Piezoelectric Micromotor Based on the Structure of Serial Bending Arms

Jianhua Tong, Tianhong Cui, Peige Shao, and Liding Wang

***Abstract*—This paper presents a new piezoelectric micromotor based on the structure of serial bending arms. Serial bending arms are composed of two piezoelectric bimorphs with one end fixed and the other end free, driven by two signals of a biased square wave with a phase difference of $\pi/2$. The free end of a cantilever arm will move along an elliptic orbit so that the cantilever is used to drive a cylinder rotor. The rotor's end surface contacts the free end of the cantilever, resulting in the rotor's rotation. There are six serial bending arms anchored on the base. The driving mechanism of the micromotor is proposed and analyzed. A new micromotor prototype, 5 mm in diameter, has been fabricated and characterized. The maximum rotational speed reaches 325 rpm, and the output torque is about 36.5 μNm.**

I. Introduction

Recently, the miniaturization of equipment, such as mini cameras, mini robots, mini secondary planes, etc., has been paid more and more attention. As an important drive unit, the micromotor has been investigated and developed rapidly over several years. Electromagnetic micromotors have been applied to many fields, but they have many technique limits in both manufacturing and miniaturization. Electrostatic micromotors can be very small according to the scaling law. However, their low torque hardly can be used in engineering. Piezoelectric micromotors have many advantages for a variety of applications, such as simple structure, easy and cheap fabrication, quick response, high output torque compared with other micromotors at the same scale and weight, and no electromagnetic induction disturbance without electromagnetic induction force involved [1]–[6].

A new piezoelectric micromotor, with the structure of serial bending arms, is presented in this paper. Six serial bending arms are fixed on a stator, and an elliptic movement of the free end of the beams drives a rotor to rotate. The serial bending arms act as a displacement amplifier, driven by two signals of biased square waves with a phase difference of $\pi/2$. The rotor is driven by the beams via frictional force between the rotating terminal surface of the rotor and the free surface of the arms. Based on this mechanism, a motor with six serial bending arms is constructed. Higher rotational speed and larger torque are obtained, compared with the previous motor arms driven by one signal of a biased square wave with three serial bending arms. The rotation speed is increased from 110 rpm to 325 rpm, and the static torque is increased from 4.5 μNm to 36.5 μNm [7]–[9].

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II. Mechanism and Structure

Serial bending arms are composed of two piezoelectric bimorphs. The free end of serial bending arms, with the other end fixed, will move along an elliptic orbit when the arms are driven by two signals of biased square waves with a phase difference of $\pi/2$, as shown in Fig. 1(a) and (b). At time period 1, because the two electric fields are zero, the serial bending arm will not move. At time period 2, when the electric field of arm 1 is zero and the electric field of arm 2 is positive, the serial bending arm will bend to the right. At time period 3, when the electric field of arm 1 is negative and the electric field of arm 2 is positive, arm 1 bends to the left and arm 2 bends to the right. At time period 4, arm 1 bends to left and arm 2 keeps its shape. In a cycle, as a result of the electric fields and inertia, the free end of the serial bending arm can move along an elliptic orbit and drive a rotor contacted with the free end to rotate [6], [7].

There are six serial bending arms anchored on the base. Half of them are classed into group 1 and driven by signal 1. The others are classed into group 2 and driven by signal 2, as shown in Figs. 1 and 2. There is a phase delay of $\pi/2$ between these two signals. While group 1 is at their driving stages, group 2 is free, and vice versa. In this way, the six serial arms can drive the rotor to rotate continuously and stably. The rotor can not only rotate along the axis, but also vibrate up and down.

The structure is illustrated in Fig. 3. Six serial bending arms are inserted in the six grooves on the cylinder base. Each serial bending arm is formed by linking two bimorphs. Serial bending arms are to drive the rotor to rotate by the frictional force between the rotating terminal surface of the rotor and the surface of the beams.

The driving and control circuit is composed of a square signal generator and an amplifier. The signal generator generates four routes of square signals with phase differences of $\pi/2$ by phase shift. The amplifier takes the square signals as gates and controls the frequency of the driving voltage. The driving voltage can be adjusted from 0 $V_{p\text{-}p}$

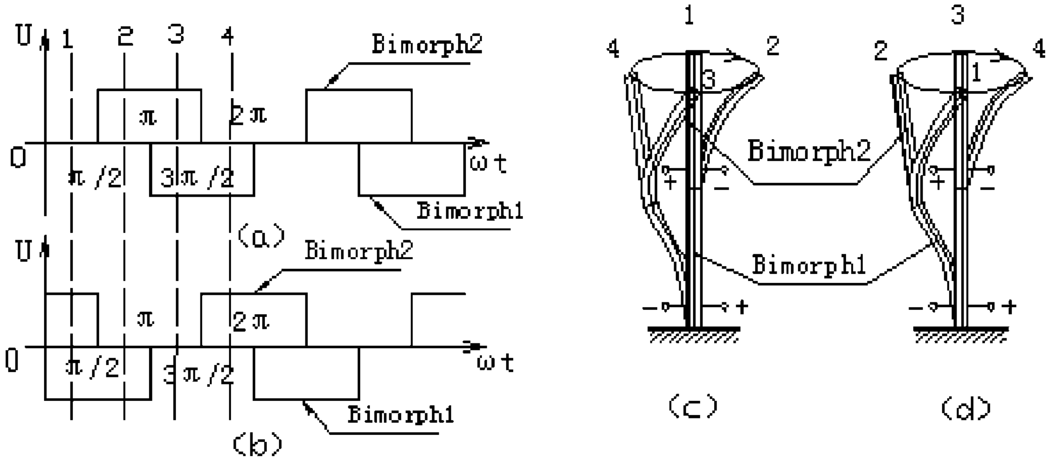


Fig. 1. Working principle of two groups of serial bending arms. (a) Driving of group 1 arms. (b) Driving of group 2 arms. (c) Movement of group 1 arms. (d) Movement of group 2 arms.

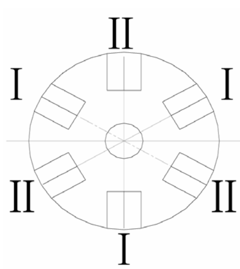
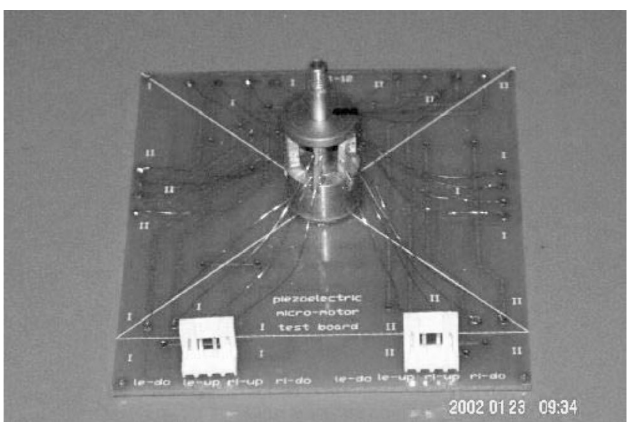
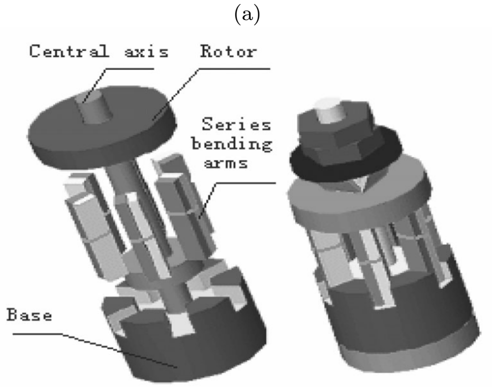


Fig. 2. Top view of six serial bending arms.



(a)



(b)

Fig. 3. The structure of the piezoelectric micromotor.

TABLE I
MAIN PARAMETERS OF PZT-5 PIEZOELECTRIC CERAMICS.[1]

K_{31}	d_{31} (10^{-12} C/N)	f_m (C/S)	f_n (C/S)
0.28	170	115,500	119,000

[1] K_{31} is the electromechanical-coupling coefficient. d_{31} is the piezoelectric constant (m/v), f_m is the maximal admittance frequency (Hz), f_n is the minimal admittance frequency (Hz).

to 300 $V_{p\text{-}p}$, and the driving frequency can be adjusted from 0 Hz to 20 kHz.

III. Fabrication

The stator of the micromotor consists of a substrate with six grooves and six piezoelectric ceramic serial bending arms. Each serial bending arm has a dimension of 0.8 mm wide, 0.9 mm high, and 6.4 mm long, and consists of alternating PZT blocks and silver electrodes. Six serial bending arms are inserted in the six grooves, and fixed to the stator by epoxy. A central shaft is inserted into the stator's hole. The edge of the center shaft also can make the six serial bending arms arrange more accurately. The leads are welded onto the electrodes directly by precision welding. The rotor is a circular plate with a hole in the center. The rotor and the stator are made of copper, and the stator is fixed onto a printing circuit board, as shown in Fig. 3. The material parameters of the PZT piezoelectric ceramics are listed in Table I.

IV. Experiments

Rotational speed, torque, and efficiency are the main factors to evaluate a micromotor. Driving voltage and frequency are the main factors to determine the rotational speed and output torque of a micromotor. Because the

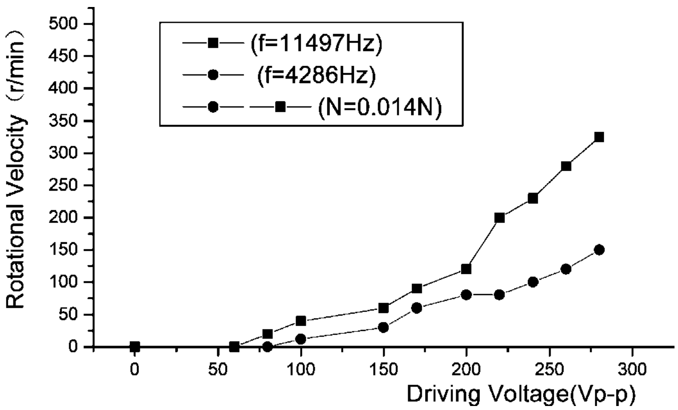


Fig. 4. Relationship between the rotational speed and the driving voltage without external load.

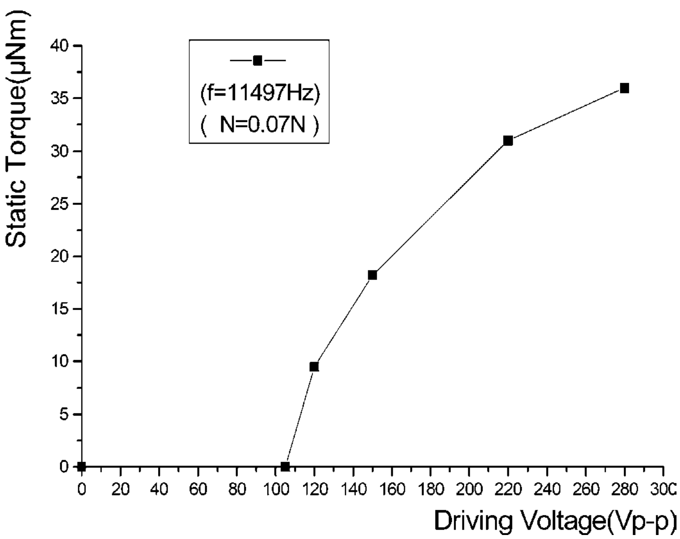


Fig. 5. Relationship between the static torque and the driving voltage.

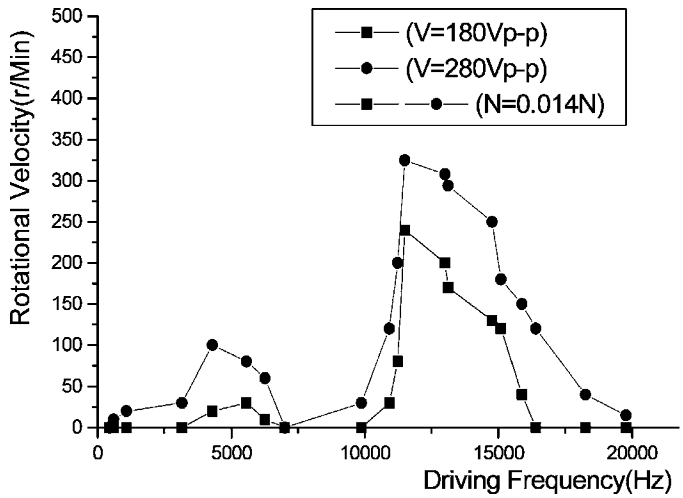


Fig. 6. Relationship between the rotational speed and the driving frequency with external load.

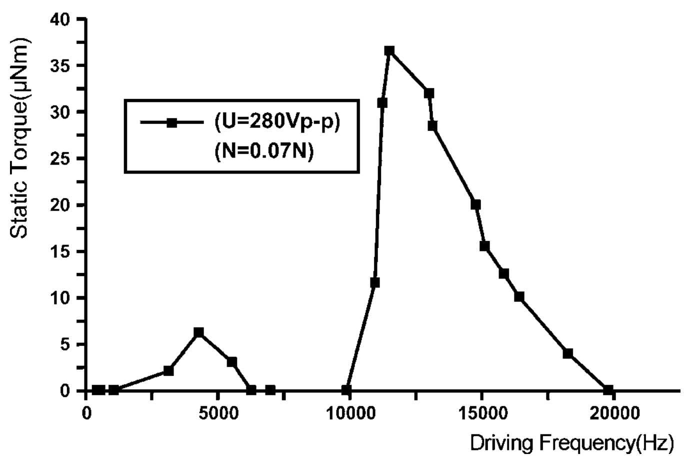


Fig. 7. Relationship between the static torque and the driving frequency.

bending arms vibrate, the free ends of the arms will reach the maximal vibrational displacement when they are working under resonance. The experimental characteristics of the piezoelectric micromotor are presented in the following.

Figs. 4 and 5 show that the rotational speed and output torque are approximately proportional to the driving voltage.The driving voltage is limited to 300 $V_{p\text{-}p}$ to avoid the breakdown of the piezoelectric bimorphs. The driving frequency affects the output very much, as shown in Figs. 6 and 7. When the serial bending arms are at resonance, the micromotor can achieve better performance. The maximum speed without an external load is 325 rpm when the driving voltage is 280 $V_{p\text{-}p}$ and the driving frequency is 11,497 Hz. The contact force between the rotor and the beams is 0.014 N. Under the same conditions except a pressure of 0.07 N, the micromotor's output torque reaches its maximum of 36.5 μNm. This indicates that the maximum output torque of a piezoelectric micromotor based on the serial bending arms can be obtained at the resonant status of the serial bending arms. When the beams are under their resonance, the beams can get their maximum output displacement and driving force, which can transform to the output power ultimately. The relationship between the rotational speed and the output torque is shown in Fig. 8. It indicates that the rotational speed is inversely proportional to the output torque approximately. The rotational speed increases and the torque decreases. Fig. 9 shows the relationship between the efficiency and the output torque. When the output torque is half of the maximal torque, the efficiency reaches its maximum of 3.45%. The average efficiency of the piezoelectric micromotor is low due to the low electromechanical-coupling coefficient of the piezoelectric ceramic and the manufacturing error of the micromotor. High output efficiency probably can be achieved through selecting the piezoelectric bimorphs with high electromechanical-coupling coefficient and improving the precision of manufacturing. The contact force between the terminal surface of the rotor and the surface of the beams plays an important role in the output of the

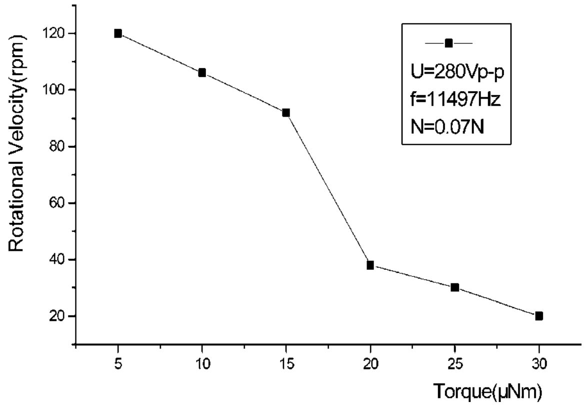


Fig. 8. The relationship between the rotational speed and the output torque with a fixed driving frequency of 11,497 Hz and a driving voltage of 280 Vp-p.

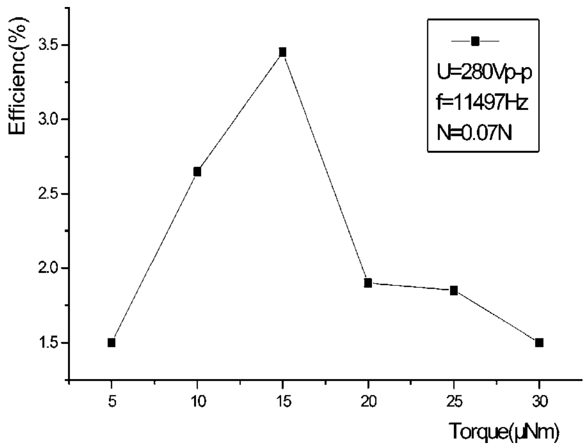


Fig. 9. The relationship between the efficiency and the output torque with a fixed driving frequency of 11,497 Hz and a driving voltage of 280 Vp-p.

micromotor. Excessive pressure will confine the movement of the rotor, and too little pressure obviously will reduce the driving capability. In this experiment, a proper contact force of 0.07 N was selected.

V. Conclusions

In this paper, the driving mechanism of the piezoelectric micromotor based on serial bending arms was proposed. The serial bending arms as well as the driving circuit of a piezoelectric micromotor prototype, 5 mm in diameter, are designed and fabricated. The experimental characteristics were obtained and discussed. The maximum rotational speed without an external load is 325 rpm, and the maximum static output torque is 36.5 μNm. This type of piezoelectric micromotor can be further developed to meet a variety of applications in the future.

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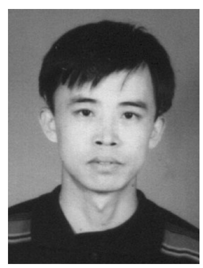

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