of the simulation model, and (b) relationship between the natural frequency of the three-wave mode and the length L.

The piezoelectric elements PZT1 and PZT3 have been adhered to the surface of the metallic cube with opposite orientations: the outside of PZT1 is the positive pole, while the outside of PZT3 is the negative pole. When we apply the voltage E_1 to both of these piezoelectric elements, the vibration amplitude becomes in principle twice the magnitude of the vibration amplitude obtained using only one of the piezoelectric elements. When E_1 is applied to PZT1 and PZT3, PZT1 expands and PZT3 contracts (or PZT1 contracts and PZT3 expands). Through the repeated expansion and contraction of PZT1 and PZT3, the stator generates the three-wave mode with a higher amplitude. The piezoelectric elements PZT2 and PZT4 are also adhered to the cube surface with opposite orientations. When E_2 is applied to PZT2 and PZT4, the stator similarly generates the second three-wave mode with a higher amplitude.

3. Design and prototype

3.1. Modal analysis using FEM

A modal analysis using the finite element method (FEM) shows both the mode shape and the natural frequency of the three-wave mode. Using FEM software (Pro/Mechanica, PTC Co., Needham, MA), we determine whether the natural frequency of the three-wave mode is independent of the stator length. The stator model is a square cuboid with a through-hole, and the dimensions of this model are given in Fig. 3(a). We denote the length L as being variable and vary it from 0.1 to 10 mm. The material characteristics are those of phosphor bronze (Young's modulus = 103 GPa; density = 8.85 × 10^3 kg/m^3; Poisson ratio = 0.34). Fig. 3(b) shows the relationship of the natural frequency to the length L. Although the frequency increases slightly at longer lengths, the natural frequency stays almost constant. When the stator is cubic (L = 1 mm), the natural frequency is shown to be 953 kHz.

Another important aspect of the motor design is to avoid interference from other vibration modes to produce stable rotation. Let us examine the possibility that other vibration modes may exist near the natural frequency of the three-wave mode. Fig. 4 shows the other possible vibration modes and their frequencies determined by modal analysis over the frequency range from 700 to 1100 kHz. Fig. 4(a) shows the stator without any change. From the lower frequencies, the stator changes its sides to form a rhomboid at 876 kHz,

Download English Version:

https://daneshyari.com/en/article/737104

Download Persian Version:

https://daneshyari.com/article/737104

Daneshyari.com