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Prototype of Micro Ultrasonic Motor using a Stator of One Cubic Millimeter

1 ミリ立方メートルのステータを用いた
小型超音波モータの試作

Tomoaki Mashimo[1†]
([1]Electronics-inspired Interdisciplinary Research Institute, Toyohashi University of Technology)
真下智昭 [1†]
([1]エレクトロニクス先端融合研究所，豊橋技術科学大学)

1. Introduction

A variety of micro-actuators would be used for small medical devices such as catheters and endoscopes. One of promising micro-actuators is ultrasonic motors that have high energy density (high ratio of output to volume) [1]. Application into watches is a good example; an ultrasonic motor with diameter 4.5 mm and height 2.5 mm has been used for rotating calendar rings [2]. The authors mentioned that the torque of the miniature ultrasonic motor is fifty times larger than that of similar-sized electromagnetic motor.

For this decade, several researchers have been prototyping micro-ultrasonic motors. Typical micro-ultrasonic motors use a bending vibration mode of the stator as the driving principle. This is because the bending vibration mode can generate large vibration amplitude and determine rotational directions. Another interesting driving principle is the use of coupling axial and torsional vibration modes of the stator. An advantage is that this motor is excited by one piezoelectric element. The smallest ultrasonic motor uses this driving principle: A stator with 0.25 mm diameter and 1 mm length is excited by a piezoelectric element and generates the rotation of a sphere [3]. However, total size including magnets for preload is over a few millimeters.

We propose a micro ultrasonic motor using a vibration mode that generates three waves inside the hole of a stator. Fig. 1 shows the prototype of the motor that is comprised of a single metallic cube with a side length of 1 mm and a through-hole of 0.7 mm at its center. Four piezoelectric elements are bonded to the four sides of the stator and generate vibration. This simplicity of the stator makes the manufacturing easy and makes the size small. An output shaft (rotor), which is inserted to the through-hole, generates rotation when AC voltages are applied to the piezoelectric elements and the vibration mode is excited. In following sections, we report the driving principle and experimental results.

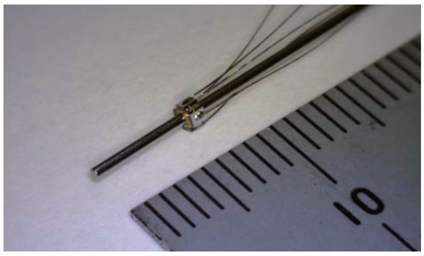


Fig. 1 Prototype of micro ultrasonic motor

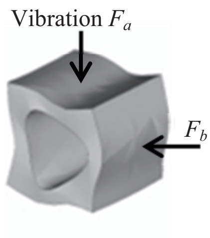


Fig. 2 Vibration mode that generates three waves inside the hole of the stator

2. Driving principle

The stator uses a vibration mode that excites three waves along the circumference of the through-hole (3-wave mode) shown in Fig. 2. When a vibration F_a acts on the top surface of the stator, 3-wave mode, which is a standing wave, is generated. When the other force F_b acts on the next surface with 90 degrees, the other 3-wave mode is excited. By coupling these two 3-wave modes with the temporal phase difference of π/2 which is one-quarter of a cycle, the travelling wave is produced on the inner surface of the through-hole. While producing the traveling wave, elliptical motion is generated, and this elliptical motion can rotate the rotor. This driving principle of the rotation is the same as that of the traveling type ultrasonic motor, although the design appears different.

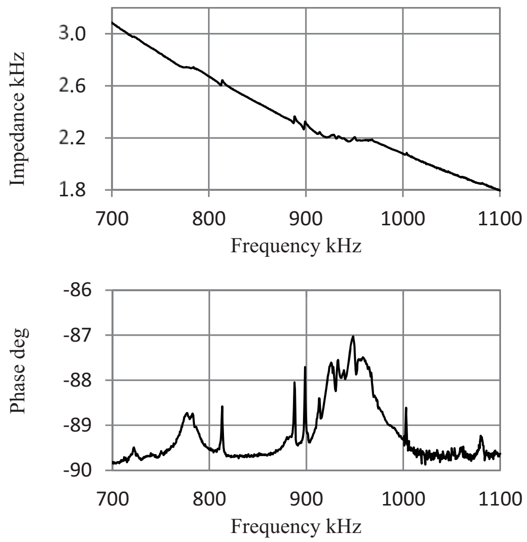


Fig. 3 Impedance characteristics of the prototype motor

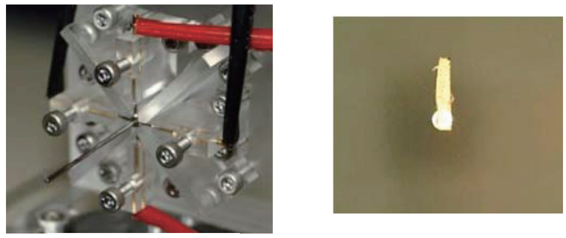
3. Prototype of the micro ultrasonic motor

A Modal analysis using finite element methods (FEM) clarifies the mode shapes and natural frequencies of the stator. The material characteristics of the FEM model of the stator are those of phosphor bronze (Young's modulus E = 103 GPa, density ρ=8.85×103 [kg/m3], Poisson's ratio = 0.34). The stator is a single metallic cube with a side length of 1 mm and a through-hole of 0.7 mm. The modal analysis shows the mode shape of 3-wave mode as shown in Fig. 2. The natural frequency of 3-wave mode is approximately 953 kHz.

The resonant frequency of the prototype micro ultrasonic motor can be found by an LCR meter (3532-50, Hioki E. E. Co., Japan). Two wires from the electrode of two piezoelectric elements and a ground wire from the metallic cube are connected to the LCR meter. Fig. 3 shows the frequency characteristics of the impedance and phase of the stator. A change in the impedance is observed at the frequency close to the natural frequency of the 3-wave mode. The resonant frequency of R3 mode is shown at approximately 900-960 kHz. These frequencies are accorded with the frequency estimated by the FEM modal analysis.

4. Experiment

The prototype of micro ultrasonic motor is installed on the experimental setup as shown in Fig. 4 (a). Four corners of the stator are hold by plastic parts of the experimental setup. AC voltages with amplitude 50 V_{p-p} and frequency 920 kHz are applied to the stator. The value of the frequency has been adjusted to obtain maximum rotational speed.



(a) (b)

Fig. 3 Experimental setup

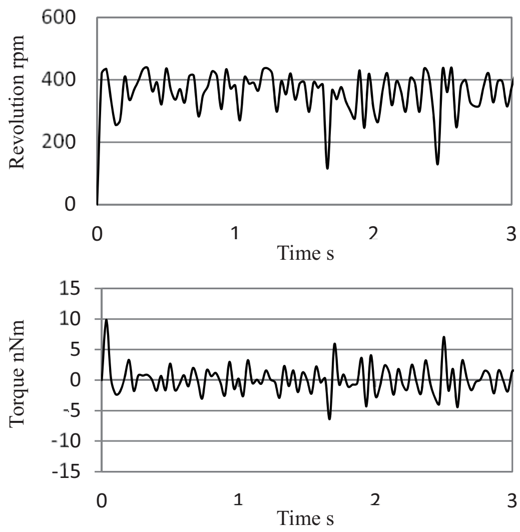


Fig. 3 Rotational speed and torque of the motor

To measure the rotational speed, revolution of the rotor is measured by the video camera and is calculated from angular displacement per a flame of the video. Fig. 4 (b) shows the end of the rotor with a marker.

Fig. 5 (a) shows the time history of the rotation when the AC voltages are applied. Within one flame (33 ms), the rotation achieves steady-state. The rotational speed is approximately 350 rpm. The variation in the rotational speed is observed; It is due to the surface condition and friction between the stator and the rotor. Fig. 5 (b) shows the torque of the motor calculated from the product of the angular acceleration and the moment of inertia. The value of maximum torque is 10 nNm, but the torque peaks within first flame of video and it should be higher than the value. Use of a video camera with high flame rate would measure the correct value of torque.

References

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