A Novel Stick-Slip Type Rotary Piezoelectric Actuator

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1. Introduction

Piezoelectric actuators have been widely used in many fields [1], such as biomedical engineering [2], semiconductor manufacturing [3], optics focusing, and scanning microscopy [4], because of their compact size, large output force, rapid response, and high resolution [5, 6]. According to their working principles, piezoelectric actuators can be divided into direct-drive actuators, ultrasonic actuators, inchworm actuators, and inertial actuators. Direct-drive actuators have a high positioning resolution and compact structure but limited stroke [7–9]. Ultrasonic actuators have advantages for high-speed use but generate much heat and have wear problems [10–13]. Inchworm actuators produce a large output force but their structure and control system are complicated [14–17]. Inertial actuators have a compact structure, long stroke, and high resolution and are more promising for low-load precision applications [18–20]. There are two types of inertial actuator: the impact-inertial type and stick-slip type. This paper mainly discusses the latter.

Inertial stick-slip actuators [21–24] can be categorized by their control approach as signal-control type [5, 25], friction-control type [26], and mechanism-control type [27, 28]. Actuators. A signal-control actuator uses an excitation signal having an asymmetric waveform to generate unequal speed in two directions. The mechanism-control actuator uses an asymmetric mechanical structure to realize asymmetric operating motion. The friction-control actuator achieves motion by changing the friction force on the surface between the moving part and base in different motion stages.

Considering that the structure of the mechanism-control actuator is usually too complex and bulky for application and the friction-control actuator has drawbacks of low precision and limited stability [18], we propose a novel stick-slip piezoelectric rotary actuator based on the signal-control method. The proposed rotary piezoelectric actuator is designed for an optical path adjustment system. The actuator provides precision angle displacement of at least 5 μrad, with a high velocity, infinite stroke, and structure for light to pass through, while having a relatively small volume and low weight.

The remainder of the paper is organized as follows. Section 2 clarifies the configuration and working principle of the actuator. Section 3 analyzes the dynamic model and discusses simulation results. Section 4 describes the experimental system and results for the actuator’s characteristics. Section 5 presents conclusions.
2. Configuration and Operating Principle

2.1. Configuration. Figure 1 depicts the configuration of the proposed rotary piezoelectric actuator. The actuator mainly comprises six components: a base, a bearing, two piezoelectric stacks placed in a rhombic mechanism, two preload springs, a joint plate, and a shell.

The bearing’s inner ring is interference fitted on the base while the bearing’s outer ring rotates freely and smoothly. Each piezoelectric stack is nested in a rhombic mechanism, which is used to protect the fragile piezoelectric stack and properly control the output displacement of the piezoelectric stack. The rhombic mechanism contains a friction block that is in contact with the bearing’s outer ring and a fixing hole that is used to fix the mechanism on the surface of the base. The preload springs produce sufficient pressure between the friction block and outer ring of the bearing. The joint plate is interference fitted on the bearing’s outer ring so that it rotates as the bearing rotates. The shell, which prevents the actuator from the environment, is fixed on the joint plate by screws and also rotates with the bearing.

The dimensions of the actuator are 56 mm × 56 mm × 12 mm. The diameter of the aperture is 24 mm. The dimensions of the bearing are 25 mm × 37 mm × 7 mm. The dimensions of each piezoelectric stack are 3 mm × 3 mm × 9 mm. The base, joint plate, shell, and rhombic mechanism of the piezoelectric stack are all made of Al7075 aluminum alloy.

The structure of the rotary actuator is designed for an optical path adjustment system as discussed in Section 1. The structure has an aperture at the center to let light pass through. The actuator rotates step by step to realize an unlimited stroke through stick-slip motion. Owing to the rhombic mechanism, the displacements of the piezoelectric stacks can be designed to have precision resolution. Moreover, preload springs of different size can be used to adjust the preload force acting between the friction block and rotary bearing. The proposed actuator has a compact structure and is lightweight.

2.2. Operating Principle. The operating principle and force analysis of the proposed piezoelectric rotary actuator are illustrated in Figure 2. When the piezoelectric stack is driven by a sawtooth waveform, it undergoes extension and contraction deformation, resulting in the friction block moving with respect to the bearing in a stick-slip manner.

1. Initial state: when time \( t = t_0 \), no voltage is applied, the piezoelectric stack is not deformed, and there is no movement between the friction block and bearing.

2. Slow extension stage: from times \( t_0 \) to \( t_1 \), the applied voltage increases slowly, the piezoelectric stack extends slowly, and the friction block sticks on the bearing, rotating the bearing through a small angle \( \theta \).

3. Quick contraction stage: from times \( t_1 \) to \( t_2 \), the applied voltage decreases rapidly and the piezoelectric stack contracts rapidly. At the same time, the rotor remains still while the friction block returns to its original position; that is, the friction block slips on the bearing.

Afterward, the rotor rotates though a small angle \( \theta \) anticlockwise, and the friction block and piezoelectric stack return to the same position as for the initial state. Through the repeating cycle of the sawtooth wave voltage, the actuator outputs an infinite stroke step by step. The actuator rotates clockwise if we change the applied voltage such that it first increases rapidly and then decreases slowly.

2.3. Design of the Rhombic Mechanism. The rhombic mechanism is commonly used to amplify the deformation of the piezoelectric stack. This article uses the same principle to design the rhombic mechanism. The purpose is to constrain the displacement of the piezoelectric stack and protect the piezoelectric stack. The designed mechanism is actually arc-shaped mechanism. The groove is processed by slow wire cutting inside the mechanical structure, and the piezoelectric stack is placed in the groove for driving. The length of the groove is slightly shorter than the original length of the piezoelectric stack by 5–10 \( \mu \)m, so the piezoelectric stack can be preloaded.

In the finite element analysis we can simplify the piezoelectric stack as a homogeneous solid material which will produces equivalent deformation with respect to voltage input [29]. The structure of the designed mechanism and finite element analysis results are shown in Figure 3. The deformation which is tested by experiment method of the piezoelectric stack driven by the voltage of 120 V is 9 \( \mu \)m. The simulation results of the deformation and stress diagram of the driving part constrained by the rhombic mechanism at the voltage of 120 V are shown in Figure 3. The maximum displacement is 7.1 \( \mu \)m, which is a loss of 1.9 \( \mu \)m compared to the unconstrained displacement. The maximum stress is 113.9 MPa, which is less than the yield stress of 500 MPa for aluminum alloy 7075. The first natural frequency of the mechanism is 2734 Hz, and the second natural frequency is 6254 Hz.

3. Dynamic Model and Simulation

3.1. Dynamic Model. In the dynamic model depicted in Figure 4, we simplify the rhombic mechanism and piezoelectric stack as a spring-damping-mass system, referred to as the PE subsystem. The spring stiffness and damping coefficient are denoted as \( k \) and \( c \), respectively. When the driving voltage is applied to the piezoelectric stack, a driving force \( F_p \) is generated, and a friction force \( F_f \) is generated on the contacting surface of the PE part and rotor part. \( F_f \) drives the rotor with stick-slip motion.

This dynamic model is governed by the following equations:

\[
\begin{align*}
mx + cx + kx &= F_p - F_f, \\
J\ddot{\theta} &= M_f - M_{load},
\end{align*}
\]

(1)
where $F_p = k_p \cdot d_e \cdot V(t)$ is determined by the properties of the PE subsystem, $J$ is the rotational inertia, $M_f$ is the output torque, $M_{load}$ is the load torque, $\theta$ is the angular acceleration, and $F_f$ is the friction force acting between the rotor and PE subsystem.

Figure 5 shows the deflected bristle in LuGre friction model. The friction force acting between the rotor and PE subsystem is dominated by presliding and is properly described by the LuGre friction model [30]: where $\sigma_0$ is the contact stiffness; $\sigma_1$ is the damping of the tangential
compliance; $\sigma_5$ is the coefficient of viscous friction; $z$ is the average deflection of the bristles on the contact surface; $f_s$ is the stiction force; $f_c$ is the Coulomb friction force; and $v_s$ is the Stribeck velocity.

$$F_f = \sigma_0 z + \sigma_1 \frac{dz}{dt} + \sigma_2 v,$$

$$\frac{dz}{dt} = v - \frac{|v|}{g(v)} z,$$  \hspace{1cm} (2)

$$\sigma_0 g(v) = f_c + (f_s - f_c) e^{-\left(\frac{v}{v_s}\right)^2},$$

3.2. Simulations. To investigate how the step displacement and speed of the actuator are affected by the parameters of the proposed dynamic model, such as $F_p$ and $F_f$, we built a Simulink model in MATLAB software and conducted simulations. The key parameters we used in the analysis are shown in Table 1.

Parameters $m$, $c$, and $k$ for a properly designed PE subsystem are easily measured in experiments. In the simulations, we keep the radius and rotational inertial of the rotor unchanged to evaluate the effect of the input waveform on the performance of the actuator.

Figure 6(a) presents the driving voltage signal of a 90 V sawtooth waveform applied to the PE subsystem. The failing edge of the voltage spans 40 $\mu$s, which is short enough to ensure a slip motion. Figure 6(b) depicts the displacement of the actuator under this driving voltage while Figure 6(c) presents the friction force.
The rotational speed of the actuator increases with the frequency of the driving voltage, while the angular step displacement increases with the amplitude of the driving voltage.

4. Experiments and Actuator Characteristics

4.1. Experiments. Figure 10 shows the prototype of the proposed piezoelectric rotary actuator. The actuator has dimensions of 56 mm × 56 mm × 12 mm and a mass of 51.68 g. A series of experiments were conducted to test the performance and characteristics of the actuator.

Figure 11 shows the experimental system adopted to test the characteristics of the designed actuator. The waveform generator generated the required sawtooth waveform signal. The power amplifier amplified the signal from the waveform generator. The amplified signal was applied to the piezoelectric stacks in the actuator such that the actuator output rotary motion. A laser sensor with a resolution of 0.1 μm was employed to measure the motion behavior of the actuator. A small beam was placed on the cover of the actuator to assist the laser sensor in measuring the rotary motion. When light hits the beam vertically, and the displacement measured by the laser sensor was about 100 μm within a small angular displacement, the conversion formula for the output angular displacement is

\[ \theta(\mu r a d) = \frac{S(\mu m)}{R(m)}. \]  

where \( S \) is the displacement measured by the laser sensor and \( R \) is the effective turning radius of the laser point on the beam. The personal computer was used to process the data from the laser sensor.

Figure 1(b) shows that the actuator contains two piezoelectric stacks. A series of experiments was conducted to investigate the performance of the prototype in different situations. Only one piezoelectric stack was installed and used in some experiments while two piezoelectric stacks were installed and used in other experiments.

4.2. Displacement Varying with Frequency. Figure 12 presents displacement data obtained directly from the laser sensor when the actuator installed with only one piezoelectric stack was driven by a sawtooth wave signal having a voltage of 93 V and symmetry of 100% and different frequencies.

First, we see that the displacement has a good linear relationship with time and the displacement has no visible backwards motion. This means that in the quick contraction stage, when the applied voltage decreases rapidly, the friction block slips on the bearing’s outer ring, which remains still. The absence of backwards motion means that the actuator rotates stably and ideally.

Second, the velocity, which is presented as the slope of the line, increases with frequency. A higher frequency means that there are more steps in the same time period, resulting in larger displacement.

4.3. Velocity Varying with Frequency. To evaluate the performance of actuators at different frequencies of the driving
Figure 6: Simulation results under sawtooth signal of 500 Hz 90 V. (a) Driving voltage. (b) Displacement. (c) Friction force.

Figure 7: Simulation results of rotation displacement of the PA under 90 V sawtooth waveform.
voltage, we applied a sawtooth wave signal having a voltage of 93 V and 100% or 0% symmetry on the piezoelectric stack. In this experiment, we installed one piezoelectric stack in the actuator. The sawtooth wave with 100% symmetry rotates the actuator clockwise while the sawtooth wave with 0% symmetry rotates the actuator anticlockwise.

The experimental results are shown in Figure 13. The clockwise motion and anticlockwise motion have nearly the same velocity at the same frequency, and both velocities increase with frequency. The relationship of the velocity and frequency has good linearity.

In the high-frequency range, the velocity does not increase with frequency. That is because of the bandwidth of the driving mechanism. When the frequency is increased beyond the bandwidth, the displacement output of the driving mechanism output would fall sharply, resulting in a decreased step angle. Besides, the time cost of the fast falling edge of the driving voltage is always fixed at about 100 μs due to the hardware limitation. An increase in the driving frequency reduces the total time of a single cycle waveform. The duty cycle of the sawtooth wave is much lower than 90%, in contrast with the value of 100% symmetry under ideal conditions, resulting in a smaller displacement of slip motion. So the velocity in each direction thus remains nearly the same when the frequency is around 3000 Hz.

4.4. Velocity Varying with Voltage. We applied a sawtooth wave signal having 100% symmetry and varying voltage and frequency to the piezoelectric stack, to clarify the
relationship between the driving voltage and the actuator performance.

Figure 14 shows the relationship between the angular velocity and applied voltage. As the applied voltage increases, the angular velocity increases regardless of the frequency of the applied voltage. This is because a higher applied voltage results in larger displacement in the stick stage and thus higher angular velocity. The lowest voltage that produces stable rotation is approximately 13 Vp-p.

Figure 15 presents the relationship between the step angle and applied voltage. The step angle decreases as the applied voltage decreases or as the frequency of the applied voltage increases. A smaller step angle means that the actuator can reach higher resolution. The smallest step angle is

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**Figure 11: Experiment system.**

**Figure 12: Output displacement under different frequencies of a 93 V sawtooth waveform.**
approximately 0.2 millidegrees when the applied voltage is 13 Vp-p at a frequency of 3000 Hz.

4.5. Velocity Varying with Number of Piezoelectric Stacks. The prototype of the proposed actuator worked well when only one piezoelectric stack was installed. The prototype also worked well when two piezoelectric stacks were installed and applied with the same sawtooth wave signal.

Figure 16 compares driving by one piezoelectric stack and driving by two piezoelectric stacks. When the frequency of the applied voltage is lower than 1600 Hz, the angular velocities of the one piezoelectric actuator and two-piezoelectric actuator are similar in that both velocities increase with frequency with good linearity. When the frequency is higher than 1600 Hz, the velocity of the two-piezoelectric actuator decreases with increasing frequency. This is because the two piezoelectric stacks do not work perfectly at the same time and the two driving mechanisms have slightly different response times for the applied voltage. The difference is greater at a relatively high driving frequency. Another possible explanation is resonance.

Figure 17 shows the results obtained when we installed two driving mechanisms in the actuator but only applied voltage to one piezoelectric stack. This experiment simulates the situation that one piezoelectric stack is faulty and does not provide the expected driving motion. The red line shows
results obtained when the voltage was applied to both piezoelectric stacks and the blue line shows results obtained when the driving voltage was applied only to one of the piezoelectric stacks.

It is seen that the actuator still works well under the extreme situation that only one piezoelectric stack does not work. The faulty piezoelectric stack does not provide a driving force but a friction force, working as an extra load for the actuator. The actuator rotates well at a lower speed. Irrespective of whether the driving voltage is applied to one or two piezoelectric stacks, the actuator rotates through 360° under a low applied voltage. The angular velocity maintains a good linear relationship with the applied voltage at most frequencies.

5. Conclusion

In this work, following a comparison of the features of different types of piezoelectric actuator, we developed a novel stick-slip piezoelectric actuator for optical application. A dynamic model of the rotary piezoelectric actuator was established to simulate how the input driving voltage affects the stick-slip motion of the actuator. Simulation results show that the rotational speed of the actuator increases with the frequency of the driving voltage, while the angular step displacement increases with the amplitude of the driving voltage.

The actuator has been proposed, fabricated, and tested. An experimental system was built to evaluate the performance of the actuator at different frequencies, voltages, and numbers of driving piezoelectric stacks. Experimental results show that the minimal output stepping angle is 3.5 μrad (0.2 millidegrees) under a sawtooth waveform having a voltage of 13 V and frequency of 3000 Hz while the velocity reaches 0.44 rad/s (25°/s) under a sawtooth waveform having a voltage of 93 V and frequency of 3000 Hz, while the stroke is infinite. The proposed actuator provides stable and accurate rotary motion and realizes a high velocity.

The actuator has merits of high resolution, good stability, high speed, infinite stroke, and compact size and has good application potential not only in an optical path adjustment system but also for other uses, such as positioning.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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