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# Study on precision piezoelectric rotary step motors with inner anchor/loosen and outer drive

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**Abstract** A new precision rotary piezoelectric (PZT) actuator is proposed to improve its drive performance. Based on piezoelectric technology, the actuator adopts the principle of bionics, with a new method of stator inner anchor/loosen/rotor outer drive and a distortion structure of a thin shelf flexible hinge. This structure improves the stability of the anchor/loosen and step rotary. Its characteristics are evaluated by finite element analysis. The experiment shows that the new rotary PZT actuator works with higher frequency (40 Hz), higher speed (325  $\mu\text{rad/s}$ ), wider movement ( $360^\circ$ ), high resolution (1  $\mu\text{rad/step}$ ) and high torque (30 N·cm). The novel actuator can be applied in wide movement and high resolution driving devices such as those for optics engineering, precision positioning and some other micro-manipulation fields.

**Keywords** piezoelectric element, stator inner anchor/loosen, rotor outer drive, thin shelf flexible hinge, resolution

## 1 Introduction

With the recent development of micron and nanotechnology, driving accuracy is now required to reach a nanometer level. Super precision drives at sub-micron, micron and nanometer levels are urgently required in many fields such as optics engineering, microelectronics manufacture, aeronautics and astronautics, super precision mechanics fabrication, micro-robots, earthquake monitoring, biology, physics, genetics and other engineering fields. Under this context, the precision piezoelectric (PZT) driving motor characterized by high-level driving is developed [1–6].

The PZT material has stable output displacement with nanometer-level accuracy during driving. Moreover,

piezoelectric driving features good linearity, convenient control, high resolution, good frequency response, no heat generation, no magnetic disturbance, and no noise. In addition, the piezoelectric driving motor is small, light and high-powered [7–9]. Therefore, super precision driving can be better realized by adopting the piezoelectric actuator.

Using the stator inner anchor/loosen to realize step-by-step revolution motion is new in this field. The machine with four thin shelf flexible hinges can transform the linear movement of the PZT ceramics into rotary movement. High precision rotary step movement is achieved through anchor/loosening and driving, which is called bionic movement [10,11]. The motion structure sheds light on research on the precision PZT rotary step motor.

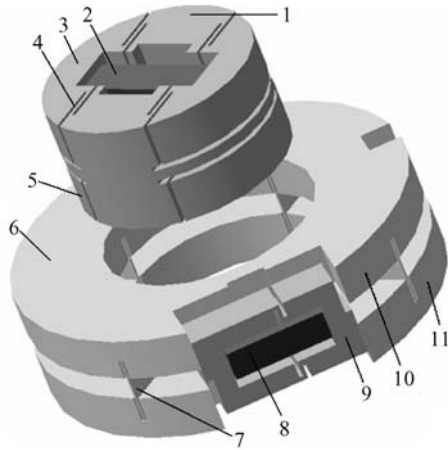
## 2 Structure and principle

The structure of the precision PZT rotary step motor with inner anchor/loosen is shown in Fig. 1. The motor consists of the stator anchor/loosen, the rotor, the driving PZT ceramics joint, the anchor/loosen PZT ceramics element and the driving PZT ceramics element. The stator anchor/loosen consists of an upper stator part and a lower stator part. The upper stator part of the anchor/loosen is connected with the upper rotor, while the down stator of the anchor/loosen is connected with the nether rotor. Four evenly distributed thin shelf flexible hinges link the upper rotor with the nether rotor. Driving PZT ceramics denoted by 8 is installed on the driving PZT ceramics joining denoted by 9. One side of the driving PZT ceramics joining touches the upper rotor, while the other side touches the nether rotor. There is a flexible hinge in the joining. The working principle of the motor is as follows:

1) In the original state, the PZT ceramic 2 and the PZT ceramic 8 have a free shape. The nether anchor/loosen PZT ceramic, which is not shown in Fig. 1 and connected with Part 5, is galvanized. Part 5 then anchors fast to Part 11.

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**Fig. 1** Structure of PZT motor.

1–anchor/loosen part; 2–upper anchor/loosen PZT ceramics element; 3–upper anchor/loosen part; 4–anchor/loosen flexible hinge; 5–lower anchor/loosen part; 6–rotor; 7–rotary thin shelf hinges; 8–driving PZT ceramics element; 9–driving PZT ceramics element joint; 10–upper rotor; 11–lower rotor

2) Because the nether rotor is fixed, when the driving PZT ceramic 8 is galvanized and elongated, the upper rotor 10 revolves clockwise at an angle  $q$  based on the hinge's elasticity in the joining 9.

3) The upper anchor/loosen PZT ceramic 2 is galvanized, then the anchor/loosen 3 anchors fast to the upper rotor 10.

4) The nether anchor/loosen PZT ceramic turns to be free from anchor/loosening, separating Part 11 from Part 5.

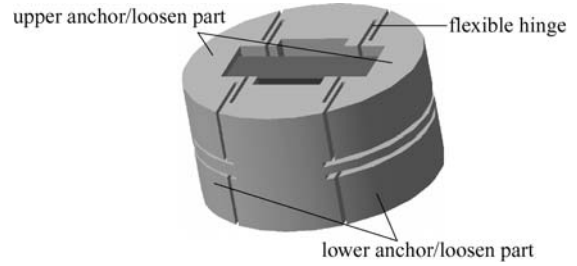
5) The driving PZT ceramic 8 is loosened, then the nether rotor 11 revolves clockwise at an angle  $q$  based on the hinge's elasticity and the nether anchor/loosen PZT ceramic restarts to anchor/loosen. Thus, it completes a circular movement and the organization rotates by one step clockwise. By repeating the step, the precision motor may realize a clockwise step-by-step revolution continuously. According to the same principle, it may also realize a counter-clockwise rotation.

### 3 Working process and analysis

#### 3.1 Anchor/loosen analysis

The stator anchor/loosen structure of the precision piezoelectric rotary step motor with inner anchor/loosen and outer drive is shown in Fig. 2. The upper and lower anchor elements are designed with bilateral thin flexible hinges, which can decrease the anchor/loosen disturbance and ensure that the thin flexible hinge elongates only in the direction of the piezoelectricity element; elongating in other directions prevents the processing of added torque on the stator. In practice, there will be no gap, or only a very small

gap between them because the stator element contacts the rotors. Therefore, the thin flexible hinges are hardly distorted and only transfer the anchor/loosening power.



**Fig. 2** Stator structure of PZT motor

In the process of step driving, anchor/loosen performance directly affects the step motion. The anchor/loosen performance parameter involves anchor power  $F$ , anchor response frequency  $f_1$  and anchor stability parameter  $S$ . A large  $F$  results in stable anchoring, and a high  $f_1$  leads to sensitive anchoring. Therefore, the motor can work with high frequency and speed. The anchor stability parameter  $S$  affects the anchor process to the extent where the anchor process does not produce added torque, thus improving the step repetition. The  $S$  can be denoted by the anchor/loosen error.

For the static and dynamic analyses of the anchor/loosen system, we assume that the anchor power  $F$  is constant. The mass of the anchor/loosen is  $M$ . Based on the material mechanics, the anchor element can produce a displacement under  $F$ :

$$S = \frac{F_f l_1}{48EI} \tag{1}$$

The inherence frequency of the anchor/loosen system is:

$$\omega_n = \sqrt{\frac{48EI}{\left(M + \frac{34pl_2}{35}\right)l_1^3}} \tag{2}$$

where  $EI$  is the thin flexible hinge cross-section resisting curved stiffness modulus and  $M$  is the mass of the anchor element.

Under preconditions when the anchoring is stable and rigid enough, the inherence frequency of the system can be improved if we reduce  $M$  to a maximum and use materials with appropriate  $EI$  and structure. The resisting curved power  $F_e \ll F$  due to the effect of the thin flexible hinge section.  $F$  effectively operates on rotors, and then the friction anchoring power  $F_f$  is induced:

$$F_f = K_s(F - F_e) \approx K_s F \tag{3}$$

The anchoring torque  $M_f$  is induced:

$$M_f = F_f r, \tag{4}$$

where  $K_s$  is the static friction coefficient between the stator and the rotor;  $r$  is the stator radius. In the working process, three factors should be carefully considered:

- 1) The preload  $F_p$  of the PZT ceramics.
- 2) The connection fastness degree between the PZT ceramics and the anchor element.
- 3) The interval between the stator and the rotor.

The response frequency of the PZT ceramic element is very high (10 kHz). By making the inherence frequency of the anchor/loosen mechanism structure as high as possible, the response frequency  $f$  of the whole system will be improved. In addition, the anchor/loosen system's practice frequency  $f_1$  is consistent with  $f_2$  of the rotor system. Thus, the anchor/loosen structure design inherence frequency is consistent with the rotor structure design inherence frequency.

By analyzing the anchor/loosen structure on the basis of the finite element method (using Ansys 8.1 software), a distortion figure is obtained as shown in Fig. 3. The finite element model adopts the three-dimensional tetrahedron units named SOLID45. There are 50221 nodes and 36118 units in the finite element girding model. The joint in the flexible hinge and anchor/loosen is an immobility link, and the anchor/loosen structure is made of spring steel. The inherence frequency  $f_b = 350$  Hz, while the displacement  $\delta_A = 5.2 \mu\text{m}$ . The results from the finite element model (FEM) test are similar to those of theoretical analysis.

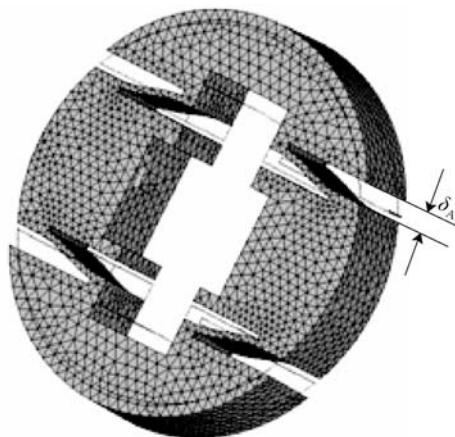


Fig. 3 FEM Displacement of stator mechanism

### 3.2 Rotation analysis

The rotor structure is shown in Fig. 4. The rotor consists of an upper rotor, lower rotor and four thin flexible hinges evenly distributed on the circle, which ensure that the upper and the lower rotor rotate around the rotor center. The driving PZT element joint touches the upper rotor on one side and the lower rotor on the other side. When the PZT element is energized and elongates, the left part presses the upper rotor and the right part presses the lower part. The four thin flexible hinges and the joint part flexible hinge

function as an elasticity restoration when the driving PZT ceramics element is drawn back. In addition, the joint part is good for protecting and pre-loading the driving PZT ceramics element. In the case of the smallest interval between the rotor and the stator and the rotor can rotate freely, high surface precision between the rotor and stator is needed. The rotor is the power take-off point and the driving part of the rotary step motor, of which driving parameters include step angle  $\Delta\theta$ , availability press  $F_e$  and angle frequency  $\omega_n$ . The step angle is related to the structure dimension, the flexible stiffness modulus, and the PZT ceramics element elongation. The step angle  $\Delta\theta$  is induced:

$$\Delta\theta = \frac{\Delta l}{\sqrt{\left(\frac{t}{2}\right)^2 + l_B^2}} \frac{180^\circ}{\pi}, \tag{5}$$

where  $\Delta\theta$  is the step angle ( $^\circ$ ),  $\Delta l$  is the displacement of the PZT ceramics element,  $t$  is the ceramic length (m), and  $l_B$  is the distance from the ceramic's centre to the hinge's centre (m).

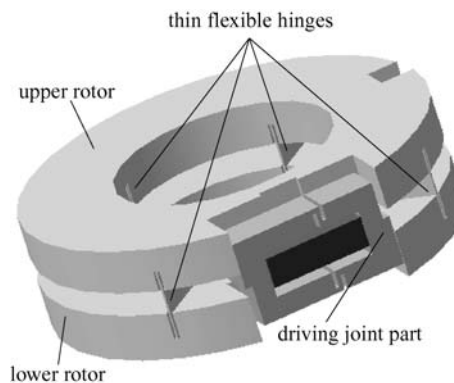


Fig. 4 Structure of rotor

It is important that the upper and the lower rotor rotate around the center axis in a micro-angle, which can be validated through the static analysis of the anchor/loosening structure based on the finite element method (using Ansys 8.1 software). Figure 5 is the analysis model result of the rotor structure.

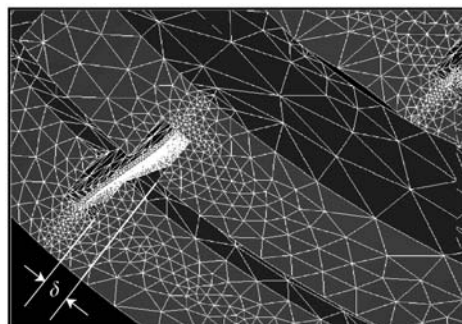


Fig. 5 FEM distortion of rotor

The lower rotor is tooted. By increasing pressure  $F$  on the left side of the PZT element, the distortion of the thin flexible hinges and the rotated displacement  $\delta$  are shown in Fig. 5. By finite element analysis of the element distributed on the circle around the rotor, the analysis point is distributed on the place before the distortion, proving that the rotor is rotating around the center axis. A different rotated displacement  $\delta$  can be obtained with a different pressure  $F$ , and their relationship is expressed as:

$$F_e = F - F_w = (K_S + K_R)\delta, \quad (6)$$

where  $F$  is the press of the PZT element produced,  $F_w$  is availability output load,  $K_S$  is the estimate/d spring modulus of the joint thin flexible hinge,  $K_R$  is the estimate/d spring modulus of the rotor thin flexible hinge, and  $\delta$  is the rotated distortion displacement of the rotor.

Rotary step driving is a complicated process that includes the response of the PZT element, the acceleration of the output load, and the inner energy wastage, where the estimate spring modulus  $K_R$ , the availability press  $F_e$ , and the availability output load  $F_w$  are adopted to denote the system. When the rotor rotates, the driving PZT element should have the same frequency as that of the anchor/loosen part. Therefore, it is important to increase the inherence frequency of the rotor system to increase the frequency of the whole system. The frequency of the stator is unchanged, but the frequency of the rotor changes with the output load. Based on the material mechanics and vibration kinetics, the frequency of the rotor is

$$\omega_n = \sqrt{\frac{K_S + K_R}{M + M_w} + \frac{2F_0}{(M + M_w)e}}, \quad (7)$$

where  $M$  is the availability mass of the upper rotor and the joint;  $M_w$  is the mass of the outer load;  $F_0$  is the preload on the PZT element; and  $e$  is swing of the rotor.

In the design of the rotor, when ensuring the stiffness and the displacement, it is important to increase the availability spring modulus  $K_S$  and  $K_R$ , while decreasing  $M$ .

#### 4 Rotary step motor control system

The control and measure system is shown in Fig. 6. As the core of the whole system, a PC controls all movement. The PC transforms digital signals into analog signals by three D/A channels to control several electrical sources. Three different sequence electrical sources enable perfect harmony between the 2 anchor/loosen PZT ceramic elements and 1 driving PZT ceramic element. In the control system, the PZT element is the capacitance part, which must be designed with a high frequency discharge circuit to discharge the PZT element. In addition, the system has precision displacement measuring equipment. Therefore, the measured data can be sent to the PC and processed in detail.

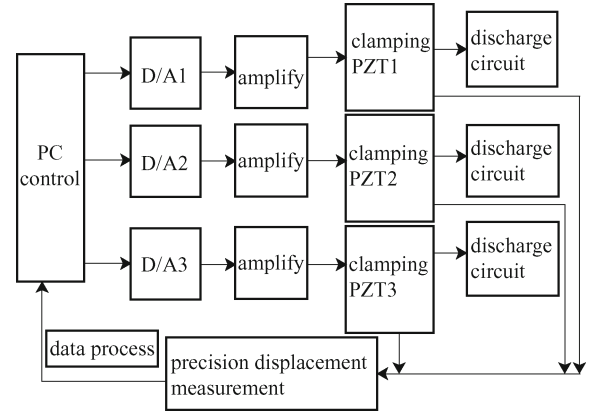


Fig. 6 Principle of control system

Electrical source signals for driving in perfect sequence are very important for the motion of the system. The phase relationship of the sequence signals from three lines is shown in Fig. 7. The first and the third lines are the anchor/loosening PZT signals and the second line is the driving PZT signals. The lines of the sequence signals are trapeziform, which may eliminate the impingement noise induced by the electrical source signals on the upper and lower edge by suddenly changing and protecting the PZT driving components. This then extends the life of the PZT ceramics. When designing the control signals, the sequence distribution of every part should be sufficiently considered. A circle  $T$  is divided into six parts and every part is  $t = T/6$ . The upper edge and the lower edge of the electrical source signal respectively takes  $\Delta t$ ,  $\Delta t \approx t/4$ . The average low voltage (blackout) time of the anchor/loosening voltage signal is  $2t$ ,  $2t = T/3$ . The average high voltage (electricity) time is  $4t$ ,  $4t = 2T/3$ . The high voltage time is equal to the low voltage time; they respectively take upper  $T/2$ . The time sequence of the left and the right voltage signals differs by  $3t$ .

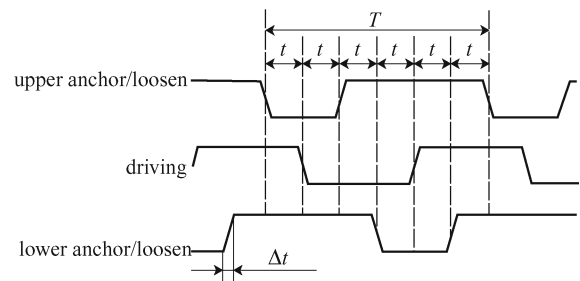


Fig. 7 Sequence control system

### 5 Experiment and measurement

#### 5.1 Equipment

The precision PZT rotary step motor is manufactured and the photo of its inner structure is shown in Fig. 8. A JPC

integrated precision generator, an LC2400A non-contact precise laser measuring instrument, an HPC series PZT ceramic driving electrical source, and a precise air floating vibrating isolation platform are used in the experiment. In the experiment, the laser of the laser measuring instrument is focused on the mobile's surface, making it stable. The rotation displacement can be obtained.



Fig. 8 Inner structure of PZT motor

### 5.2 Step resolution measurement

Resolution, as a key criterion index for the precision step motor, refers to the least step displacement for one step when the motor steps. The motor's resolution graph is shown in Fig. 9. As shown in Fig. 9, the resolution is about  $1 \mu\text{rad}$  when the driving voltage is 5 V and increases with increasing voltage. When the driving voltage is less than 5 V, there is no angular displacement. Thus, the resolution is the maximal resolution when the driving voltage is 5 V. Therefore, the 5 V driving voltage is called stoppage driving voltage.

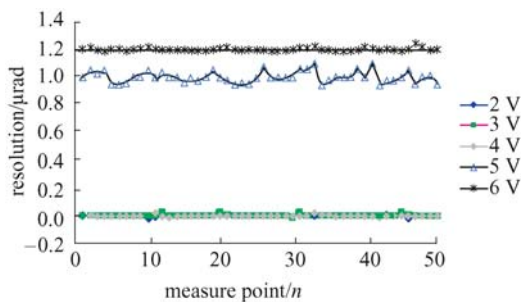


Fig. 9 Resolution test

### 5.3 Anchor/loosen force and anchor/loosen stability measurement

The measurement curve of the anchor/loosen force  $N_f$  is shown in Fig. 10. The maximal data of the system's  $N_f$  reaches 2.3 N·m in the test. Furthermore, the maximal anchor/loosen torque has an almost linear relationship with the anchor/loosen voltage. In reality,  $N_f$  reaches 1.5 N·m when the anchor/loosen voltage is 70 V and the anchor/loosen torque can meet the basic need.

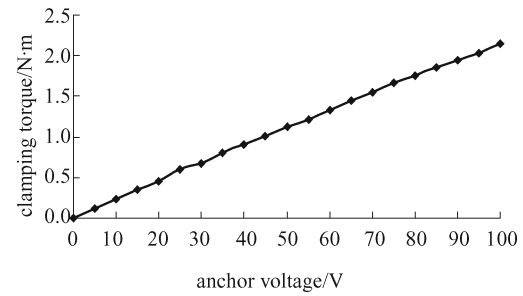


Fig. 10 Anchor/loosen force test

The anchor/loosen stability affects the step displacement of the rotor, which is called the anchor/loosen error. The result of the anchor/loosen error from the experiment is shown in Fig. 11. In the figure, the average step displacement is obtained from 100 measurement data at every voltage. The data in the figure show that the maximal anchor/loosen error is  $0.01 \mu\text{rad}$ , which emerges on special measurement points. Furthermore, the anchor/loosen error will increase with increasing voltage. However, it can be concluded that the anchor/loosen process hardly affects the rotor. Therefore, the anchor/loosen process is stable.

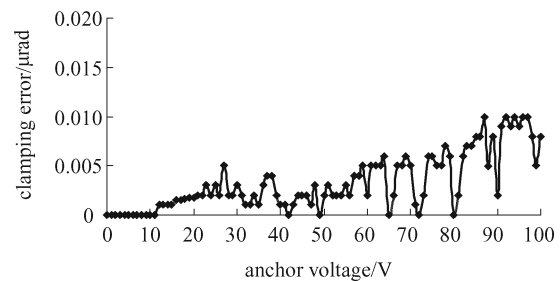


Fig. 11 anchor/loosen error test

### 5.4 Rotary step velocity measurement

The velocity of the precision PZT rotary step motor with inner clamp and outer drive is decided by the driving voltage and the step frequency. The connection among them is shown in Fig. 12. The voltage-velocity curve in several different frequencies in Fig. 12 is obtained under the unloaded status. As shown in Fig. 12, the velocity reaches  $325 \mu\text{rad/s}$  when the step frequency is 40 Hz and we can change the frequency and the voltage to get a different velocity. In addition, the slope of the PZT ceramic's closed curve is increasing and that of the voltage-velocity curve is decreasing with an increase of voltage. This happens because the additional load is engendered when the flexible hinge's distortion is increased, which is induced by the increasing step displacement and driving force of the PZT element.

### 5.5 Continuous step torque measurement

The continuous output torque is the key criterion index for the precision rotary step motor. Figure 13 shows the

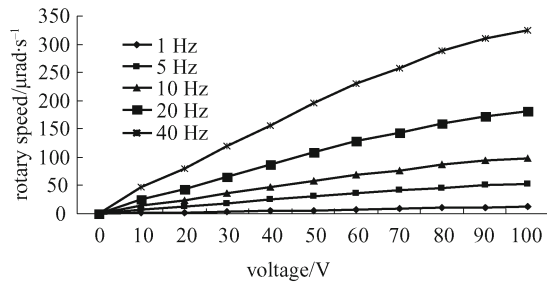


Fig. 12 Voltage-velocity curve in different frequencies

connection among the output angular displacement, output torque and the driving voltage. As shown in Fig. 13, under a settled voltage, the force impact hardly affects the displacement within a load range and the displacement has a slight downtrend when the load exceeds the range. In the experiment, with voltage 100 V, the load affects the displacement inconspicuously when the load  $M < 30$  N·cm, but the output displacement declines rapidly when the load exceeds a range. This is because the anchor/loosen force cannot handle the counterforce from the driving PZT ceramic to the anchor/loosen when the output load reaches a certain degree, at the same time the foul-up step emerges. It can be seen from the curve in the figure that under voltage 100 V, the angular displacement is relatively stable when  $M < 30$  N·cm.

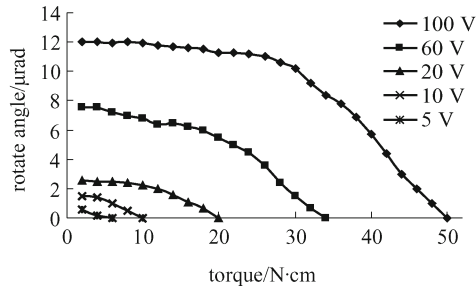


Fig. 13 Run torque test

The factors that affect the work frequency of the precision PZT step rotary motor are as follows:

- 1) The curved stiffness modulus of the double thin flexible hinges in the anchor/loosen part.
- 2) The mass of the anchor/loosen.
- 3) The curved stiffness of the four torsion/bend thin flexible hinges on the rotor.
- 4) The mass of the upper and nether rotors.
- 5) The curved stiffness of the flexible hinge in the driving PZT ceramics joint.

1) and 2) determine the inherence frequency of the stator anchor/loosen. 3), 4) and 5) determine the inherence frequency of the rotor. It can be concluded from the experiment that the maximal work frequency of the system is 40 Hz, i.e., the motor obtains the maximal velocity when the frequency is 40 Hz and the velocity will decline rapidly when the frequency exceeds 40 Hz.

## 6 Conclusions

1) The new precision piezoelectric rotary step motor has the characteristics of high frequency (40 Hz), high resolution (1  $\mu$ rad), large driving torque (30 N·cm), high driving velocity and arbitrariness in rotation angle.

2) The stator anchor/loosen structure with thin flexible hinges is characterized by high frequency, anchor fastness, and work stabilization. It also solves the contravention of high frequency and anchor fastness.

3) The methods that use the stator inner anchor/loosen, rotor outer driving and thin flexible hinges to carry out rotary step driving set an example in designing PZT rotary step motors.

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## References

1. Zhao Hongwei, Liu Jianfang, Hua Shunming, et al. Piezoelectric-type stepping precision rotary actuator. *Optics and Precision Engineering*, 2005, 13(3): 305–310 (in Chinese)
2. Ji Kehui, Guo Jifeng, Liu Xiao. Stepping characteristic of ultrasonic motor and its stepping-positioning control. *Proceedings of the Chinese Society for Electrical Engineering*, 2004, 24(1): 71–75 (in Chinese)
3. Liu Jianfang, Yang Zhigang, Cheng Guangming, et al. A study of precision PZT line step motor. *Proceedings of the Chinese Society for Electrical Engineering*, 2004, 24(4): 102–107 (in Chinese)
4. Yang Zhigang, Ma Haoxue, Yang Dongping, et al. Study on the theory and experiment of ring-type traveling wave ultrasonic motor. *Proceedings of the Chinese Society for Electrical Engineering*, 2000, 20(2): 81–84 (in Chinese)
5. Guo Jifeng, Wei Yanding, Liu Xiao, et al. Force transferring model of hybrid transducer type ultrasonic motor. *Proceedings of the Chinese Society for Electrical Engineering*, 2003, 23(5): 80–85 (in Chinese)
6. Wang Fengxiang, Zhang Qingxin, Wu Xinjie, et al. Study on inchworm linear motor of magnetically controlled shape memory alloy. *Proceedings of the Chinese Society for Electrical Engineering*, 2004, 24(7): 140–144 (in Chinese)
7. Zhao Hongwei, Wu Boda, Cheng Guangming, et al. Precise stepping rotary motor based on piezoelectric actuation. *Proceedings of the Chinese Society for Electrical Engineering*, 2006, 26(10): 166–171 (in Chinese)
8. Zhang Fuxue, Wang Likun. *Modern Piezoelectricity*. Beijing: Science Press, 2001 (in Chinese)
9. Li J, Sedaghati R, Dargahi J, et al. Design and development of a new piezoelectric linear inchworm actuator. *Mechatronics*, 2005, 15(6): 651–681
10. Frank J E, Koopmann G H, Chen W, et al. Design and performance of a high force piezoelectric inchworm motor. In: *Proceedings of SPIE-The International Society for Optical Engineering*, USA. 1999, 3668: 717–723
11. Xue Shifu, Li Qingxiang. *Precision Apparatus Design*. Beijing: Tsinghua University Press, 1991 (in Chinese)