Development of the Screw-driven Motors by Stacked Piezoelectric Actuators

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Abstract

The purpose of the present paper is to develop a screw-driven piezo motor, which can be driven at low voltage. The motor consists of a cubic shaped stator and a rotor with external thread. The stator is formed by placing stacked piezo actuators in the side hollowed cubic elastic body. Also, a screw hole was designed in the stator and exactly fitting the screw rod to be pushed. In this study, three kinds of motor were designed, their driving characteristics are compared and discussed for improving the motor performance. The finite element analysis software ANSYS was used to analyze the vibration characteristics of the stator. In the experiment, one type of the screw-driven motor prototype fabricated according to the designed results was measured. It showed that the translational speed of the screw-driven motor is 2.137 mm/s when applying 8 V_{pp} without mechanical load. The translational speed of the motor is 1.174 mm/s with 16 g mechanical load under 8 V_{pp} driving.

Keywords: screw rod, piezoelectric motor, shear vibration mode.

1. Introduction

With the rapid development of nanotechnology and biotechnology, the demand for ultra-precision positioning and measurement devices has been gradually increasing in various technical fields. For a large size of the positioning devices, the electromagnetic motor and screw rod are usually used to form the transmission mechanical component in the positioning and measurement systems. And the screw rod is a transmission mechanical component for converting rotary motion into linear motion in the systems. However, there is a demand of a mini-size

screw-driven motor that can be driven at low voltage for ultra-precision positioning application, and there is no appropriate magnetic motor and screw rod set exists.

In 2000, Fujimura proposed a screw driving mechanism using ultrasonic vibration ⁽¹⁾. There are four piezoelectric vibrators in this mechanism. Two piezoelectric vibrators form a set of screw driving unit to make the screw rod rotate clockwise, and the other two piezoelectric vibrators form another set of screw driving unit to make the screw rod rotate counterclockwise. The screw driving mechanism proposed by Fujimura is unlikely to be miniaturized due to its complicated structure. In 2004, Kawano and Ando proposed a piezo-driven screwdriver based on the operating principle of an ultrasonic motor, which was used to lock screws, and a Langevin vibrator was used in the screwdriver for locking bolts ⁽²⁾.

In 2005, Henderson proposed a screw-driven motor driven by the bending vibration mode of the stator ⁽³⁾. In this motor, the stator contains four rectangular piezoelectric plates attached onto a threaded nut to generate ultrasonic vibration to drive the rotational motion of the threaded shaft. The motor speed was 5 mm/s under the 20 V_{pp} drive at 150 kHz, and the maximum thrust force is 20 g. In 2009, Zhou studied a nut-type screw-driven motor for a application on focus system of a mobile phone ⁽⁴⁾. It consists of a stator of a threaded nut bonded piezoelectric plates and a rotor of a screw rod. The motor speed was 1 mm/s under the 40 V_{pp} drive at 17 kHz, and the maximum thrust force is 5 g.

In 2015, Hua studied a screw-driven motor driven by two Langevin vibrators ⁽⁵⁾. The motor speed was 61 rpm under the 300 V_{pp} drive at 9 kHz, and the maximum thrust force is 2.1 N. The drawback of these motors is that the driving voltage of the motor needs too high.

A screw-driven piezo motor has been developed in a

previous study by the authors of this paper ⁽⁶⁾. Its stator is formed of four multilayered piezo actuators embedded in a cubic elastic structure. This structure is characterized by a simple structure and easy miniaturization, and low voltage is sufficient to drive the screw rod, so as to implement the high-precision linear motion in the axial direction of the screw rod. However, previously designed piezo motor has some drawbacks need to improve. Such as, it uses too many piezo actuators in the motor that results in high production cost. The purpose of this study is to explore a new design, expect for developing a screw-driven piezo motor that can be driven at a lower voltage but improve the shortcomings of the previous motor.

2. Working Principle

The screw-driven motor consists of a cubic shaped stator and a screw rod, as shown in Fig.1. The cubic stator is a symmetrical structure with respect to the z-axis. The motor developed in this study is a double-mode type piezo motor, so two orthogonal mechanical vibration modes are necessary to be designed in the stator for the generation of elliptical motions on the screw hole. In addition, the two vibration modes are necessary to be orthogonal at the screw hole and shown in Fig.2, one is the z-x shear vibration mode and the other is the z-y shear vibration mode.

Figs.2 also shows the principle of the rotary motion for the screw-driven motor driven by two orthogonal vibration modes. The cubic stator is driven by two sine voltages with phase difference to make the screw hole implement elliptical deformation motion. While the two sine voltages of 90° phase difference are applied separately to the stator, the elliptical trajectory is formed at the screw hole of the stator. In addition, when the frequency of the input sine voltage approaches the natural frequency of the stator, the resonance effect can be used. Thus, the vibration displacement of the screw hole of the stator is magnified, and the piezo motor is driven by low voltage.

The elliptical rotation on the screw hole of the stator can be modeled by two vibration equations as follows.

$$m_x \ddot{u}_x + d_x \dot{u}_x + k_x u_x = A_x v_A \quad (1)$$

$$m_y \ddot{u}_y + d_y \dot{u}_y + k_y u_y = A_y v_B \quad (2)$$

where m_x , d_x , k_x represents the effective mass, damping, and stiffness for the z-x shear mode, respectively. m_y , d_y , k_y represents the effective mass, damping, and stiffness for the z-y shear mode, respectively. A_x and A_y are the force

factors of the piezo actuators PZT A and PZT B. The input voltages v_A and v_B are applied to piezoelectric actuators PZT A and PZT B, respectively.

When $v_A = V \sin(w_r t)$ and $v_B = V \cos(w_r t)$, Eqs. (1) and (2) lead to the equation of the elliptical motion at the screw hole, as follows.

$$\frac{U_x^2}{A_x^2} + \frac{U_y^2}{A_y^2} = \frac{V^2}{(k - m\omega_r^2)^2 + d^2 \omega_r^2} \quad (3)$$

where $m = m_x = m_y$, $d = d_x = d_y$, and $k = k_x = k_y$ due to the stator is a symmetrical structure with respect to the z-axis. U_x and U_y represent the displacement amplitude u_x and u_y , respectively.

Fig. 1. Exploded diagram of the motor.

Fig. 2. The z-x and z-y shear vibration modes.

3. Finite Element Analysis

3.1 Design of the Stator

To implement aforementioned screw-driven piezo motor, the stator should be designed to have two orthogonal mechanical vibration modes. Thus, the designed stator consists of multiple piezo actuators and a cubic structure. When a sine wave voltage with phase difference is applied to the two sets of piezo actuators, the overall cubic stator is deformed, and an elliptical deformation motion is generated at the screw hole of the stator. The frictional effect enables the elliptical deformation motion of cubic stator to drive the screw rod to rotate, so that the screw rod

implements linear motion. In this study, we designed three types of cubic stator for comparison. One is a cubic stator driven by four piezo actuators with free boundary condition, the second is a bottom fixed cubic stator driven by four piezo actuators, the other one is a cubic stator driven by two piezo actuators.

3.2 Design of the Four Piezo Actuators Drive Stator

Figs. 3 show the cubic stator driven by four piezo actuators. The main structure is a one-piece structure made by hollowing the cubic structure and this cubic structure has three orthogonal axial directions. The z-direction is made through the screw hole for the screw rod to screw in, and the other two axial directions are made through square holes. Four piezo actuators (PZT A, PZT B, PZT C, and PZT D) are diagonally embedded in the four square holes of the cubic structure. The axial screw linear motion of the screw rod can be driven by sine voltage when the bottom of stator is fixed.

The vibration of a cubic stator in various boundary conditions was simulated using the finite element analysis software to predict the dynamic characteristics of the stator. The cubic stator of the screw-driven motor was designed with dimensions with 12.5 mm long on each side of the cube structure. The size of the stacked piezoelectric actuators is 2mm×3mm×9mm. Generally speaking, the stator composed of piezo actuator, and metal elastic body may present different dynamic characteristics due to different fixing positions. In this study, the boundary conditions of the stator was set as Case A: the bottom fixed, and Case B: the free condition. Fig.4(a) and (b) show the shear mode shapes of the stator for Case A and Case B. Fig.5 shows the impedance characteristics when the stator bottom is fixed and the piezo actuators PZT B and PZT D are applied by two mutually inverted sine voltages, respectively. Similar impedance characteristics can be obtained by simultaneously applying two mutually inverted sine voltages to piezoelectric actuators PZT A and PZT C. The natural frequency of the first shear mode for Case A is 16652 Hz. Fig.6 shows the impedance characteristics of the stator with free boundary condition, the natural frequency of the first shear mode for Case B is 30823 Hz.

Fig.7 shows the x- and y-direction vibration displacements of points a and c on the screw hole edge of the stator obtained by applying the sine voltages with 90 degree phase difference for Case A. In Fig.7, the maximum displacement occurs in 16652 Hz of the first shear modes; the x-direction displacements of point a are

2.63 $\mu\text{m/V}$ and the y-direction displacements of point c are 2.49 $\mu\text{m/V}$, respectively.

Fig. 3. A cubic stator driven by four piezo actuators.

Fig. 4. The shear vibration modes: (a) Case A: the bottom fixed, (b) Case B: the free condition.

Fig. 5. Impedance response of the stator with bottom fixed B.C.

Fig. 6. Impedance response of the stator with free B.C.

Fig.8 shows the x- and y-direction vibration displacements of points a and c on the screw hole edge of the stator obtained by applying the sine voltages with 90 degree phase difference for Case B. In Fig.8, the maximum displacement occurs in 32880 Hz of the first shear modes; the x-direction displacements of point a are $0.549 \mu\text{m/V}$ and the y-direction displacements of point c are $0.528 \mu\text{m/V}$, respectively.

Fig. 7. Vibration response of the stator with bottom fixed B.C.

Fig. 8. Vibration response of the stator with free B.C.

3.3 Design of the Two Piezo Actuators Drive Stator

Considering production cost, the stator is also designed by two piezo actuators. Figs. 9 show the cubic stator driven by two piezo actuators. Two piezo actuators (PZT A, PZT B) are diagonally embedded in the cubic structure. The axial screw linear motion of the screw rod can be driven by sine voltage when the bottom of stator is fixed. The vibration of a cubic stator with bottom fixed boundary condition was simulated using the finite element analysis software to predict the dynamic characteristics. The cubic stator was also designed with dimensions with 12.5 mm long on each side. And the size of the stacked piezo actuators is also $2\text{mm} \times 3\text{mm} \times 9\text{mm}$.

Fig.10 shows the x-, y- and z-direction vibration displacements of points a on the screw hole edge of the stator obtained by applying the sine voltages with 90 degree phase difference for the two piezo actuators drive stator. In Fig.10, the resonance peak value $1.3335 \mu\text{m/V}$ occurs in 10750 Hz for the the x-direction, while the resonance peak value $1.334 \mu\text{m/V}$ occurs in 15550 Hz for the y-direction.

Fig. 9. A cubic stator driven by two piezo actuators.

Fig. 10. Vibration response of the stator with bottom fixed B.C.

Fig. 11. Operating sequence of the stator for a driving cycle.

Comparing the vibration frequency response of Fig.10 with that of Fig.7, it shows the resonance amplitude in Fig.10 is 2 times the resonance amplitude in Fig.7. In the same driving voltage, only half of the amplitude can be generated by the two piezo actuators drive motor in comparison with the four piezo actuators drive motor. Fig.11 shows the operating sequence of the stator for a driving cycle, the stator deformation patterns corresponding to the phase changed in one cycle time are simulated by ANSYS software. The top views of the stator show that the two piezo actuators drive stator has the ability to push the screw rod to rotate.

4. Experiment Results

A piezoelectric screw-driven motor has been designed and fabricated, as shown in Fig.12 and Fig.13. The actuators are chosen commercial stacked piezo actuators PSt150/2x3/7, Piezomechanik Ltd in Germany, with size of 2mm×3mm×9mm. The driven screw rod is an M8 fine pitch screw. It is made of stainless steel, as the vibration deformation in the screw hole of the stator must be considered in design to adopt and appropriate exact fit.

Performance of the screw-driven motor prototype in Fig.12 is experimentally measured when the stator bottom is fixed, as shown in Fig.14. Fig.14 shows the relation curve of driving voltage and the motor speed obtained by measuring the axial movement of the screw rod when the piezoelectric screw motor is driven at the same frequency but under different voltages. The applied driving voltage waveform is sine voltage at 15840 Hz, the voltage changes from 0 V_{pp} to 9 V_{pp} . Since the screw-driven motor uses friction force to drive the screw rod, when the motor is driven under 3.5 V_{pp} , the vibration deformation generated by the stator is insufficient to drive the screw rod, so that the axial speed of screw rod is zero, and this type of piezoelectric motor has a dead zone of driving voltage below 3.5 V_{pp} . When the driving voltage is higher than 3.5 V_{pp} , the screw rod is moved, and the axial speed is 0.791 mm/s. In the voltage interval of 3.5 V_{pp} to 8 V_{pp} , the axial speed of the screw rod increases with the driving voltage. When the driving voltage is 8 V_{pp} , the axial speed of the screw rod approaches maximum 2.137 mm/s. When the driving voltage is higher than 8 V_{pp} , even though the voltage is increased, the axial speed of the screw rod is decreased. When the driving voltage is 9 V_{pp} , the axial speed of the screw rod is decreased to 1.969 mm/s.

Fig. 12. The four piezo actuators drive motor.

Fig. 13. The two piezo actuators drive motor.

Fig. 14. Speed of the screw driving motor.

In the screw-driven motor, the tolerance between the screw rod and the threaded hole of the stator will influence the relation curve, as shown in Fig.9. Since the vibration deformation of the threaded hole edge increases with the driving voltage, when the driving speed increases to 3.5 V_{pp} , the vibration deformation is large enough to let the threaded hole edge contact the thread of the screw rod, and adequate friction force is generated to drive the screw rod. Afterwards, the vibration deformation of the threaded hole edge is increased; as the driving voltage is continuously increased, higher friction thrust is applied to the screw rod, so that the helical motion speed of the screw rod increases. In the voltage interval of 3.5 V_{pp} to 8 V_{pp} , there is almost linear proportional relationship between axial speed of the screw rod and the driving voltage. When the driving voltage is higher than 8 V_{pp} , as the vibration deformation is

too large, normal force is too high between the threaded hole edge of the stator and the screw rod, obstructing the rotary motion of the screw rod. When the driving voltage is higher than $8 V_{pp}$, the axial speed of the screw rod is decreased as the voltage is increased. When the driving voltage is increased to a limit value, the axial speed of screw returns to zero. Due to the effect of the tolerance between the screw rod and the threaded hole, the most ideal driving voltage of the screw-driven motor is $8 V_{pp}$, the maximum axial speed is 2.137 mm/s, and the maximum load is 16 g.

5. Conclusions

This article describes a development of the screw-driven motor. In this motor, the stator is made by obliquely embedding piezo actuators in a hollowed cubic structure. Three kinds of the motor were designed, their driving characteristics are compared and discussed for improving the motor performance. Vibration deformation generates at the screw hole of the stator when sine voltages of 90° phase difference are applied to the piezoelectric actuators. Through friction effect, the helical motion of the screw rod is driven by the ultrasonic vibration generated at the threaded hole of the stator.

According to the aforementioned operating principle and design concept, a screw-driven motor prototype was made and assembled for verification. In the experiments, the performance of the prototype was also measured. It shows that the ideal driving voltage of the screw-driven motor is $8 V_{pp}$, the maximum axial speed without load is 2.137 mm/s, and the axial speed is 1.174 mm/s under 16 g load.

Acknowledgment

The authors would like to thank the National Science Council, Taiwan, R.O.C. for financially supporting this research under project MOST 104-2622-E-151-005-CC3.

References

- (1) K. Fujimura: "Mechanism for Driving Screw Rod by Supersonic Vibration". United States Patent 6147435, 2000.
- (2) H. Kawano and H. Ando: "Study of a Recessless Screw and a Piezoelectric Screwdriver", Proceeding of 2004 IEEE/RSJ International Conference on Intelligent

Robotics and Systems, pp. 903-907, 2004.

- (3) D. A. Henderson: "Ultrasonic screw motor", United States Patent 6940209, 2005.
- (4) T. Zhou, J. Zhang, Y. Chen: "A Nut-type Ultrasonic Motor and Its Application on Focus System", PIERS Proceedings, pp. 23-27, 2009.
- (5) S. Hua, Y. Meng, Y. Lou, Z. Li, X. Wang: "Screw-type Actuator Driven by Piezoelectric Transducers", Advances in Mechanical Engineering, pp. 1-10, 2015.
- (6) S.-T. Ho, W.-H. Chiu, "A Piezoelectric Screw-driven Motor Operating in Shear Vibration Modes," Journal of Intelligent Material Systems and Structures, 27, pp. 134-145, 2016.