Development of Thin-type Ultrasonic Spindle-motors for High-speed Applications

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***Abstract*— Several types of high-speed ultrasonic motor have been proposed and evaluated experimentally by the authors. Usually, high torque at low speed is one of major special features of an ultrasonic motor. However, they have a possibility on high-speed applications. They have advantages of input power and thin structure to ordinal electromagnetic motors. This paper deals with motor constructions and experimental results of performances of some ultrasonic spindle motors. Each motors have good high-speed characteristics are obtained.**

I. Introduction

An ultrasonic motor can produce a high torque at a low speed, so that it is not necessary to use gears, and direct drive is possible. This is one of the major features of an ultrasonic motor (USM). However, if a load is a little light and a constant high-speed revolution is required as uses in a disk drive or a micro fan, high torque is not necessary.

In recent years, the reduction in size of personal digital assistants (PDA), personal computers (PC), and other portable electric equipments has been demanded, and equipped spindle motors are also required to be more compact and improved in performance. In general, a thin electromagnetic d.c. motor (DCM) has been widely used in these applications. However, it is not easy to thin DCMs more than 1mm. Although the miniaturization of a spindle motor has been actively studied, it is not easy to obtain the necessary performance. On the contrary, as there is flexibility in choosing the shape of USM, some types of USM are suitable to be made less than 1mm thickness. Small USMs are able to yield mechanical output power greater than an electromagnetic motor of similar size. These are a large advantage to DCMs.

From the viewpoint of their shapes, USMs can be selected or designed for more suitable applications. If USMs can revolve faster over a long-time continuous operation, its application would spread widely. This study is a response to new challenges of developing a new field of applications of USMs. The above stated backgrounds are the motivation of this study. This paper deals with design concepts and experimental results of some types of our proposed high-speed ultrasonic spindle motors.

II. Concept and Investigated Items

Research projects of thin ultrasonic spindle motor are based on the following design concepts, and several types of a thin USM have been considered as shown in Table I.

1) Small volume, simple structure and simple drive: USMs and its drive circuit used in portable electric equipments are required to reduce their volume as much as possible. Hence a single-phase-drive motor, which needs a simple drive circuit, is suitable for saving an occupied space. Some single-phase-drive motor using a longitudinal vibration or flexural one of the thin plate-type of stator vibrator are proposed and experimented.

2) Low drive voltage (multilayer ceramics): Portable electric equipments require the operation in low drive voltage. Multilayer structure piezoceramics can reduce the drive voltage. A single-phase-drive motor using diagonally symmetrical multilayered ceramic plate is examined.

3) Lead-free ($LiNbO_3$ rectangular plate USM): Ordinal piezoelectric ceramics (PZT) which is widely used in many applications contain lead, but a lead-free will be required in the near future. As one of solution of lead-free, stator vibrators using $LiNbO_3$ which is piezoelectric single crystal are proposed and experimented.

4) New operating principle (Gyro-moment motors): It is not necessary to be particular about a friction drive as an ultrasonic motor. A new operating principle using a gyro-moment generated by vibrations is proposed.

TABLE I
DESIGN CONCEPTS AND MOTORS CONSIDERED IN THIS PROJECT

Concept and Item / Motor types	*1)Simple drive & structure*	*2) Low drive voltage*	*3)Lead free*	*4)New operating principle*
A: PZT plate with shim	◎			
B: Multilayer ceramics	◎	◎		
C: Single crystal ($LiNbO_3$)	◎		◎	
*D:*Gyro-moment motor	○	○	○	◎

Operating principles and examination results of some types of spindle USM shown in Table I are simply described blow.

III. Motor Type A: Annular Plate-Type Spindle USM Using Nonaxisymmetric ((1,1)) Vibration Mode

A vibrating-piece type of ultrasonic motor using a plate vibrator is suitable for obtaining high-speed rotation and can be easily constructed with thickness less than 1mm. For this reason in this study, ultrasonic motors using the thin annular plate stator vibrator of nonaxisymmetric ((1,1)) mode, in which a single vibrating pieces is arranged, are considered. This type of ultrasonic motor has a simple structure, and it can probably be arranged around a rotating shaft more effective than a rectangular plate type ultrasonic spindle motor under the condition of similar output power [1].

A. *Operating principle:*

The stator vibrator using annular plate is designed by the finite element method analysis (ANSYS), as shown in Fig.1(a). Total thickness of this stator vibrator is 0.6mm. Its vibration modes including the movement of a vibrating-piece arranged in the plate are shown in Fig. 1(b). The stator vibrator is composed the piezoelectric ceramics of annular plate form bonded on upper and bottom surfaces of a thin metal plate, and their electrode is divided into two portions of piezoceramics. Poling in the two portions is in thickness direction, but in opposite direction in each portion. Therefore, applying the driving electric voltage of same phase on each electrode, the nonaxisymmetric vibration of ((1,1)) mode shown in Fig. 1.(b) can be driven. At the same time, vibrating-pieces arranged in the inner side of the annular plate vibrator as shown in the same figure, and then elliptic motions yield at the top of pieces. Therefore, such motions make the rotor rotation by picking the rotor with vibrating pieces.

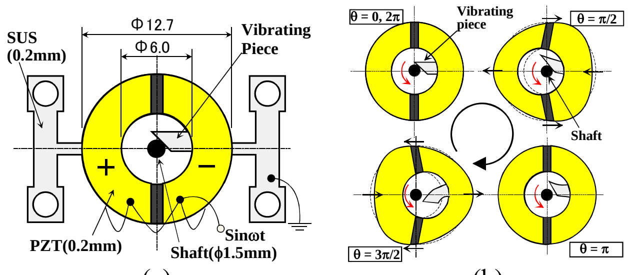


Fig. 1. (a)Construction of a stator vibrator and (b) vibration mode and operating principle.

B. *Measured results:*

This stator vibrator had the resonance frequency of 172kHz and input admittance of 163ms. The stator vibrator is set on the measurement apparatus shown in Fig. 2. It is supported by screws at four end portions of T-type bars of its both sides. Measured characteristics of the prototype motors are shown in Fig. 3. Revolution speed of 6300rpm and input power of 0.91W were obtained under the condition of driving voltage 30$V_{p\text{-}p}$, driving frequency of 170.9kHz.

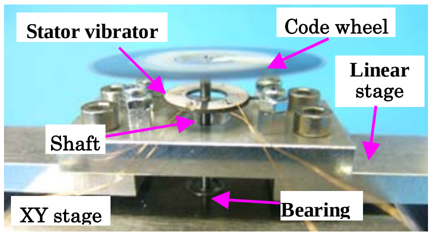


Fig. 2. Measurement apparatus of the ultrasonic spindle motor using an annular plate-type vibrator.

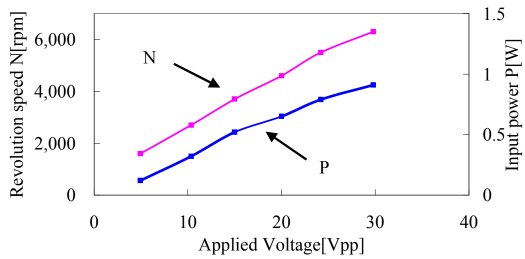


Fig. 3. Measured results of revolution speed and input power to applied voltage.

IV. Motor Type B: Multilayer Piezoceramic Ultrasonic Motor

Ultrasonic motors based on the coupling longitudinal and flexural vibrations using a diagonally symmetric form piezoelectric vibrator has the advantage of realizing a single-phase-drive motor to use the mode-coupling phenomenon [2]. This type of motor consists of a simple plate without electrode division and this is suitable for multilayer vibrator.

A. *Mode-coupled vibrator and its vibration modes*

Figure 4 shows a piezoelectric ceramic multilayer vibrator used in this study, where the vibrator is layered by 12 pieces of thin ceramic plate and its thickness is 2.0mm. Two mode patterns of the vibrations simulated by FEM analysis are shown in the right of Fig. 4.

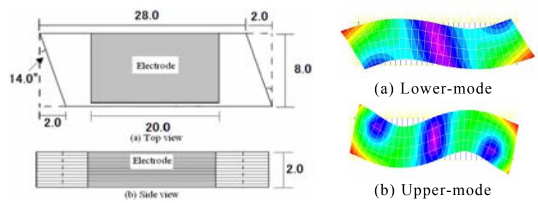
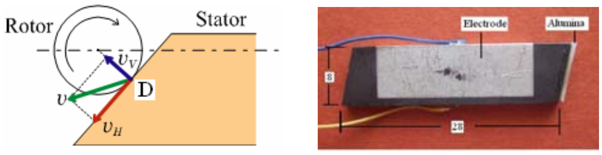


Fig. 4. Diagonally symmetrical multilayer ceramic vibrator and its vibration modes by FEM.

B. *Operating principle and motor construction*

We consider a motor construction that the driving force is delivered form point D shown in Fig. 5(a). When the vibrator is contacted to the rotary shaft, the surface of shaft is pushed in the central and circumferential directions by the vertical and horizontal displacement u_V and u_H at the contact point, respectively, and the shaft can be rotated. The vibrator used in this experiment is shown in Fig. 5(b). Friction material is bonded at the contact surface. The trial motor construction is shown in Fig. 6. The vibrator is supported by a screw at its center, and each long side edge near the top of the vibrator and the bottom side edge are softly hold with supporting jig. The supporting apparatus with the vibrator is attached on a slider table and the center point of the top side edge of vibrator is pressed to a rotor with 3mm in diameter.



(a) (b)

Fig. 5. (a)Operating principle of the trial motor and (b)photo. of its stator vibrator.

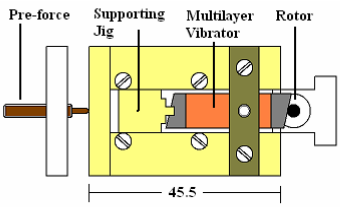


Fig. 6. Trial motor construction.

C. *Operating characteristics of the trial motor*

Figure 7 shows characteristics of revolution speed and input voltage as a function of the input power in the cases of the lower mode and rotor diameter of 1.5mm. The motor rotates smoothly even at high revolution speed. The speed and the input voltage were obtained over 5000rpm and 3.3Vrms, respectively at the input power 400mW. Load characteristics for the lower-mode are shown in Fig. 8. Under the condition of the torque of 1.5mN-m, the input power of 400mW and input voltage of 3V, the maximum efficiency became near 35%. We have confirmed that the motor using a piezoelectric multilayer vibrator is suitable for a high revolution speed motor at low input voltage and has relatively high efficiency characteristic. Load characteristics for the upper-mode were less than those of the lower-mode. In order to improve the operating performance, the motor structure, especially, supporting method of the vibrator must be investigated hereafter.

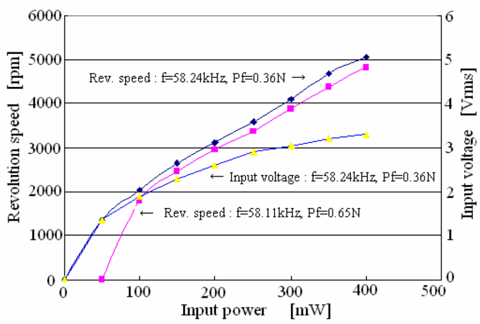


Fig. 7. Characteristics of the motor. (Lower-mode, Rotor diameter:1.5mm)

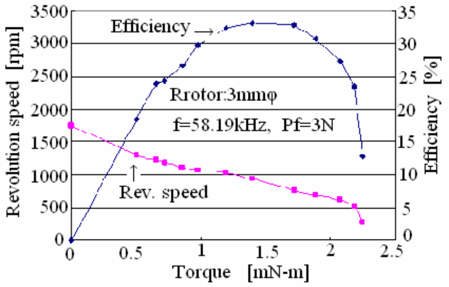


Fig. 8. Load characteristics. (Lower-mode, Rotor diameter: 3.0mm).

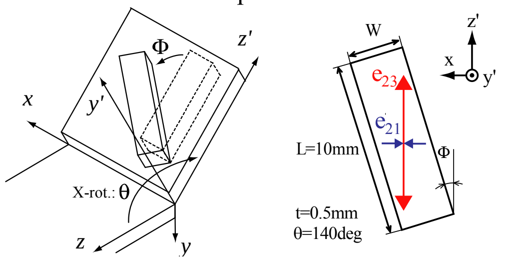
V. MOTOR TYPE C: PIEZOELECTRIC SINGLE CRYSTAL ULTRASONIC MOTOR USING

Several ultrasonic motors using a $LiNbO_3$ crystal vibrator have been proposed before [3]. We newly propose a motor using the mode-coupling of a $LiNbO_3$ rectangular plate vibrator. The crystal anisotropy of $LiNbO_3$ can easily realize mode-coupling in the rectangular-shape.

A. *FEM analysis for vibrator design*

The mode-coupled vibrator is provided from an X-rotated Y-cut wafer with additional rotation Φ in the *y'*-axis as shown in Fig. 9. The width-to-length ratio *W/L* and rotation angle Φ are designed with FEM analysis to obtain a reversible motor.

Figure 10 shows analyzed result of the relationship between the *W/L* and resonance frequency, when the X140°-rotated Y-cut $LiNbO_3$ is used. When the angle Φ=0°, the first longitudinal and second flexural modes appear. Otherwise, for example in Φ=15°, a pair of coupled mode is obtained as shown in Fig. 11. Finally, the vibrator is designed in *W/L*=0.255 and Φ=14°. The center of the end facet is used for a contact point with a rotor.



(a) Cut angle definition (b) Parameters of vibrator

Fig. 9. Design parameter of vibrator.

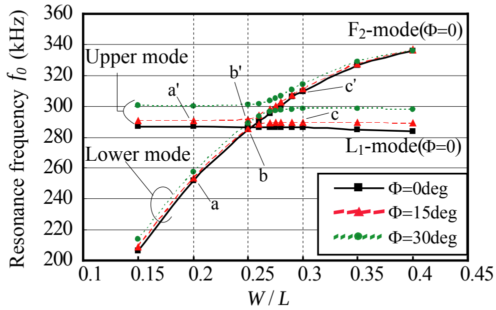


Fig. 10. Analysis result of the resonance frequency correlate with the width-to-length ratio *W/L*.

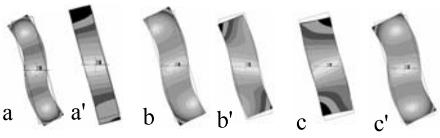


Fig. 11. Resonant vibration mode displacement at Φ=15°.

B. Experimental results of an ultrasonic motor

A stator as shown in Fig. 12 is constructed using the vibrator of analyzed dimension. Metal pins of 0.5mm in diameter are connected to the surface center of the vibrator by the conductive adhesive material for supporting and feeding the electric power. Figure 13 shows that the motor characteristics from the transient response using a rotor shaft of 1mm diameter. Rotations in directions of CW and CCW were obtained by the lower and upper mode, respectively. However, the ranges of preload force which can rotate the motor are different for the each using mode. In order to realize the reversible operation, a mechanical condition of the preload force has to be equal for both rotation directions.

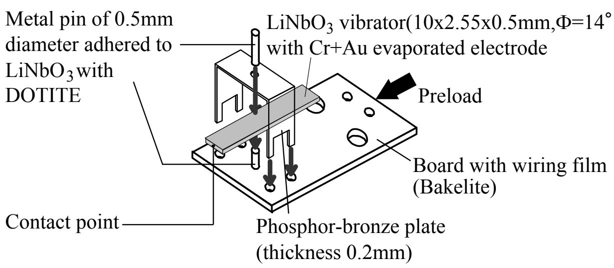


Fig. 12. Support configuration of stator vibrator.

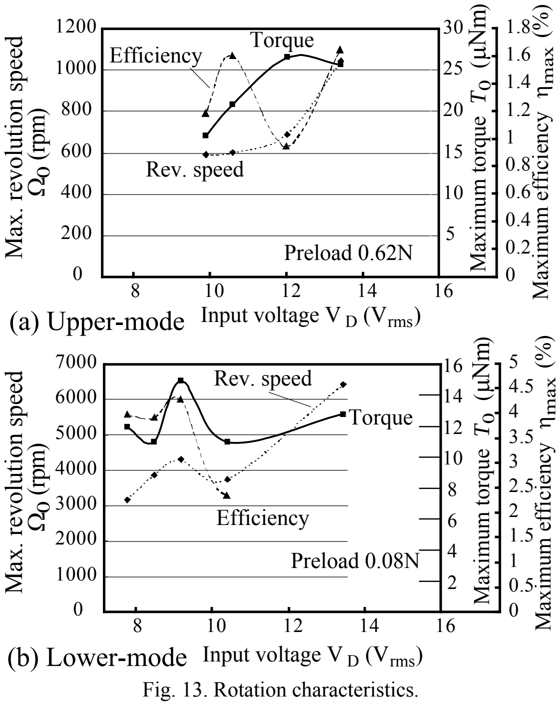


Fig. 13. Rotation characteristics.

VI. Motor type D: Gyro-moment motors

On the gyro-moment motors (GMM), we have already reported their operation principle and some experimental characteristics [4-7]. On account of the limited space, trials of GMM were simply mentioned below.

1) Increases of rotational power of a rotor and revolution speed were proved by the addition of an acceleration function in GMM. In this examination, a rotor was electromagnetically excited at the rotor position detected by an optical sensor. This method can basically be use for GMMs on MEMS using an electrostatic system.

2) As one of applications of GMM, a cooling water pump was examined. It consists of a commercial screw 10mm in diameter connecting to a rod-type GMM. If a micro-screw is provided, its application in the field of biotechnology could expand.

3) Making the most of the operating principle of GMM which is rather interesting and unique, applications into amusements and toys were examined. These applications are now in progress.

VII. Conclusion

High-speed ultrasonic spindle motors using several types of a stator vibrator can be easily realized in an initial level. Considering the practical use of this type of motor, problems concerning durability and stability, which are greatly influenced by the wear of a friction surface, must be solved.

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