

# A micro ultrasonic motor using a micro-machined cylindrical bulk PZT transducer

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## Abstract

In this paper, a micro ultrasonic motor using a micro-machined bulk piezoelectric transducer is introduced. The cylindrical shaped bulk piezoelectric transducer, a diameter of 0.8 mm and a height of 2.2 mm, was developed as stator transducer for traveling wave type ultrasonic motor. The transducer was made of lead zirconate titanate (PZT) bulk ceramics, and formed by micro machining, Ni plating and laser beam cutting process. Using this stator transducer, we have fabricated a cylindrical micro ultrasonic motor, a diameter of 2.0 mm and a height of 5.9 mm. We have also evaluated some characteristics and succeeded in driving the micro ultrasonic motor.

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**Keywords:** Piezoelectric actuator; Ultrasonic motor; Micro motor; Bulk piezoelectric material; Micro machining

## 1. Introduction

Micro motors have been receiving increasing attention in realizing various types of micro mechanism applications, for example, micro robots, microsurgery equipments and micro electro mechanical systems (MEMS). In this paper, micro ultrasonic motors utilizing micro-machined cylindrical bulk piezoelectric vibrators are introduced.

Ultrasonic motors have some merits for the miniaturization of motors. They have simple structure compared with other types of micro actuators, especially electromagnetic motors. In addition, ultrasonic motors need no deceleration mechanism because they have high torque output in low rotation speed. Hence, by using ultrasonic motors, we would realize micro mechanical systems driven by high power actuators.

Many types of micro ultrasonic motors have been reported [1–9]. Some of them used piezoelectric thin film for the acceleration [2–5]. However, they could not realize enough high power output for the drive of micro mechanical systems. To realize

high power output, we used bulk lead zirconate titanate (PZT) transducer [6,10].

## 2. Structure and principle

Fig. 1 shows the schematic of the piezoelectric cylindrical transducer for the micro ultrasonic motor. Cylindrical shaped bulk piezoelectric vibrators were developed as stator transducers for traveling wave type ultrasonic motors.

Since the stator transducer was fixed at the end of the cylinder, it is easy to support the vibrator and the structure of the motor was not complicated. This is important for micro ultrasonic motor because it is difficult to support the vibrator when the vibrator was miniaturized. Four electrical sources were used for the oscillation of the vibrator [2,3,6]. The inner electrode works as an equivalent electrical ground. The rotate orientation can be changed by the phase shift between the electrical sources.

Fig. 2 shows the analytical result of the vibrator deformation mode calculated by using the finite element method (FEM). One end of the cylinder was connected to the base, the cylindrical part, which has larger diameter. As a result of modal analysis, another end of the cylinder was deformed.

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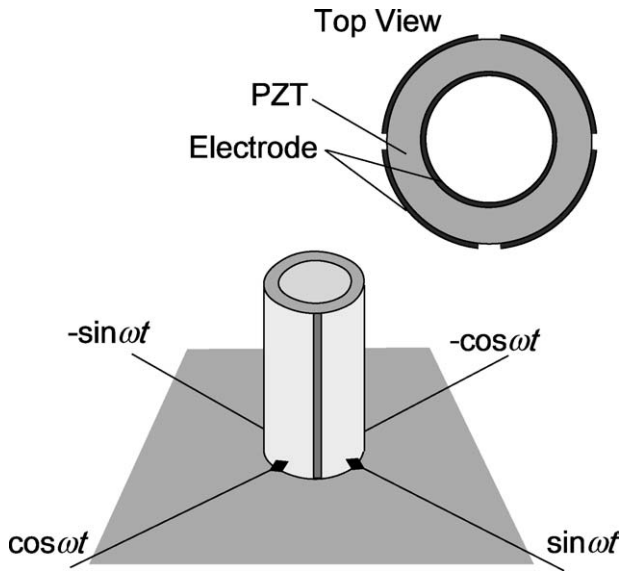


Fig. 1. Schematic of the piezoelectric cylindrical transducer for the micro ultrasonic motor.

Fig. 3 shows a cross-sectional view of micro ultrasonic motor and a photograph of fabricated micro motor. The diameter of the motor with pre-load mechanism was 2.0 mm and the height was 5.9 mm. The micro ultrasonic motor consists of a rotor, the stator transducer, casing parts, spring and a bearing. The rotor, whose diameter was 0.8 mm, was pressed to the end of the stator transducer by using the spring whose diameter was 0.8 mm. The pre-load was given by the spring. The output shaft was united with the rotor and the diameter of the shaft was 0.4 mm. The shaft and rotor was made of SUS630. The bearing was made of poly tetra fluoro ethylene (PTFE).

The finite element method was used for the design of motor. The modal analysis by FEM gave the calculation results about the vibration mode. It is important that the stator transducer was fixed at one end and the motor case cannot be excited by the vibration of transducer. As shown in Fig. 4, the dimensions of

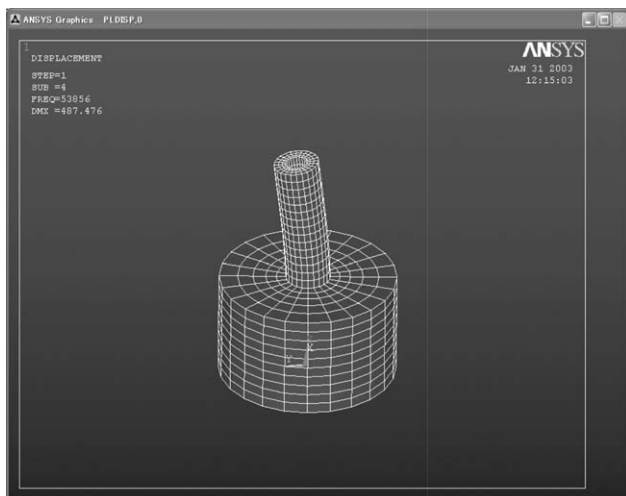


Fig. 2. Analytical result of the vibrator deformation mode by the finite element method.

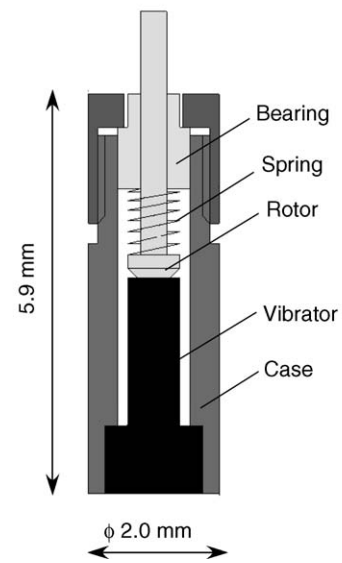


Fig. 3. Cross-sectional view of the micro ultrasonic motor using cylindrical bulk transducer and its parts.

the vibrator, those of the case and their material properties gave suitable vibration mode.

### 3. Fabrication of transducer

The stator transducers were fabricated by the micro machining of the bulk cylindrical piezoelectric ceramics.

The fabrication process of the stator transducer is shown in Fig. 5. The bulk piezoelectric material was cylindrical shaped hard type PZT, C-218 (Fuji Ceramics Co., Japan). The cylindrical ceramics was formed to be a pipe and step like shape by micro machining process. In addition, nickel was plated as electrodes on the surface and inside of the pipe. After the polarization process, the nickel film was divided to four electrodes by the laser beam cutting. Each pitch between two electrodes is 0.1 mm.

Fig. 6 displays the schematic view of the piezoelectric transducer. We fabricated two types of transducers. About those transducers, dimensions are shown in Table 1. In both types of transducers, the dimensions of the pipe shaped part are an outer diameter of 0.8 mm, an inner diameter of 0.4 mm and a height of

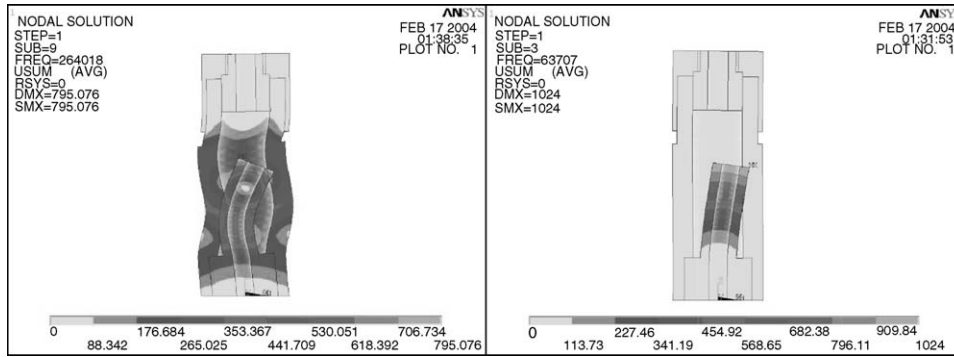


Fig. 4. Analytical result of the deformation mode about the micro ultrasonic motor by using the finite element method.

2.2 mm. The transducers A and B have different dimensions of the base. The transducer A was for evaluating basic characteristics about transducer. This type transducer has larger base and the bending vibration can be excited at the pipe shaped part. The transducer B was built in micro motor as shown in Fig. 3. Fig. 7 shows photograph of transducers A and B. Divided electrodes are deposited on the PZT cylinder.

**4. Evaluation of transducer**

Some characteristics of stator vibrator were evaluated. For the driving of the micro ultrasonic motor, bending vibration in

two orthogonal orientations was used as illustrated in Fig. 1. We evaluated the relationship between admittance and frequency about each orientation. The transducer A was used for the measurement. The experimental results are shown in Fig. 8. Each

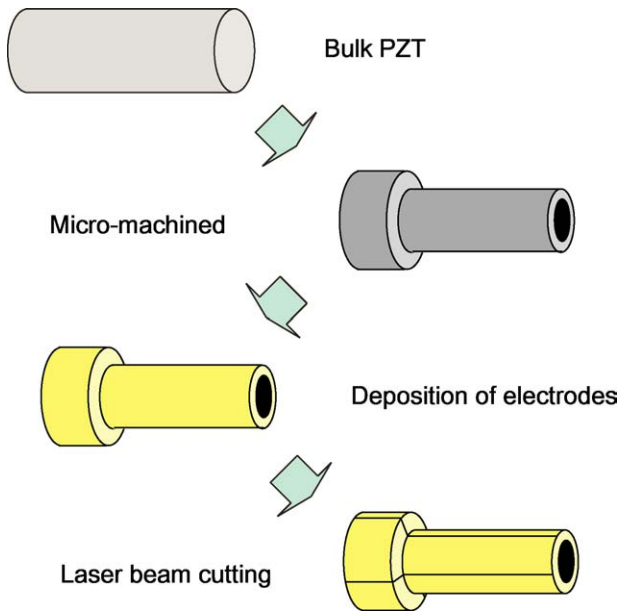


Fig. 5. Fabrication process of the piezoelectric transducer.

Table 1  
Dimensions of the cylindrical bulk piezoelectric transducers

	Transducer A	Transducer B
a (mm)	0.8	0.8
b (mm)	0.4	0.4
c (mm)	2.2	2.2
d (mm)	2.8	1.0
e (mm)	4.0	1.5

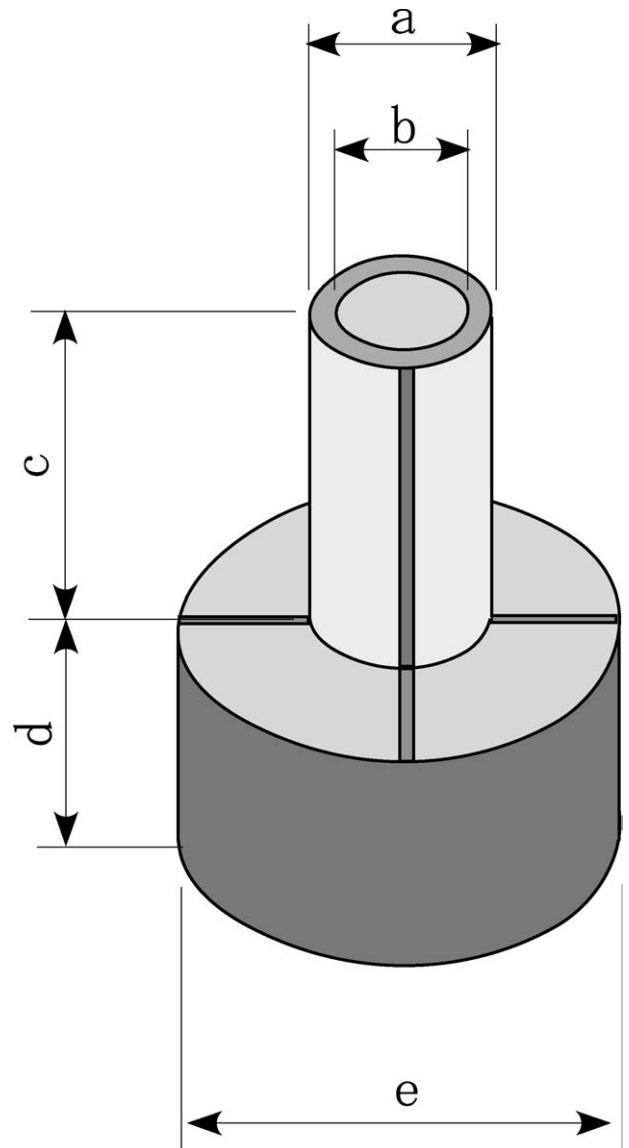


Fig. 6. Schematic show of the cylindrical bulk piezoelectric transducer.



Fig. 7. Photograph of the cylindrical bulk piezoelectric transducer.

graph displays that the resonance frequency was approximately 70 kHz.

The vibration velocity at the end of the vibrator was also evaluated. The maximum vibration velocity at the resonance frequency was measured about the transducer A. The vibration velocity was measured with laser Doppler vibrometer. Figs. 9 and 10 indicate the experimental results. Fig. 9 displays the relationship between the vibration velocity and the frequency. As shown in this graph, the resonance frequency was 69 kHz. Fig. 10 shows the relationship between the vibration velocity and the applied voltage. The measured relationship has

linearity. When the applied voltage was 40 V<sub>p-p</sub>, the resonance frequency was 69 kHz and the maximum vibration speed was 715 mm/s, causing the vibration displacement was 1.6 μm<sub>o-p</sub>.

Some characteristics of motor were evaluated by using the transducer A and a rotor. The pre-load mechanism of the motor and transducer B were not used in this experiment. This is because it is difficult to change the pre-load value by using the pre-load mechanism built in the motor case. We evaluated the relationship between the rotation speed, applied voltage and the

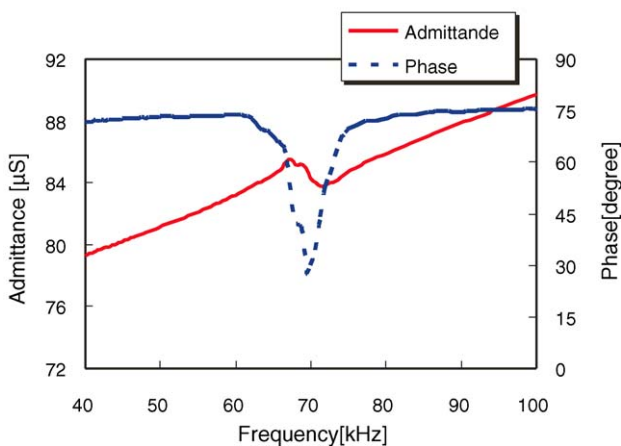
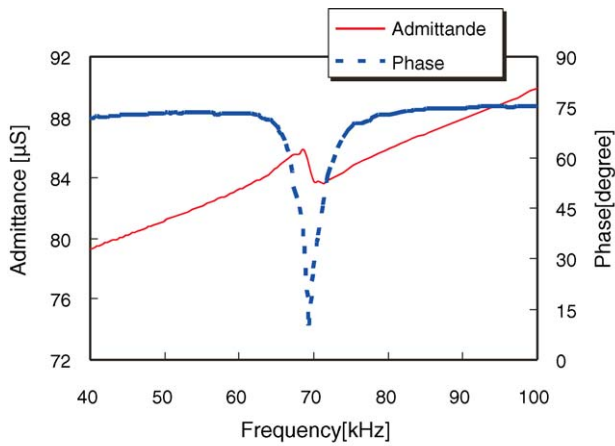


Fig. 8. Relationship between admittance of the vibrator and frequency.

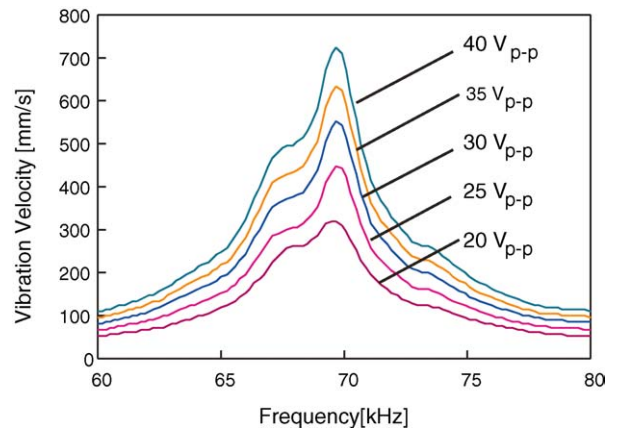


Fig. 9. Relationship between the vibration velocity at the tip of the transducer A and the frequency.

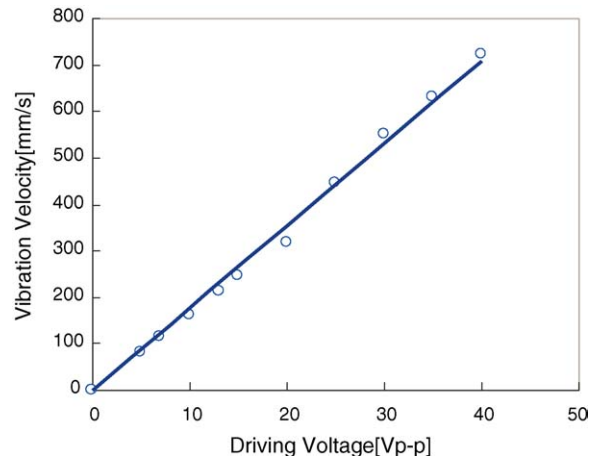


Fig. 10. Relationship between the vibration velocity and driving voltage about the transducer A.

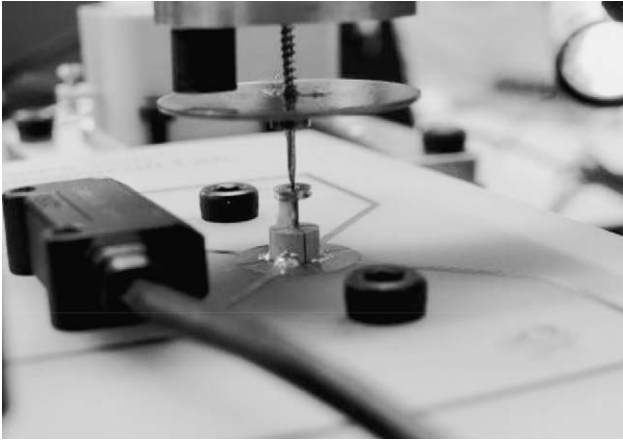


Fig. 11. Experimental setup for the measurement of the relationship between the revolution speed, pre-load and applied voltage.

pre-load values. The relationship between the output torque of the motor, applied voltage and the pre-load values was also evaluated.

The experimental setup is displayed in Fig. 11. The transducer A, a rotor, a pre-load mechanism and a laser counter were used for the measurement. The pre-load was given by a spring through a needle. The rotor was pushed by the needle tip and has a contact with the end of the vibrator. The pre-load value was changed by the length of spring and the length was measured by using a gap sensor. The rotation speed of the rotor was measured by using the laser counter [6].

Fig. 12 shows the relationship between the rotation speed and pre-load values. The frequency of the applied voltage was set at the first bending mode frequency of the stator transducer. The applied voltage was changed from 25  $V_{p-p}$  to 40  $V_{p-p}$ . The maximum revolution per minute was  $3.85 \times 10^3$  at the applied voltage of 40  $V_{p-p}$  and the pre-load of 0.5 mN. The experimental results show that the rotation speed was decreased suddenly when the pre-load increased.

The static torque of the micro ultrasonic motor was also evaluated. The load cell was used for the measurement of the tension of thread pull by the rotor. Hence, the measured torque values mean the static torque. Fig. 13 shows the experimental results. This

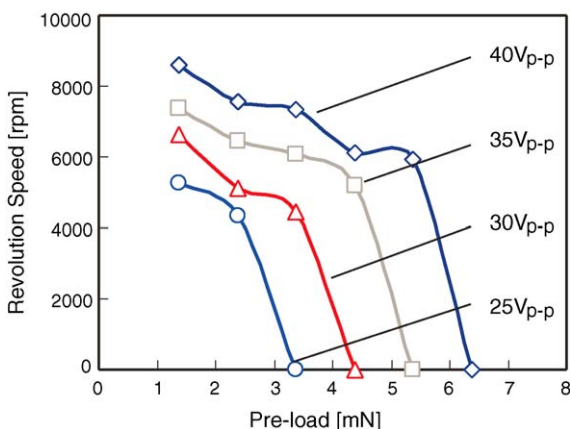


Fig. 12. Relationship between the revolution speed of rotor and pre-load against the rotor.

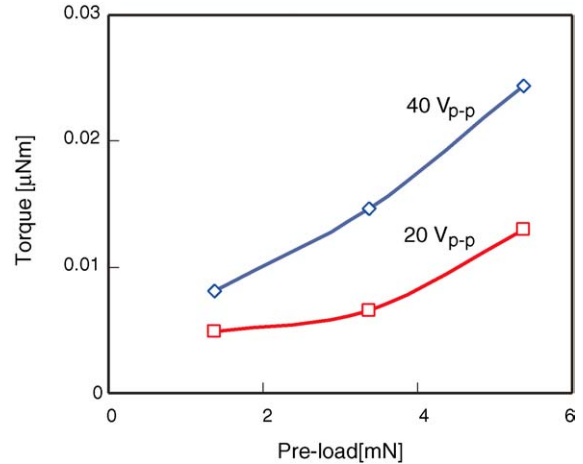


Fig. 13. Relationship between the static torque and the pre-load against the rotor.

graph shows the relationship between the output torque and pre-load. The maximum output torque was  $2.5 \times 10^{-2} \mu N m$  when the pre-load was 5 mN and the applied voltage was 40  $V_{p-p}$ . As shown in Fig. 12, the rotation stopped when the applied voltage was 40  $V_{p-p}$  and the pre-load was larger than 5 mN.

### 5. Micro ultrasonic motor

The transducer B was used as the stator vibrator as shown in Fig. 3. It was confirmed that the output shaft united with the rotor was driven by the vibrator. The direction of the rotation was changed by the polarity of the electrical sources.

An analytical result of the deformation mode calculated by using the finite element method about the transducer B is shown in Fig. 14. To miniaturize the motor, the base part of the stator transducer must be miniaturized. In this result, the figure shows the deformed shape when the diameter of the base part of the stator is 1.5 mm about the transducer B.

The structure of the micro ultrasonic motor using cylindrical bulk transducer and its parts are shown in Fig. 13. The diameter of the motor with pre-load mechanism was 2.0 mm and the height

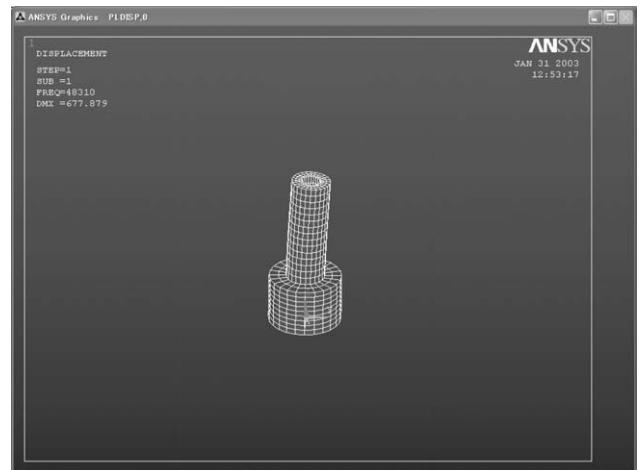


Fig. 14. Deformation of transducer B at the resonance frequency; calculation result of the modal analysis by FEM.



Fig. 15. Photograph of the micro ultrasonic motor and piezoelectric vibrator, transducer B on US one cent coin.

was 5.9 mm. A rotor, whose diameter was 0.8 mm, was pressed to the end of the stator vibrator by using a spring whose diameter was 0.8 mm. An output shaft was united with the rotor and the diameter of the shaft was 0.4 mm.

Fig. 15 shows the micro ultrasonic motor and the piezoelectric vibrator used for the micro ultrasonic motor. We have succeeded in driving this motor and controlling the rotating direction.

The revolution speed of shaft was measured with laser counter. Experimental result is shown in Fig. 16. This graph displays the relationship between revolution speed of shaft and driving voltage. The vibrator was oscillated at the resonance frequency of this motor, 58 kHz, and the pre-load was  $4.9 \times 10^{-2}$  mN. This pre-load value means that the pre-load was only obtained by the load of rotor. When the driving voltage was  $40 V_{p-p}$ , the revolution speed was  $2.4 \times 10^3$  rpm.

When the driving voltage  $40 V_{p-p}$ , the measured revolution speed generated by transducer B built in motor was 64% of maximum revolution speed generated by transducer A displayed in Fig. 12. This decrease of the revolution speed was thought to be due to the damping of vibration. Fig. 17 shows the relationship between the admittance of transducer B built in the micro motor and the frequency. In comparison with Fig. 8, the admit-

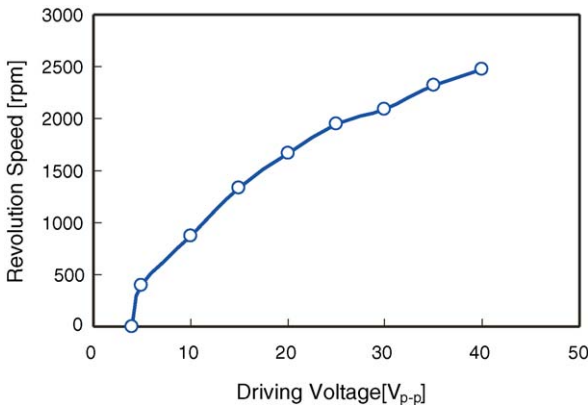


Fig. 16. Relationship between the revolution speed and the driving voltage of micro ultrasonic motor.

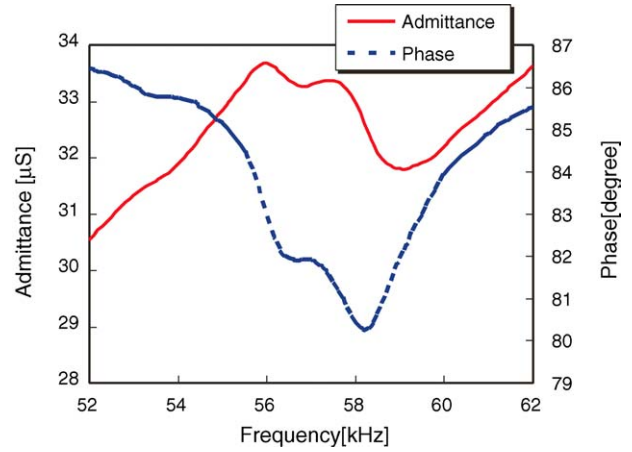


Fig. 17. Relationship between the admittance of transducer B built in the micro motor and the frequency.

tance of transducer A, the value of admittance and  $Q$  factor are diminished in Fig. 17, those of transducer B.

### 6. Evaluation of output torque

The theoretical output torque value of this micro ultrasonic motor can be estimated by using equivalent circuit of transducer.

Fig. 18 illustrates the equivalent circuit. In this figure,  $V$ ,  $F$ ,  $A$ ,  $L_m$ ,  $C_m$  and  $R_m$  mean applied voltage, output force, force factor, equivalent mass, equivalent compliance and equivalent viscoelastic loss, respectively. The mechanical output force at the mechanical terminal in right side of equivalent circuit is obtained by the force factor, the conversion ratio between mechanical part and electrical part, and the applied voltage against the electrical terminal in left side of the circuit. The relationship can be expressed as:

$$F = AV. \tag{1}$$

The force factor  $A$  used in Eq. (1) is derived from the vibration mode and piezoelectric equations [3]. The vibrator used in the experiments is oscillated in its fundamental excitation mode. In addition, the vibrator has a fixed end and a free end. Under this boundary condition, vibration mode can be derived. When  $\lambda$ ,  $l$ ,  $R_o$ ,  $R_i$  and  $e_{31}$  are a constant equivalent to 1.875, the length of vibrator, the outer radius of vibrator, the inner radius of vibrator and the piezoelectric constant, respectively, the force factor  $A$  of transducer can be described as:

$$A = \frac{1}{\sqrt{2}} \frac{\lambda}{l} \frac{(R_o + R_i)R_o e_{31}}{\cos \lambda \sinh \lambda - \sin \lambda \cosh \lambda} \tag{2}$$

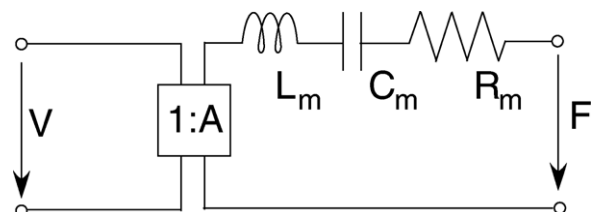


Fig. 18. Equivalent circuit of piezoelectric transducer.

Table 2  
Parameters of transducer

$\lambda$	1.875
Length of vibrator, $l$ (mm)	2.2
Outer radius of vibrator, $R_o$ (mm)	0.4
Inner radius of vibrator, $R_i$ (mm)	0.2
Piezoelectric constant, $e_{31}$ (N/(V m))	-11

From the summarized values in Table 2 and Eq. (2), the estimated force factor  $A$  of transducer is  $3.85 \times 10^{-4}$  N/V.

When the applied voltage is  $40 V_{p-p}$  and the radius of the rotor is 1.0 mm, the estimated output torque is  $7.7 \mu\text{N m}$ . Experimentally, the static torque was 0.3% of this value. Mainly, this difference would be due to the damping of vibration as shown in Section 5.

## 7. Conclusion

We have fabricated micro ultrasonic motor using micro-machined bulk piezoelectric transducer. Cylindrical shaped bulk piezoelectric vibrator, a diameter of 0.8 mm and a height of 2.2 mm, was developed as stator transducer for traveling wave type ultrasonic motor. We have succeeded in driving this motor and could measure some characteristics. The maximum revolution per minute was 3850 at the applied voltage of  $40 V_{p-p}$  and the pre-load of 0.5 mN. We have also evaluated the output torque of the motor. The maximum output torque was  $2.5 \times 10^{-2} \mu\text{N m}$  when the pre-load was 5 mN and the applied voltage was  $40 V_{p-p}$ .

In the evaluation of this paper, the output torque of the micro ultrasonic motor was not enough to drive micro mechanism. The improvement of the pre-load mechanism and contact condition between the rotor and the stator vibrator is important to obtain high output micro ultrasonic motor.

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