*Journal of* ELECTRICAL ENGINEERING, VOL. 58, NO. 3, 2007, 169–172

COMMUNICATIONS

# DEVELOPMENT OF A NOVEL PIEZOELECTRIC MICROMOTOR

**Zhu Hua — He Honglin — Li Huafeng — Zhao Chunsheng** *

A new rod-shaped travelling wave piezoelectric micromotor is developed. In the micromotor, five pieces of piezoelectric ceramics clamped by 2 metal cylinders are used as its stator. The driving principle of the rod-shaped piezoelectric motor is simulated. The stator structure and the position to lay these piezoelectric ceramics are calculated to improve the electro mechanical conversion efficiency. A flexible rotor is designed to reduce the radial slip between the stator and rotor and to improve the motor efficiency. The prototype motor and its micro-driver tested. The motor is 9 mm in out-diameter and 15 mm in length and 3.2 g in weight. When the motor operates with its first bending mode (72 kHz) of the stator, its maximal speed and torque reach 520 rpm and 4.5 mNm. Results show that the motor has good stability. The speed fluctuation is controlled within 3 % by the frequency automatic tracking technique.

K e y w o r d s: piezoelectric motor, micromotor, actuator

## 1 INTRODUCTION

Piezoelectric motors have superior characteristics, such as high torque at low speed, the fast response, simple structure, absence of magnetic interference etc. Because of these advantages, it becomes a good candidate for micro aircraft, medical application and other industrial fields [1]. Piezoelectric ceramics with high energy density are used for the energy conversion from electric to mechanical, so piezoelectric micromotors have higher output power than other types of motors with the same structure size [2]. Therefore piezoelectric micromotors are more suitable for the actuators of micro electro mechanical systems. The micromotor investigation is mostly based on this type in recent years because poling configuration of piezoelectric ceramics of rod-shaped piezoelectric motor is simple.

In 1998, Ref. [3] succeeded in fabricating a cylindrical shaped piezoelectric micromotor of 2.4 mm in diameter and 10 mm in length by using a hydrothermal method. In 2000, a micromotor with the same structure of 1.4 mm in diameter and 5 mm in length was fabricated in Ref. [4]. In 2001, a micromotor of 1 mm in diameter was constructed in Tsinghua University by using a cylindrical piezoelectric ceramic as the stator in Ref. [5]. In 2002, a micromotor of 2.4 mm in diameter was developed in Ref. [6]. This motor used a hollow metal cylinder as a stator, and two rectangular piezoelectric plates perpendicular to each other were bonded on the flat surface on the cylinder. Two bending modes with a certain phase difference and orthogonal to each other can be generated when one ceramic was excited. A piezoelectric piezoelectric micromotor was developed in Ref. [7], using a PZT ceramic and metal composite tube stator that was 1.5 mm in diameter and 7 mm in length.

A new rod-shaped piezoelectric micromotor is proposed in this paper. The driving principle, the structure design and the performance of the motor are discussed.

## 2 STRUCTURE DESIGN

The piezoelectric motor is composed of the rod-shaped stator, the flexible rotor, the shell and other accessories. The 3-D model of this motor is shown in Fig. 1.

Five pieces of piezoelectric ceramics clamped by metallic upper-mass and lower-mass are used as the stator. The depth of the trough on the upper-mass is sensitive to the first bending modal frequency and the harmonic response. The amplitude of response is improved and the modal frequency is reduced by increasing the trough depth. The lower-mass can adjust the mode shape of the stator. The configuration of piezoelectric ceramics is shown in Fig. 2. The bending mode can be excited by one piece of ceramic that was poled in two opposite directions.

When the stator is in resonance, an alternating voltage is produced on the fifth ceramic due to the piezoelectric effect. The amplitude of voltage is linear depending on the output speed of motor, so the voltage can be used as a feedback to keep the speed stability of the motor.

As mentioned above, there is a radial slip between the stator and the rotor. By increasing the flexibility of rotor, the relative displacement between the stator and the rotor is obviously reduced because of the rotor deformation.

## 3 DRIVING PRINCIPLE

The rod-shaped micromotor is worked with bending mode of Langevin vibrator. The amplitude of vibration is much less than the structure size of stator, so assuming

* Research Center of Ultrasonic Motor (RCUM) Nanjing University of Aeronautics and Astronautics (NUAA) Nanjing,Box 359, No.29, Yudao Street, 210016 Nanjing, China; E-Mail: riczhuhua@yahoo.com

ISSN 1335-3632 

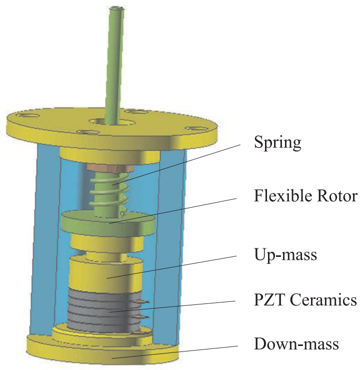


**Fig. 1.** Structure of the micromotor.

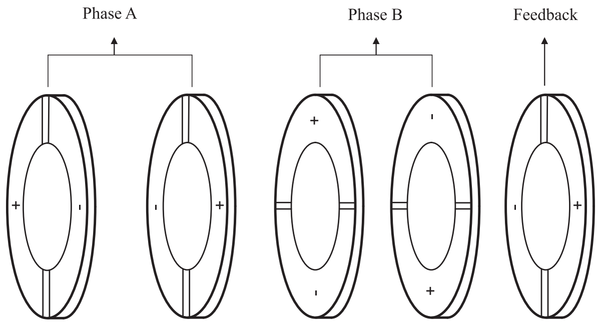


**Fig. 2.** Configuration of ceramics.

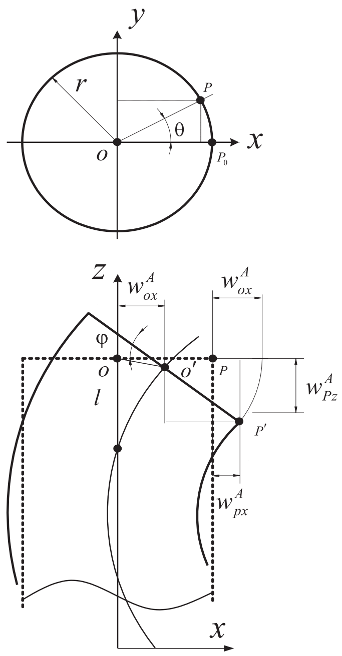

**Fig. 3.** Motion analysis for driving surface.

that no deformation of the contact surface during the vibration period. Figure 3 shows the stator surface reaches its maximum amplitude only when phase A is excited.

Because it is rigid-body motion and $\beta_0$ is very small, the surface is assumed to be moved $w_0$ in $x$ direction and then clockwisely rotate $\beta_0$. Only when phase A is excited, displacements of particle $P$ in $x$ and $z$ direction are

$$\begin{aligned} w_{px}^A &= [w_0 - r(1-\cos\beta_0)]\sin\omega t \approx w_0 \sin\omega t\,,\\ w_{pz}^A &= -r\cos\theta\sin\beta_0\sin\omega t \approx -r\beta_0\cos\theta\sin\omega t \end{aligned} \tag{1}$$

When phase B is excited, displacements of $P$ in $y$ and $z$ direction are

$$\begin{aligned} w_{py}^B &= w_0\cos\omega t\,,\\ w_{pz}^B &= -r\beta_0\sin\theta\cos\omega t\,. \end{aligned} \tag{2}$$

If both A and B are excited at the same time, the displacement of $P$ in $z$ direction is

$$w_{pz} = w_{pz}^A + w_{pz}^B = -r\beta_0(\omega t + \theta)\,. \tag{3}$$

The decomposition of displacement of $P$ in tangential $\tau$ and radial $r$ direction is shown in Fig. 4, the displacement in $\tau$ direction is

$$w_{p\tau} = w_{py}\cos\theta - w_{px}\sin\theta = w_0\cos(\omega t + \theta)\,. \tag{4}$$

The tangential velocity in $\tau$ direction is obtained by the displacement derivative in the tangential direction with respect to time $t$

$$w'_{p\tau} = -\omega\, w_0\sin(\omega t + \theta)\,. \tag{5}$$

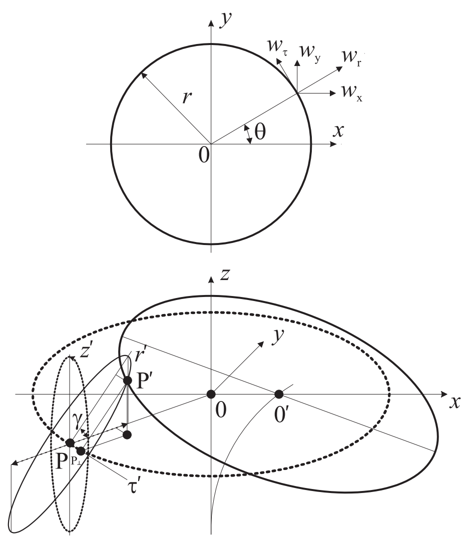

**Fig. 4.** Elliptical motion.

Equations (3) and (5) show that the displacement in $z$ direction of $P$ and its velocity reach maximum amplitude at the same time. Assuming that the rotor is rigid and there is no relative slip between the stator and the rotor, (5) can be used for estimating the output speed of the motor.

The displacement in direction can be expressed as

$$w_{pr} = w_{px} \cos\theta + w_{py} \sin\theta = w_0 \sin(\omega t + \theta)\,. \qquad (6)$$

In the local coordinate system $r'P\tau'$, the track of particle $P'$ is an ellipse

$$\frac{\tau'^2}{w_0^2} + \frac{r'^2}{w_0^2 + r^2\beta_0^2} = 1\,. \qquad (7)$$

An angle $\gamma$ exits between the ellipse plane and the stator surface

$$\tan\gamma = \frac{w_z}{w_r} = \frac{r\beta_0}{w_0}\,. \qquad (8)$$

The elliptical motion can be decomposed to the motion in local coordinate system $z'P\tau'$ and in $r$ direction. Actually it is the elliptical motion in $z'P\tau'$ driving the rotor. The effective elliptical motion can be expressed as

$$\frac{\tau'^2}{w_0^2} + \frac{z'^2}{r^2\beta_0^2} = 1\,. \qquad (9)$$

Figure 5 shows the simulation of the track of 12 particles on the stator surface in one period. It displays the relationship between the elliptical motion of the particle and rocking-head motion of the stator surface. Amplifying the effective elliptical motion and reducing the radial slip between the stator and rotor could improve the efficiency of the motor.

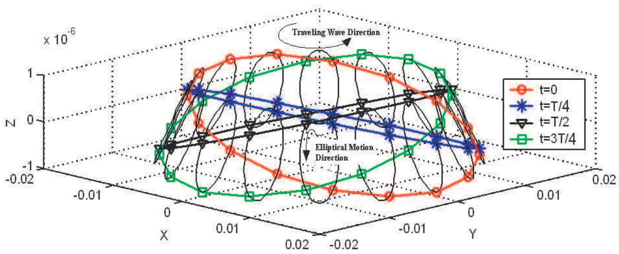


**Fig. 5.** Simulation of the elliptical motion.

## 4 EXPERIMENT AND PERFORMANCE

The amplitude and velocity of the vibration of the assembled stator are measured by Doppler Laser Vibration Meter of Polytec Corporation (PSV-300-B). Magnitude & frequency response characteristics of the stator are shown in Fig. 6. The first bending modal frequency of the stator with free boundary condition in two orthogonal directions is 63453 Hz and 63546 Hz respectively. The mode shape of stator is shown in Fig. 7. The result shows that the velocity and displacement of the driving surface on the upper-mass are much larger than those on the lower-mass through the structural optimal design.

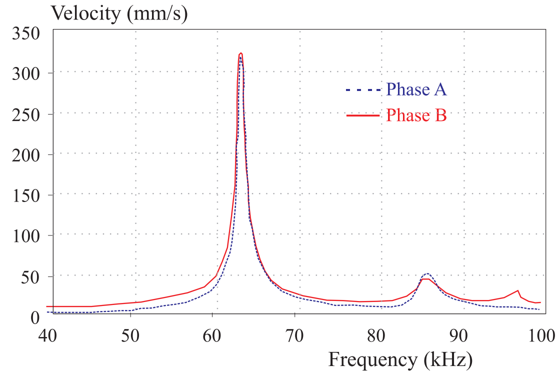


**Fig. 6.** Magnitude & frequency response.

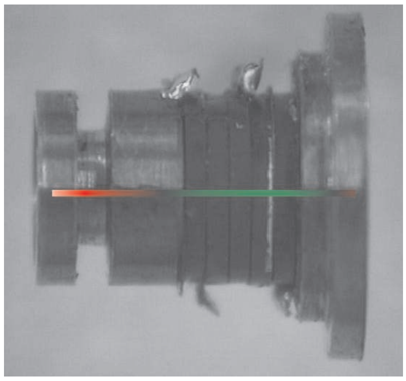

**Fig. 7.** Mode shape of the assembled stator.

According to the structure design, the prototype motor of 9 mm in out-diameter, 15 mm in length, 3.2 g in weight is manufactured. The motor life depends on the abrasion performance of the contact face between the stator and the rotor, so the stator made of stainless steel is coated with a nitride film. The prototype motor and its driver [8] are shown in Fig. 8. The resonance frequency is 72 kHz and the admittance is 0.302 mS. This frequency is higher than that of the stator with free boundary because of two factors: (1) the down-mass of the stator is mounted on the shell instead of free boundary condition; (2) the pre-pressure put on the stator, acting as the modal force, increases the modal stiffness of the stator.

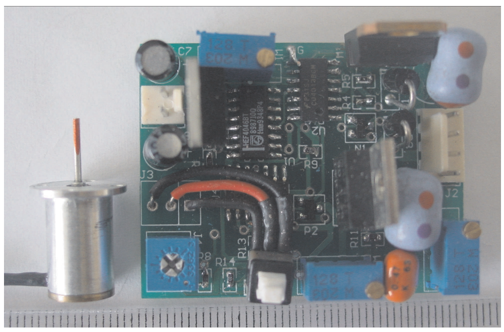

**Fig. 8.** Rod-shaped micromotor and its driver.

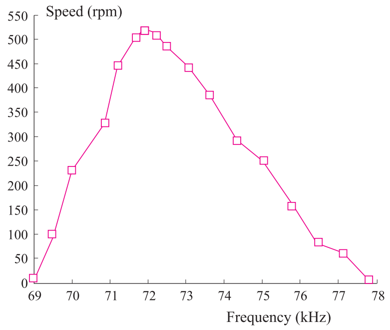


**Fig. 9.** Speed-frequency relation.

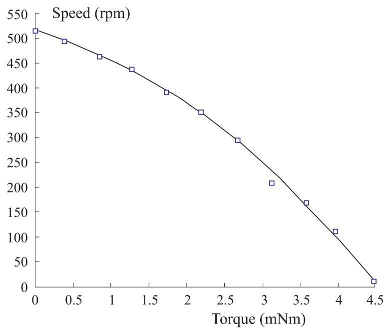


**Fig. 10.** Speed-torque relation.

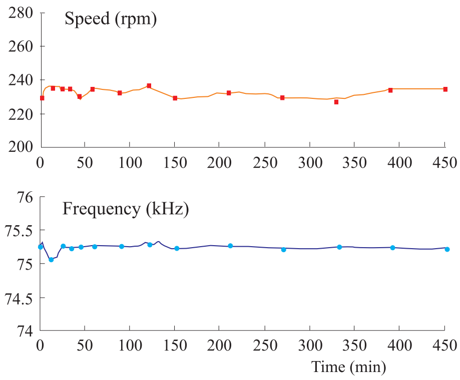


**Fig. 11.** Speed-frequency relation.

Figure 9 shows the rotor speed as a function of the drive frequency. The motor reaches its maximum speed of 520 r/min at the resonance frequency of 72 kHz. Figure 10 shows the speed dependence on output torque and its maximum torque is 4.5 mNm. Its speed fluctuation is controlled within 3 % by frequency automatic tracking technique as shown in Fig. 11.

## 5 CONCLUSION

A compact rod-shaped piezoelectric micromotor is manufactured. The driving principle, structure design, the stator experiment and its performance are introduced. This motor shows good stability in the experiment. It is also suitable for automatic production because of its simple structure.

## Acknowledgement

This work was supported by the Natural Science Foundation of China through Contract No. 50235010 and No. 50407004.

## References

[1] ZHAO, C.: New Development of Piezoelectric Motor in the World, Journal of vibration, Measurement & Diagnosis **24** No. 1 (2004), 1–5.

[2] FLYNN, A,—TAVROW, L.—BART, S.: Piezoelectric Micromotors for Microrobots, Journal of Micro Electro Mechanical System **1** No. 1 (1992), 4450.

[3] MORITA, T.—KUROSAWA, M,—HIGUCHI, T.: A Cylindrical Micro Piezoelectric Motor Using PZT Thin Film Deposited by Single Process Hydrothermal Method, IEEE Transactions on Piezoelectrics, Ferroelectrics, and Frequency Control **45** No. 5 (1998), 1178–1187.

[4] MORITA, T.—KUROSAWA, M.—HIGUCHI, T.: A Cylindrical Shaped Micro Piezoelectric Motor Utilizing PZT Thin Film (diameter 1.4 mm and L 5.0 mm stator transducer), Proc. of Int. Conf. on Solid-state Sensors & Actuators, Transducers 99, 1999 Sendai, 2,1744–1747.

[5] ZHANG, K.—ZHOU, T.: Study on Piezoelectric Cylinder Micro Piezoelectric Motor with 1 mm Diameter, Acta Acustica **29** No. 3 (2004), 258–261.

[6] KOC, B.—UCHINO, K.: A Piezoelectric Motor Using Two Orthogonal Bending Modes of a Hollow Cylinder, IEEE Transactions on Piezoelectrics, Ferroelectrics, and Frequency control **49** No. 4 (2002), 495–500.

[7] DONG, S.—LIM, S.—LEE, K.: Piezoelectric Piezoelectric Micromotor with 1.5 mm Diameter, IEEE Transactions on Piezoelectrics, Ferroelectrics, and Frequency control **50** No. 4 (2003), 361–367.

[8] LI, H.—ZHAO, C.: Micro-Driver for Piezoelectric Motor Based on Complex Programmable Logical Device, J. Electrical Engineering **56** No. 11-12 (2005), 327330.

Received 1 July 2006

**Zhu Hua**, PhD candidate of Nanjing University of Aeronautics and Astronautics, Nanjing, P.R.China. He was born in 1978 and obtained Bachelor's Degree of Engineering at NUAA, 2003. His research field is piezoelectric micromotors and piezoelectric actuators.

**He Honglin**, Associate professor of Nanchang Institute of Aeronautical Technology, Nanchang, China. He was born in 1967 and obtained his Bachelor's Degree of Engineering at HUST, June 1996. His research field is piezoelectric motor and its control system. Li Huafeng, Associate professor of Nanjing University of Aeronautics And Astronautics, Nanjing, China. He was born in 1974 and obtained his Bachelor's Degree and Doctor's Degree of Engineering at HUST, June 1997 and June 2002 respectively. His research field is piezoelectric motor and its control system.

**Li Huafeng**, Vice Professor at Nanjing University of Aeronautics and Astronautics, Nanjing, China. He was born in 1974 and obtained his Bachelor's Degree and Doctor's Degree of Engineering at HUST, June 1997 and June 2002 respectively. His research field is ultrasonic motor and its control system.

**Zhao Chunsheng**, Professor, University of Aeronautics And Astronautics, Nanjing, China. He was born in 1938. He received the bachelor degree in Aerodynamics from the Nanjing University of Aeronautics and Astronautics, China, in 1961, and the Doctor of Engineering from the "Ecole Nationale Superieure d'Art et Métiers-Paris", France, in 1984. He is a senior member of the Review Committee for the Division of Materials and Engineering of the National Natural Science Foundation of China. He also is the Vice-president of the University Association of Mechanical Engineering Measurement Technologies and the chief editor of the Journal of Vibration, Measurement & Diagnosis. His research interests are in the USM techniques and their applications.