

Article

Research on the Influence of Friction Pairs on the Output Characteristics of the Piezoelectric Ultrasonic Actuator

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Abstract: The piezoelectric ultrasonic actuator is driven by the friction coupling between the stator and mover. Its friction pairs are very important, but there are few studies on the long-term output stability. Therefore, zirconia (ZrO_2) is selected as a stator material to form friction pairs with four different wear-resistant materials: silicon nitride (Si_3N_4), ZrO_2 , bearing steel (GCr_{15}) and polyether ether ketone (PEEK). Experiments show that the friction pair composed of ZrO_2 - Si_3N_4 is the best, and the attenuation percentage of the speed from the initial state to the end state in the speed rising stage of 50 m is 3.66%. A linear piezoelectric platform is developed based on the best friction pair; a maximum speed of 426.2 mm/s and a resolution of 85 nm are achieved.

Keywords: piezoelectric ultrasonic actuator; friction pairs; stable output characteristics; long service life



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1. Introduction

The piezoelectric actuator has the advantages of a flexible structure design, no electromagnetic interference, a fast response speed and no reducer [1–6]. Therefore, it has attracted more and more attention from researchers and is widely used in aerospace, military, robotics, medical and other fields [7–11]. According to the difference of actuation modes, piezoelectric actuators can be divided into four actuation modes: inertia [12,13], direct drive [14], inchworm [15] and ultrasonic [16–18]. With the advantages of a high output speed, a strong load capacity, a simple structure, a flexible design and an unlimited stroke, the piezoelectric actuator has been well used in precision linear motion platforms [19–22]. The output force of the PUA is transmitted by the friction coupling between the stator and the mover. Therefore, the selection of friction materials has a great impact on the driving effect and the service life of the piezoelectric actuator [23].

In order to reduce the wear between the stator and the mover, a lot of research is carried out. The selection of friction materials not only needs to meet the high friction coefficient but also needs to have excellent wear resistance [24]. Friction pairs usually contain three combinations: organic materials and organic materials, organic materials and inorganic materials and inorganic materials and inorganic materials. In terms of the friction characteristics between organic materials and organic materials, Gu et al. studied the dry sliding friction and wear of polytetrafluoroethylene (PTFE)/Kevlar composites under different vacuums, loads, sliding speeds and temperature performances; the results show that the friction coefficient of the PTFE/Kevlar composite material under vacuum conditions is lower than that of normal temperature conditions, and it has good wear resistance under low and medium vacuum conditions and poor wear resistance under high vacuum conditions. Under vacuum conditions, the friction coefficient and wear rate decrease with the increases in the sliding speed, load and temperature within a certain range [25]. So, the application of the friction pair of organic materials in vacuum is greatly affected by the degree of vacuum, load and temperature.

In terms of the friction characteristics between organic materials and inorganic materials, Liu et al. studied the influence of the PTFE composite and polyimide (PI) composite as mover friction materials on the energy conversion efficiency and mechanical output performance of PUA with phosphorous bronze as the stator friction material. The experimental results show that the PI composite as a friction material can significantly improve the output performance of PUA compared with the PTFE composite. The maximum energy conversion efficiency of the PUA is increased from 24.27% to 41.32% by replacing the PTFE-based friction material with the PI composite material [26]. Song et al. used graphite, molybdenum disulfide or PTFE-filled aramid fiber/PI composite materials as friction materials, which were formed friction pairs with phosphor bronze, respectively, and each friction pair was used to carry out the reciprocating friction and wear systematic research. A comparative study of the friction reduction and wear resistance of polyimide composites shows that graphite exhibits the best lubricity with a lower friction coefficient and wear rate [27]. Qu et al. glued polyphenylene (EKonol) composites to the stator of a traveling-wave PUA, which was combined with rotors of grade 45 steel, copper, stainless steel and aluminum, respectively, and the influence of the drive mode and friction pair combination on the tribological properties of the motor contact interface was analyzed. The experimental results show that, when polyphenylene (EKonol) is combined with a copper rotor, the contact layer can obtain a greater coefficient of friction, a higher output torque and a better wear performance, which can meet the actual operation needs of a traveling wave ultrasonic motor [28]. Therefore, the friction pair composed of suitable organic materials and inorganic materials has a positive effect on improving the energy conversion efficiency, output torque, friction stability and wear resistance of the actuator.

In the research on friction pairs composed of inorganic materials and inorganic materials, Zhang et al. selected ZrO_2 , alumina (Al_2O_3), silicon carbide (SiC) and silicon nitride (Si_3N_4) ceramics as the contact material of the stator, which is matched with the ZrO_2 , Al_2O_3 , SiC and Si_3N_4 ceramic of movers, respectively, and the output performance, friction, wear characteristics and performance life of the standing wave linear PUA in the contact interface are studied, respectively. The experimental results show that the combination of SiC- ZrO_2 , Si_3N_4 - ZrO_2 and ZrO_2 - ZrO_2 stator and rotor friction pairs has a better working reliability and durability [29]. Adachi et al. used Al_2O_3 as a stator and mover materials, respectively, to form friction pairs. The research results show that a smooth wear surface can be formed by two processes of micro-wear and small-wear particles filling surface depression [30]. Olofsson et al. carried out disc and ball tests with Al_2O_3 as the friction material under different humidity conditions, and the results show that the wear characteristics of the brake disc remained stable between 14,000 and 200,000 RPM under all humidity conditions. For the water lubrication test, the width of the wear track increases significantly between 800 and 200,000 RPM but does not increase significantly in the dryer test. The friction coefficient is the highest under dry conditions and the lowest under water lubrication conditions [31]. Under high temperature and high-pressure conditions, friction sintering of the wear particles is possible when Al_2O_3 is in friction with itself. Under dry conditions, the friction coefficient is at its maximum when the wear is at its minimum. Therefore, the friction pairs composed of inorganic and inorganic materials and the selection of suitable friction pairs and lubrication conditions have an important impact on the stability and life of the actuator.

Although the research work of friction pairs has been carried out for a long time and a lot of research work has been done, the previous research work mainly aims to evaluate the output characteristics. The research focused on the efficiency and wear characteristics under different environments and different combinations of friction pairs. So, this work uses PUA to study the output speed, output force and long-term running speed stability of different friction pair materials and selects the friction pair with the best output characteristics to develop a linear motion platform, which will provide an idea for improving the long-term running stability of the ultrasonic motor. The main content of the work is as follows. The experimental platform of the friction pair is constructed, and the speed, output force and

speed stability of different friction pairs are illustrated in Section 2. The experimental results were discussed, and the material of the friction pair with better characteristics was selected in Section 3. The linear motion platform was developed, and platform characteristics were tested in Section 4.

2. Experimental Platform Construction and Friction Pair Performance Test

The basic configuration and principle of the actuator is introduced first, and then the friction pair testing system built by the actuator is presented. ZrO_2 is used as the stator material in the experiment, which constitutes the friction pairs with silicon nitride (Si_3N_4), ZrO_2 , bearing steel (GCr15) and polyether ether ketone (PEEK), respectively. The speed, output force and motion stability of different friction pairs were tested, respectively.

2.1. Configuration of the Actuator and Actuating Principle

A. Actuator configuration

Considering the working stability and output characteristics of PUA, the sandwich PUA with four zones of the d_{33} working mode was selected as the basic configuration in this work. As shown in Figure 1a, the actuator is composed of a luffing lever made of 2A12, six pieces of the four-zone ceramic, six pieces of the electrode plate, a pedestal and a connecting bolt. Two sets of sinusoidal signals with a phase difference of $90^\circ/270^\circ$ were selected to apply to the ceramic in the horizontal and vertical directions, respectively. Under this driving condition, the motion trajectory of the driving foot is a positive ellipse when it is actuated. The motion trajectory under the excitation signal is shown in Figure 1b, which can ensure that the motion trajectory of the point on the actuator driving foot is a positive ellipse. The main structural parameters of the piezoelectric ultrasonic actuator are shown in Figure 1c. Its overall dimensions in the X, Y and Z directions are 30 mm, 30 mm and 34.2 mm, respectively, and its mass is 0.074 kg.

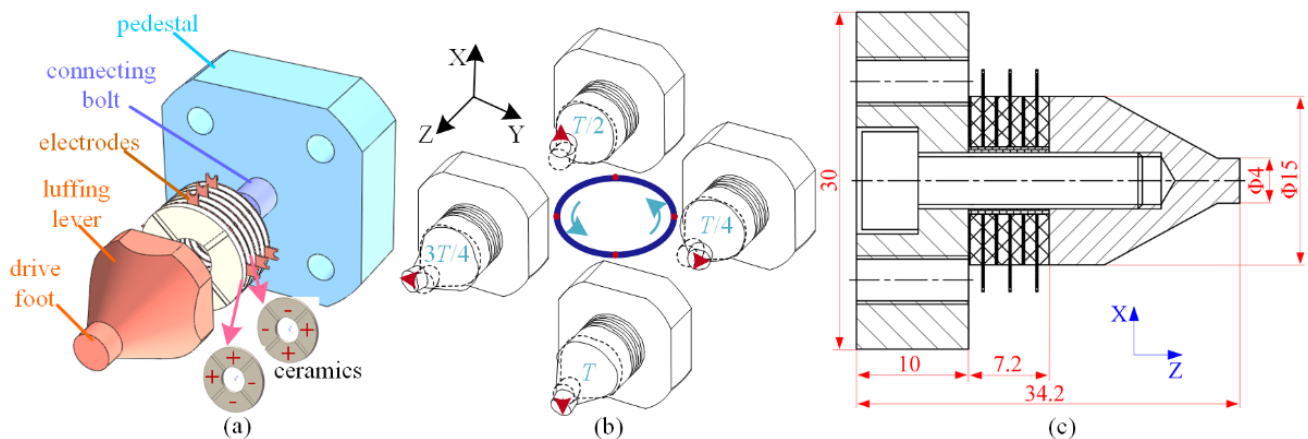


Figure 1. Actuator configuration and driving signal. (a) Basic structure. (b) The movement process of the stator. (c) The dimensions of the stator.

B. Actuating principle

The motion process of the PUA in a sinusoidal AC excitation signal cycle and the working process of the PUA in one cycle (T) is illustrated by the motion states of the PUA at four special time points: $T/4$, $T/2$, $3T/4$ and T .

- (1) $t = T/4$: The excitation voltage applied to the two vertical zones of the piezoelectric ceramics reaches the maximum positive value, and the bending displacement of the PUA along the negative direction of the Y axis reaches the maximum to press down the actuator.
- (2) $t = T/2$: The excitation voltage applied to the horizontal two regions of the piezoelectric ceramic reaches the maximum value, and the bending displacement of the

- PUA reaches the maximum along the positive direction of the X-axis. The driving foot moves along the positive X-axis of the actuator between $t = T/4$ and $t = T/2$.
- (3) $t = 3T/4$: The excitation voltage applied to the two vertical zones of the piezoelectric ceramics reaches the maximum negative value, the bending displacement of the PUA along the positive direction of the Y axis reaches the maximum and the driving foot leaves the actuator. The driving foot does not contact the mover between $t = T/2$ and $t = 3T/4$.
 - (4) $t = T$: The excitation voltage applied to the left and right zones of the piezoelectric ceramics reaches the maximum negative value, and the bending displacement of the PUA along the negative direction of the X axis reaches the maximum. The driving foot does not contact the mover between $t = 3T/4$ and $t = T$.

This is the working process of the PUA in an excitation signal cycle. The PUA pushes the mover in the positive direction of the X-axis during each excitation signal cycle. The mover can realize the movement of a large stroke by the continuous accumulation of multiple cycles. The reverse driving process of the mover can be realized when the phase difference of two sinusoidal AC excitation signals is changed to 270° .

2.2. Friction Pair Performance Test

A. Configuration friction pair performance test

The experimental device shown in Figure 2 was used to test the mechanical output performance and long-term operation output speed stability of the PUA. Because the main wear mechanism of ceramic materials is mechanical fracture, ZrO_2 materials have a higher fracture toughness and less wear [20]. In the experiment, ZrO_2 was used as the stator material to form friction pairs with four different wear-resistant materials: Si_3N_4 , ZrO_2 , $GCr15$ and PEEK. The material parameters are shown in Table 1. The experimental device took the bearing as the mover, the PUA drives the bearing to move, the lifting frame is connected with the force sensor, the force sensor is connected with the mover through the connecting device, the height of the lifting frame is controlled by the hand wheel, the accurate preload value between the stator and the mover can be obtained through the force sensor and the mover is pasted with reflective paper. The laser emitted by the tachometer returns to the tachometer after being reflected by the reflective paper. The speed value of the mover can be obtained by calculating the time interval of the reflected laser.

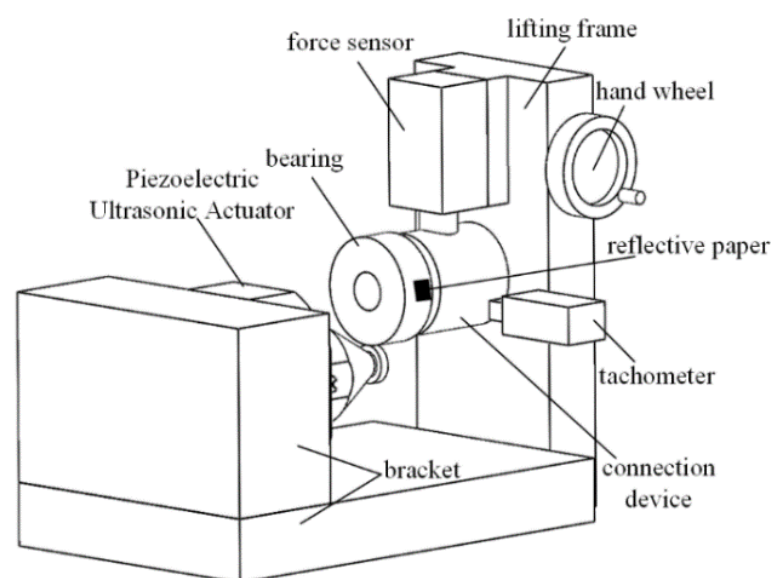


Figure 2. Friction pair test experimental device.

Table 1. Basic parameters of friction pair materials.

Material Parameters	Si ₃ N ₄	ZrO ₂	GCr ₁₅	PEEK	2A12
Density ρ (g/cm ³)	3.2	6	7.8	1.32	2.81
Elastic modulus E (GPa)	320	210	208	3.8	72
Poisson's ratio	0.26	0.3	0.3	0.4	0.33

B. Experiment development and data processing

The initial preload value was set to 1 N, the commercial ultrasonic power supply (Model: QD-8D, Harbin Jiangjun precision testing technology Co., Ltd., Harbin, China) was used to provide the excitation signal, the excitation voltage was increased from 40 V_{p-p} to 200 V_{p-p} and the relationship between the output speed of the actuator and the excitation voltage is shown in Figure 3a. The experimental results show that the output speed of the PUA increases approximately linearly with the increase in excitation voltage. The output speeds of the friction pair materials from high to low are ZrO₂-Si₃N₄, ZrO₂-ZrO₂, ZrO₂-GCr₁₅ and ZrO₂-PEEK. When the excitation voltage is 200 V_{p-p}, the maximum output speed of the ZrO₂-Si₃N₄ friction pair can reach 470.66 r/min. By contrast, the minimum output speed of the ZrO₂-PEEK friction pair is 230.95 r/min. The output speed of the ZrO₂-Si₃N₄ friction pair is about 2.04 times that of the ZrO₂-PEEK friction pair, and the ZrO₂-PEEK friction pair cannot work when the excitation voltage is less than 130 V_{p-p}.

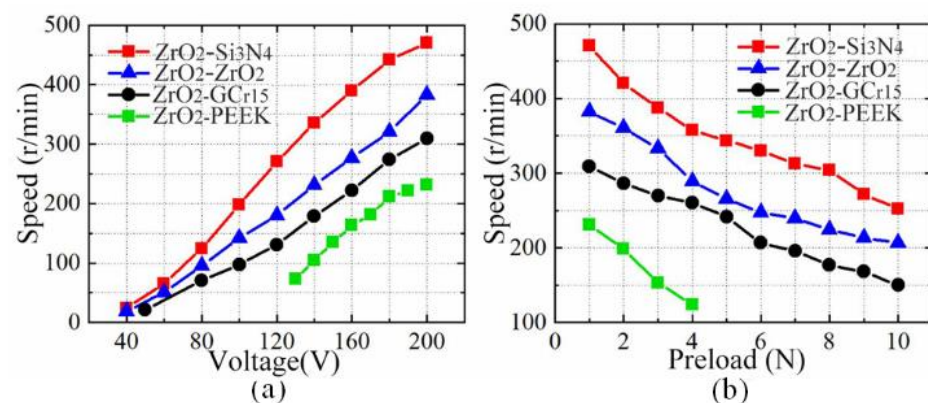


Figure 3. Characteristics of speed. (a) Relationship between the velocity and excitation voltage characteristics of the PUA. (b) Relationship between the output and preload characteristics of the PUA.

The excitation voltage was 200 V_{p-p}, and the preload between the stator and the mover was increased from 1 N to 10 N. The relationship between the output speed of the actuator and the preload is shown in Figure 3b. The experimental results show that the output speed of the PUA decreases approximately linearly with the increase in the preload. The output speeds of the friction pair materials from high to low are ZrO₂-Si₃N₄, ZrO₂-ZrO₂, ZrO₂-GCr₁₅ and ZrO₂-PEEK. When the friction pair material is ZrO₂-PEEK, the PUA cannot work when the preload is greater than 4 N.

The preload is 8 N, the value of the excitation voltage increases from 100 V_{p-p} to 200 V_{p-p} and the relationship between the actuator output force and excitation voltage is shown in Figure 4a. The experimental results show that the output force of the PUA increases approximately linearly with the increase in the excitation voltage. The friction pair materials with the overall output force from high to low are ZrO₂-Si₃N₄, ZrO₂-ZrO₂ and ZrO₂-GCr₁₅. When the excitation voltage is 200 V_{p-p}, the maximum output force of the ZrO₂-Si₃N₄ friction pair can reach 1.32 N. Under the same conditions, the minimum output force of the ZrO₂-GCr₁₅ friction pair is 0.54 N, and the output force of the ZrO₂-Si₃N₄ friction pair is about 2.44 times that.

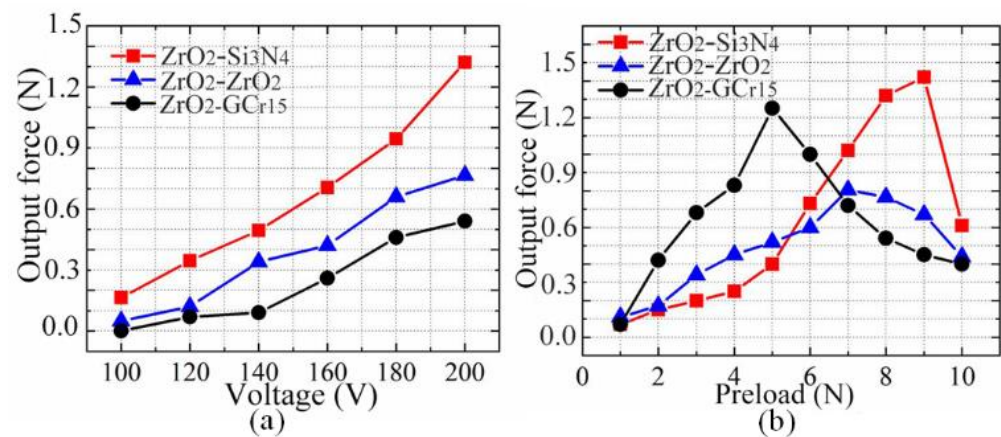


Figure 4. Characteristics of the output force. (a) Relationship between the output force and excitation voltage. (b) Relationship between the output force and preload.

The value of the excitation voltage is 200 V_{p-p}, and the preload increases from 1 N to 10 N. The relationship between the actuator output force and the preload is shown in Figure 4b. The experimental results show that the output force of the PUA first increases and then decreases with the increase in the preload. At a lower preload, the output forces of the friction pair materials from high to low are ZrO₂-GCr15, ZrO₂-ZrO₂ and ZrO₂-Si₃N₄. At a high preload, the high output forces of the friction pair materials from high to low are ZrO₂-Si₃N₄, ZrO₂-ZrO₂ and ZrO₂-GCr15, respectively. When the preload is 5 N, 7 N and 9 N, the output forces of the ZrO₂-GCr15, ZrO₂-ZrO₂ and ZrO₂-Si₃N₄ friction pairs reach the maximum, which are 1.25 N, 0.805 N and 1.42 N, respectively. When the preload force is greater than 6.5 N, the output force of ZrO₂-Si₃N₄ is always greater than that of the other friction pairs. Therefore, the output force characteristics of the ZrO₂-Si₃N₄ friction pair combination are better.

The stability of the output speed of the PUA under different material combinations of friction pairs is the key factor to evaluate each friction pair. Under the experimental conditions that the peak value of the excitation voltage was 200 V_{p-p} and the preload was 2 N, the PUA drove the bearing to run continuously for 500 m, and the variation law of its output speed with the operating distance was measured, as shown in Figure 5. Firstly, the change in the output speed of the PUA running for a long distance was analyzed. It can be seen from the experimental results that, under the four different friction pair material combinations, the output speed of the PUA experienced a process of rising at the beginning and then fell. The specific output speed changes of the four friction pairs are shown in Table 2.

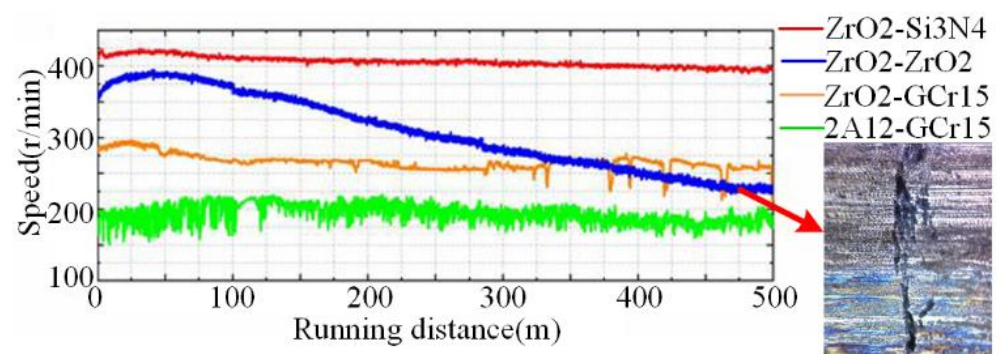


Figure 5. Output speed stability experiment under long-term operation (500 m).

Table 2. Variation in the output speed of different friction pairs.

Friction Pairs	Running Distance (m)	Initial Velocity (r/min)	Peak Velocity (r/min)	End Speed (r/min)
ZrO ₂ -Si ₃ N ₄	50	410	420	395
ZrO ₂ -ZrO ₂	40	355	390	228
ZrO ₂ -GCr ₁₅	25	285	295	258
2A12-Cr ₁₅	130	198	218	190

The running distances of the four kinds of friction pairs of ZrO₂-Si₃N₄, ZrO₂-ZrO₂, ZrO₂-GCr₁₅ and 2A12-GCr₁₅ in the rising stage are 50 m, 40 m, 25 m and 130 m, respectively; the initial speeds are 410 mm/s, 355 mm/s, 285 mm/s and 198 mm/s, respectively. The rising peak speeds are 420 mm/s, 390 mm/s, 295 mm/s and 218 mm/s, respectively. The end speeds are 395 mm/s, 228 mm/s, 258 mm/s and 190 mm/s, respectively. Through calculation, the attenuation percentages of the output speed of the four friction pairs from the initial state to the end state are 3.66%, 35.77%, 9.47% and 4.04%, respectively. The speed attenuation degree of the ZrO₂-Si₃N₄ friction pair is the lowest, which is followed by ZrO₂-GCr₁₅ and 2A12-GCr₁₅. ZrO₂-ZrO₂ is the same kind of friction material, the wear of which is the most severe, and the output speed of the PUA attenuation is the fastest.

The discreteness of the output velocity of the PUA for long-distance operation was analyzed. It can be seen from Figure 6 that the velocity dispersions of the ZrO₂-Si₃N₄ and ZrO₂-GCr₁₅ friction pairs are small, and the velocity dispersion of 2A12-GCr₁₅ is the largest. However, the output speed of the ZrO₂-GCr₁₅ combination fluctuates violently in the second half of the whole operation cycle of the PUA, which is caused by cracks on the surface of the abrasive particles and mover. The discrete type of the output speed of the PUA is accurately analyzed by a statistical method. A histogram of the output velocity distribution of the four different friction pairs is shown in Figure 6. It can be seen intuitively that the output speed distributions of ZrO₂-Si₃N₄, ZrO₂-GCr₁₅ and 2A12-GCr₁₅ are approximately normal, the output speed distribution of ZrO₂-ZrO₂ is not obvious and the speed stability is not good.

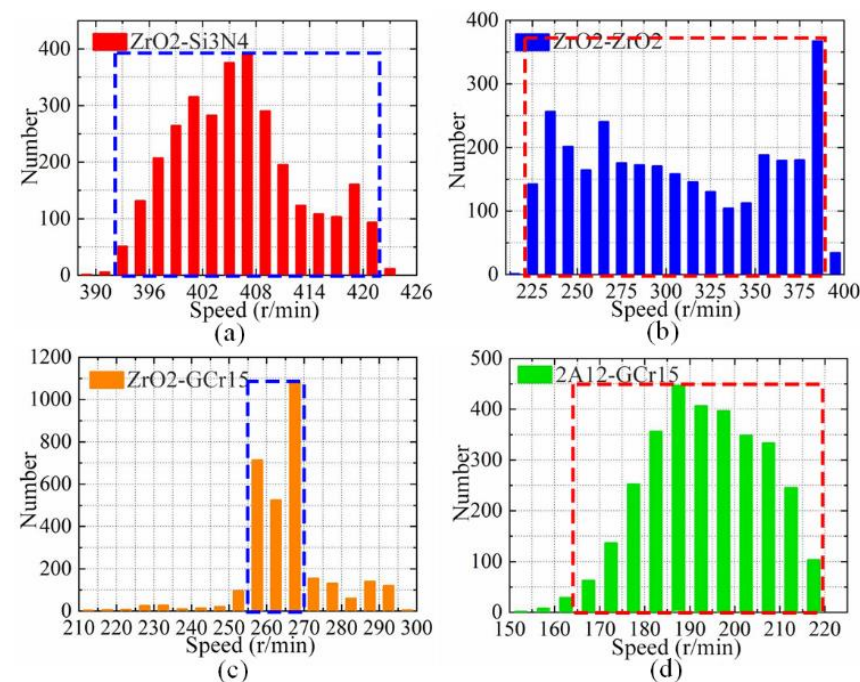


Figure 6. Statistical histogram of the output velocity of different friction pairs: (a) ZrO₂-Si₃N₄; (b) ZrO₂-ZrO₂; (c) ZrO₂-GCr₁₅; (d) 2A12-GCr₁₅.

In order to further quantitatively evaluate the stability of the output speeds of the four friction pairs, the part of the concentrated distribution of the output speeds in the dotted box in Figure 6 was selected for speed distribution analysis, and the mean value (V_m), standard deviation (SD), corrected sum of squares (CSS), coefficient of variation (CV), skewness (S) and kurtosis (K) of their output speeds were calculated, respectively. The calculation formula is as follows:

$$\left\{ \begin{array}{l} CV = \frac{SD}{\bar{x}} \\ V_m = \frac{x_1 + x_2 + \dots + x_n}{n} \\ SD = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \dots + (x_n - \bar{x})^2}{n}} \\ CSS = (x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \dots + (x_n - \bar{x})^2 \\ S = \frac{\sqrt{n(n-1)}}{n-2} \left[\frac{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^3}{\left(\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2 \right)^{\frac{3}{2}}} \right] \\ K = \frac{(n+1)n}{(n-1)(n-2)(n-3)} \sum_{i=1}^n \left(\frac{(x_i - \bar{x})^4}{s} \right) - \frac{3(n-1)^2}{(n-2)(n-3)} \end{array} \right. \quad (1)$$

where x_i is the speed sample, n is the number of samples and $\bar{x}$ is the speed average.

The calculation results are shown in Table 3.

Table 3. Discrete analysis parameters of the output speed of actuators with different friction pairs.

Friction Pairs	V_m	SD	CSS	CV	S	K
ZrO ₂ -Si ₃ N ₄	406.06	7.01	1.53×10^5	0.01726	0.36572	−0.50952
ZrO ₂ -ZrO ₂	307.39	53.29	88.5×10^5	0.17336	0.08296	−1.36762
ZrO ₂ -GCr ₁₅	265.50	11.08	3.83×10^5	0.04173	−0.03711	2.60159

The mean velocity (V_m) reflects the output performance of different friction pairs. The mean velocities (V_m) of ZrO₂-Si₃N₄, ZrO₂-ZrO₂, ZrO₂-GCr₁₅ and 2A12-GCr₁₅ are 406.06 r/min, 307.39 r/min, 265.50 r/min and 193.46 r/min respectively. The output performance of ZrO₂-Si₃N₄ is the best, followed by those of ZrO₂-ZrO₂ and ZrO₂-GCr₁₅, and that of 2A12-GCr₁₅ is the worst. The standard deviation (SD), corrected sum of squares (CSS) and coefficient of variation (CV) reflect the dispersion of speed. The order of the three evaluation indexes from small to large is ZrO₂-Si₃N₄, ZrO₂-GCr₁₅ and 2A12-GCr₁₅, ZrO₂-ZrO₂, which fully shows that the discrete type of the ZrO₂-Si₃N₄ output speed is the smallest, that of ZrO₂-GCr₁₅, 2A12-GCr₁₅ is the second smallest and the ZrO₂-ZrO₂ output speed is the largest. Skewness (S) and kurtosis (K) reflect the distribution of the output speed of the PUA, and skewness (S) reflects the symmetry of the operating speed. The skewness (S) values of ZrO₂-Si₃N₄ and ZrO₂-ZrO₂ are positive, indicating that their speed is concentrated on the left side of the mean value, and the skewness (S) values of ZrO₂-GCr₁₅ and 2A12-GCr₁₅ are negative; it shows that the velocity is concentrated on the right side of the mean value. Kurtosis (K) reflects the aggregation degree of the velocity in the mean center. The kurtosis (K) value of ZrO₂-GCr₁₅ is the largest, and the velocity aggregation degree is the best. However, in the second half of the operation, the output velocity fluctuates violently due to the generation of abrasive particles and mover surface cracks.

3. Discussion and Friction Material Selection

According to Hertz contact theory [32], when the stator of the PUA is in contact with the mover, the depth h of the driving foot pressing into the mover can be calculated as follows:

$$h = \frac{F}{\pi l} \times \frac{1 - v^2}{E} \left(2 \ln \frac{2R}{\sqrt{\frac{F}{\pi l} \times \frac{R}{E}}} - 1 \right) \quad (2)$$

$$\frac{1}{E} = \left(\frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right) \quad (3)$$

where F is the preload between the driving foot and the mover, l is the contact thickness between the driving foot and the mover (mm), R is the radius of the driving foot (mm), h is the driving foot pressuring depth into the mover, v is the equivalent Poisson's ratio of the stator, E is the equivalent modulus of the friction pair composed of the actuator and the stator, E_1 is the elastic modulus of the stator and E_2 is the elastic modulus of the mover.

The output force of the PUA was tested by combining different friction pair materials, and the variation law of the output force with the excitation voltage and preload was measured, respectively, the equivalent elastic modulus E and friction coefficient of the four friction pair materials are shown in Table 4.

Table 4. Equivalent elastic modulus and friction coefficient of different friction pair combinations.

Friction Pair Material	ZrO ₂ -Si ₃ N ₄	ZrO ₂ -ZrO ₂	ZrO ₂ -GCr15	ZrO ₂ -PEEK
Equivalent elastic modulus E (GPa)	126.8	105	104.5	3.73
Friction coefficient	0.13	0.11	0.13	0.14

Assuming $F = 100$ N, $l = 2$ mm, $R = 4$ mm and $v = 0.3$, the relationship between the depth h of the driving foot pressing into the mover and the equivalent elastic modulus E of the stator and mover is obtained, as shown in Figure 7a. It can be seen that the depth h of the driving foot pressing into the mover gradually decreases with the increase in the equivalent elastic modulus E , and the depth h of the driving foot pressing into the mover decreases rapidly when the equivalent elastic modulus E is small. When the equivalent elastic modulus E is large, the depth h of the driving foot into the mover decreases slowly.

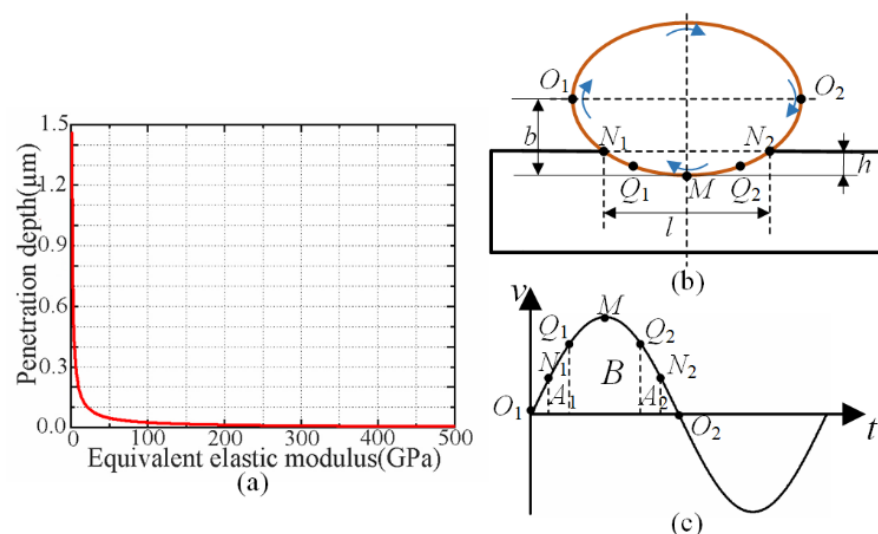


Figure 7. Micro-mechanism analysis. (a) Relationship between pressuring depth and equivalent elastic modulus. (b) Stator and mover micro-drive model. (c) Horizontal movement speed of the driving point.

The power transmission process between the stator and the mover of the PUA is analyzed. As shown in Figure 7b,c, during the elliptical motion of the point on the driving foot of the PUA, its horizontal velocity can be expressed as follows:

$$v_x = d_x' = A\omega \sin(\omega t) \quad (4)$$

where d_x represents the displacement in the horizontal direction, A is the velocity amplitude, ω is the frequency of the speed and its velocity is a sinusoidal curve. When the driving foot is at point O_1 in the initial state, the horizontal speed is 0, and when it moves to point M , the horizontal speed reaches the maximum. Then, in the process of driving the foot from point M to point O_2 , the speed gradually decreases to 0. The stator experiences the process from contact to separation with the mover. Point N_1 is the contact point, point N_2 is the separation point and points Q_1 and Q_2 are the points where the horizontal speed of the stator is equal to the speed of the mover, which is called the isokinetic point. When the stator moves from point N_1 to point Q_1 , the stator speed is less than the mover speed, and the friction does negative work to the mover. When the stator moves from point Q_1 to point Q_2 , the speed of the stator is greater than that of the mover, and the friction does positive work to the mover. When the stator moves from point Q_2 to point N_2 , the stator speed is less than the mover speed, and the friction does negative work to the mover. When the positive work and negative work done by the friction on the mover are equal, the output speed of the mover is stable.

For different friction materials, the pressuring depth h between the stator and actuator is closely related to its elastic modulus. The pressuring depth h between the stator and actuator is smaller when the equivalent elastic modulus E is larger, so the position of the contact point between the stator and actuator moves backward. In this case, if the location of the uniform point remains at the previous position, the positive work done by the friction force on the mover remains unchanged, while the negative work decreases, which does not meet the law of energy conservation. Therefore, the isokinetic point must be increased to reduce the positive work and increase the negative work to achieve an energy balance. Therefore, the friction pair combination with the larger equivalent elastic modulus E has a higher output speed.

When the equivalent elastic modulus E of the friction pair material is smaller, the pressuring depth h between the stator and the mover is larger, which leads to a larger effective contact area between the stator and the mover, and the friction force is increased to a certain extent, thus increasing the output force of the PUA. However, when the pressuring depth is too large and exceeds a certain critical value, the elliptical motion trajectory of the stator will “fall” into the mover, which reduces the power transmission efficiency and the output force of the PUA. By comprehensively comparing the mechanical output performance and the stability of the output speed of the PUA under different friction pair material combinations, it can be found that the ZrO_2 - Si_3N_4 material combination has a better performance in terms of output speed and speed stability than that of other friction pair materials. The output force of the ZrO_2 - Si_3N_4 combination is better under a high preload, but the performance under a low preload is not as good as that of other friction pair combinations. The piezoelectric ultrasonic actuated linear platform is developed in this work, which is rarely used in applications where the output force is required, so the combination of the ZrO_2 - Si_3N_4 friction pair is selected. The piezoelectric linear driving platform developed in this work has a low demand for the output force in application, so the ZrO_2 - Si_3N_4 friction pair combination is selected.

4. Results

In order to measure the mechanical output characteristics of the PUA linear motion platform, an experimental test system was built. The overall dimensions of the platform in the X, Y and Z directions are 80 mm, 51.5 mm and 66 mm, respectively, as shown in Figures 8 and 9a. The driving power supply of the system adopted the commercial QD-8D ultrasonic power supply. The magnetic grid displacement sensor (Model: MSK

200/1-0085, SIKO GmbH, Buchenbach, Germany) and the data acquisition card (DAQ card) (Model: PCI 2394, Beijing Art Technology Development Co., Ltd., Beijing, China) were used to measure the motion displacement of the linear platform and collect the test data, respectively. The collected data were displayed and processed on the PC; the weight block was placed on the platform to measure the load speed output characteristics of the linear platform.

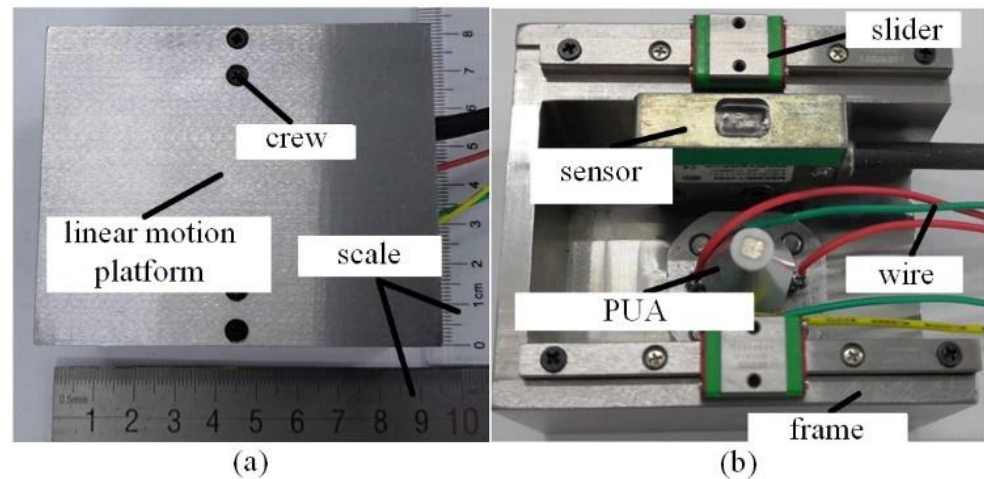


Figure 8. Linear platform system. (a) Appearance top view. (b) Internal structure.

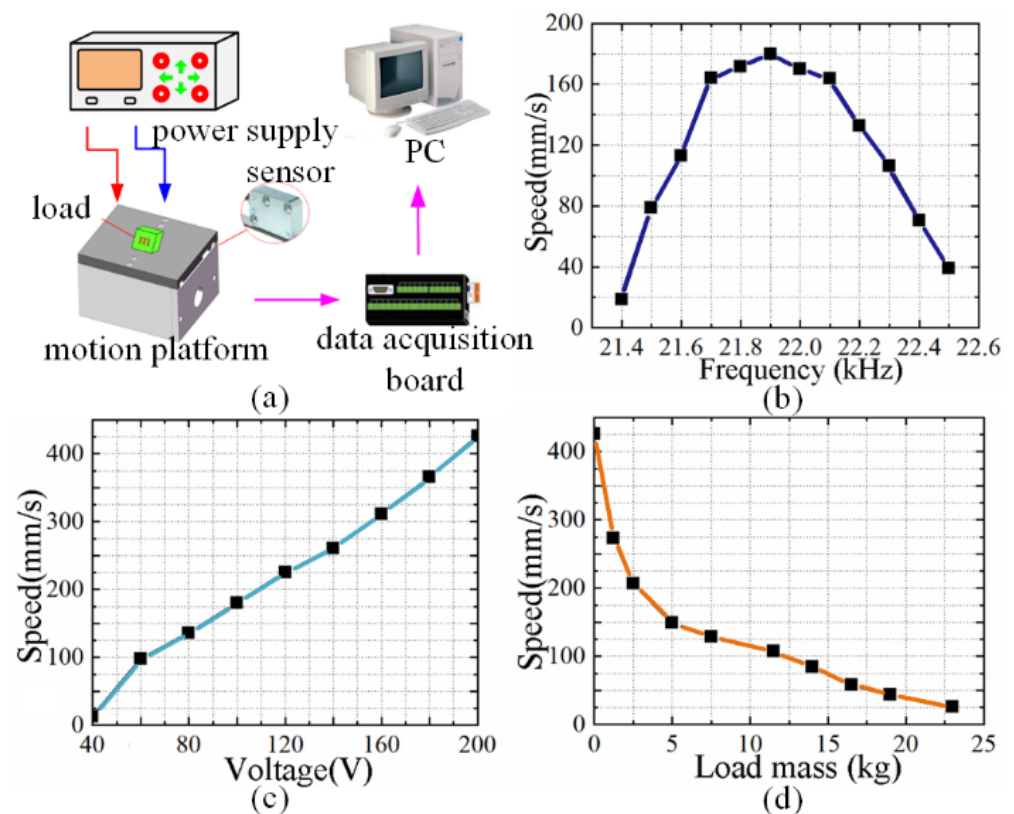


Figure 9. Application test system and experimental results. (a) Experimental test system for the mechanical output characteristics of the linear motion platform. (b) Relationship between the speed and frequency. (c) Relationship between the speed and excitation voltage. (d) Relationship between the speed and load mass.

The speed and frequency characteristics of the linear motion platform were tested to determine the best working frequency point of the linear motion platform by the experi-

mental platform. During the experiment, the excitation voltage was $100 V_{p-p}$, the phase difference of the two excitation signals was 90° , the preload between the driving foot and the mover was 18 N and the frequency of the excitation signal increases from 21.4 kHz to 22.5 kHz. As shown in Figure 9b, the experimental results show that, with the increase in the excitation frequency, the motion speed of the linear platform increases at the beginning and then decreases. When the excitation frequency is 21.9 kHz, the maximum output speed of the linear platform is 179.8 mm/s, indicating that 21.9 kHz is the best working frequency point of the linear motion platform.

The speed and excitation voltage characteristics of the linear platform were tested with the measured optimal frequency point. The experimental results are shown in Figure 9c. It can be seen from the experimental results that the output speed of the linear platform increases significantly with the increase in the excitation voltage, which is approximately linear with the excitation voltage. When the excitation voltage reaches $200 V_{p-p}$, the output speed can reach 426.2 mm/s. When the excitation voltage is less than $40 V_{p-p}$, the output speed is 0, which shows that, when the excitation voltage is less than $40 V_{p-p}$, the foot end displacement of the PUA is not enough to overcome the maximum static friction between the actuator and the mover.

The speed and load characteristics of the platform were tested under an excitation voltage of $200 V_{p-p}$, a frequency of 21.9 kHz and a phase difference of 90° . The experimental results are shown in Figure 9d. The experimental results show that the output speed decreases with the increase in the load mass. When the load mass is less than 5 kg, the output speed decreases faster, and when the load mass is greater than 5 kg, the output speed decreases slowly. When the load mass is 23 kg, the output speed of the platform is 25.75 mm/s, which performs a strong load capacity.

The output displacement resolution of the linear platform was tested under the excitation of the pulsed AC sinusoidal excitation signal, as shown in Figure 10a. The excitation voltage was $100 V_{p-p}$, the excitation signal frequency f_r was 21.9 kHz, the frequency f_s of the step cycle was 100 Hz and the preload between the driving foot and the mover was 18 N. The output displacement of the linear platform was obtained by changing the number of sinusoidal signals in a step cycle to 20, 30, 40, 50 and 60, respectively, as shown in Figure 10b. The experimental results show that, under the excitation of the pulsed AC sinusoidal excitation signal, the linear platform outputs a stepping motion, and the number n of sinusoidal signals in a step cycle significantly affects the stepping displacement of the linear platform. The measurement resolution of the magnetic grid displacement sensor is $0.5 \mu\text{m}$. When the number of signals is less than 5, the magnetic grid displacement sensor can no longer meet the measurement requirements; it was replaced by capacitive displacement sensors (PI D-E20.050, German PI Co., Ltd., Karlsruhe, Germany) with a range of $50 \mu\text{m}$ and a dynamic resolution of 1 nm. The experimental results show that, when there is only one sinusoidal signal, the linear platform can reach a motion step of about 85 nm, that is, the PUA can achieve a nano-level high resolution in the resonant working state when there is only one sinusoidal signal. The output displacement of the linear platform is shown in Figure 10c.

The comparisons between the proposed ultrasonic motor and some existing ultrasonic motors are listed in detail in Table 5. Izuhara et al. proposed a miniature linear ultrasonic motor with a size of $2.6 \times 2.6 \times 2.2 \text{ mm}^3$ and a maximum output speed of 140 mm/s at $150 V_{p-p}$. The motor has a compact structure but a small load capacity [33]. Smithmaitrie et al. proposed a dual transducer ultrasonic motor with a motor size of $85 \times 6 \times 1 \text{ mm}^3$ and a maximum output speed of 176.2 mm/s under $60 V_{p-p}$. The structure of the dual transducer is complex, and the machining accuracy is complex, so it is difficult to ensure the consistency of the actuator [34]. Shi et al. proposed a precision linear ultrasonic motor with a size of $55 \times 26 \times 14 \text{ mm}^3$, and the speed reaches 159 mm/s under a $400 V_{p-p}$ driving voltage [35]. The maximum speed of the motor proposed in this paper is 179.8 mm/s under $100 V_{p-p}$, the load mass can reach 23 kg and the resolution in the resonance mode is 85 nm. These performances are significantly better than that of the several motors listed in Table 5.

Therefore, the proposed motor has a wide application potential in the fields of high-speed, large-load and precision drive applications.

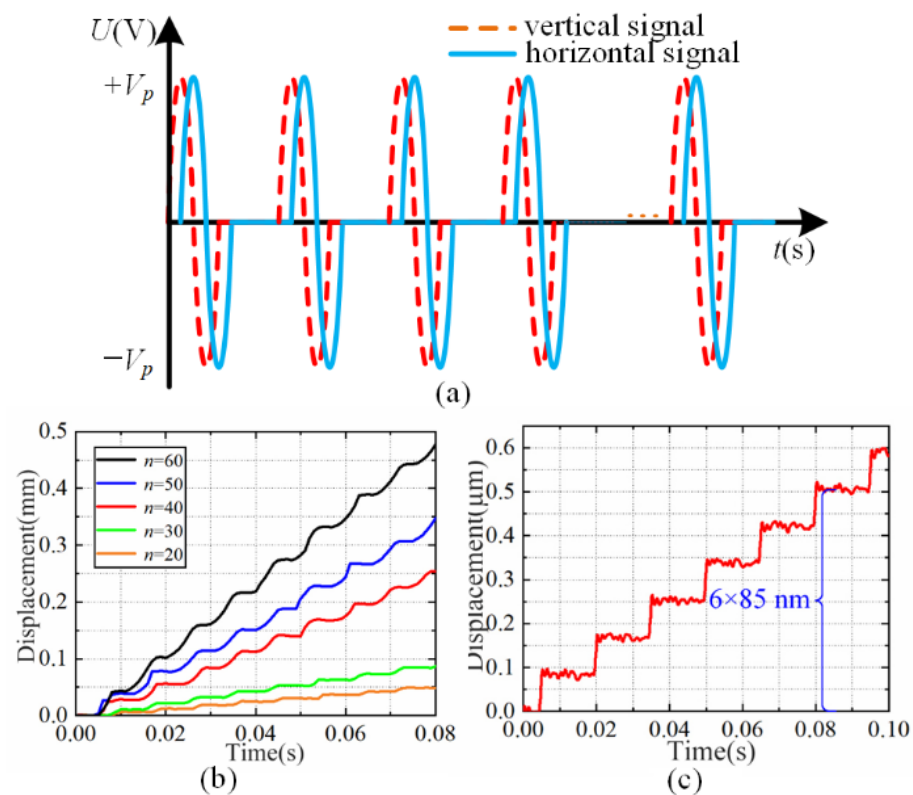


Figure 10. Excitation signal and output displacement characteristics. (a) Sinusoidal alternating current pulse signal. (b) Output displacement under the pulse signal. (c) Output displacement under one signal.

Table 5. Comparison between the proposed ultrasonic motor and some existing works.

Parameters	This Work	The Motors in [33]	The Motors in [34]	The Motors in [35]
Total size (mm)	$30 \times 30 \times 34.2$	$2.6 \times 2.6 \times 2.2$	$85 \times 6 \times 1$	$55 \times 26 \times 14$
Voltage (Vp-p)	100	150	60	400
Speed (mm/s)	179.8	140	176.2	159
Load mass (kg)	23	/	/	/
Resolution (μm)	0.085	/	/	/

5. Conclusions

In this study, ZrO_2 was used as the driving foot surface material of the PUA to form a friction pair with Si_3N_4 , ZrO_2 , $GCr15$ and PEEK, respectively. The variation rules of the output speed with the excitation voltage and preload were tested, respectively, by four friction pairs. The output speeds of the friction pair composed of $ZrO_2-Si_3N_4$ is the best under the same excitation voltage or preload. Then, the variation rules of the output force with the excitation voltage and preload were tested, respectively. The output force of $ZrO_2-Si_3N_4$ is always the largest under the same excitation voltage. When the preload force is greater than 6.5 N, the output force of $ZrO_2-Si_3N_4$ is always greater than that of other friction pairs. Under an excitation signal of $200 V_{p-p}$ and a preload of 2 N, different combinations of friction pairs are used to drive the mover for 500 m to test the output stability. In the long-term test of the friction pair composed of $ZrO_2-Si_3N_4$, the attenuation percentage of the speed from the initial state to the end state in the speed rising stage of 50 m is 3.66%. According to the experimental results, the combination of $ZrO_2-Si_3N_4$

has the best output characteristics and was thus selected and applied to the linear motion platform. The maximum output speed of the platform can reach 426.2 mm/s; it can achieve a high resolution of about 85 nm and has good load characteristics, which are important to push the technological development of high-end manufacturing equipment. This work also provides an idea for improving the output capacity and long-term operation stability of ultrasonic motors and provides a possibility for expanding the application range of ultrasonic motors.

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