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An Umbrella-Shaped Linear Piezoelectric Actuator Based on Stick-Slip Motion Principle

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ABSTRACT Piezoelectric actuators are widely utilized in many research and industrial fields, since they could achieve high positioning accuracy based on inverse piezoelectric effect. However, the working stroke of piezoelectric actuators is always limited, which restricts the further application of piezoelectric actuators. In order to solve this problem on short working stroke, this study introduces an umbrella-shaped linear piezoelectric actuator to achieve a large working stroke. Unlike traditional stick-slip actuators, the PZT stack inside the umbrella-shaped flexure mechanism is assembled vertically to the slider. The composition and motion principle are discussed, and FEM (Finite Element Method) and experiments are utilized to explore the performance of the proposed actuator. Experimental results show that the minimum stepping displacement is 0.495μm in the case that the input voltage $U = 30$V and the frequency $f = 1$Hz; the maximum speed is 992.4μm/s under the condition of the input frequency $f = 400$Hz and the input voltage $U = 120$V; the maximum load is 220g in the case of the input voltage $U = 120$V and the frequency $f = 1$Hz. This study indicates that the proposed umbrella-shaped linear piezoelectric actuator is feasible and could achieve a stable large working stroke.

INDEX TERMS Nano positioning, piezoelectric actuator, high accuracy, inverse piezoelectric effect, large working stroke.

I. INTRODUCTION

With the fast development of the nano technology, nano positioning has been applied gradually in our modern advanced fields such as aviation, optical engineering, biomedical engineering, and semiconductor processing [1]–[5]. Nano positioning requires high precision up to nano/micro accuracy which is difficult for traditional actuators to meet [6]. Piezoelectric actuator based on the inverse piezoelectric effect of piezoelectric material is becoming a new way which could meet the requirement of nano/micro accuracy to solve the problem. Piezoelectric actuator generally could be divided into direct-push type and step type based on their motion principle [7]–[9]. Direct-push type actuator pushes the output part directly when the piezoelectric material gets power to expand. The direct-push type actuator has the characteristics of simple structure, no friction and wear and fast response, but the working stroke is limited to only several microns because of the minor deformation of the piezoelectric material. To improve the working stoke, many efforts have been done such as applying flexure hinge magnification mechanism which amplify the output displacement of the piezoelectric element. However, the working stroke reaches only hundreds of microns and the working frequency drops distinctly, which seriously limits the application of the direct-push type actuator [10]. Thus, to develop a piezoelectric actuator with a large working stroke becomes a hot topic. In order to enlarge the working stroke of piezoelectric actuators, the step type actuator is proposed, which exploits the step motion for large working stroke. Even though the step

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in every motion cycle is minor, every step is accumulated to achieve a large working stroke [11], [12]. The step type actuator mainly has three types: ultrasonic type, inchworm type and stick-slip type. The ultrasonic type actuator achieves a large working stroke driving based on the inverse piezoelectric effect and the principle of ultrasonic vibration. In the working process, the inverse piezoelectric effect of piezoelectric material is used to excite the micro elliptical resonance of elastomer in the range of ultrasonic frequency. The ultrasonic type actuator has the advantages of simple structure, low noise but the wearing problem is serious and it is not suitable for continuous operation [13]. Inchworm type piezoelectric actuator which mimics the inchworm movement in nature combines the inchworm step motion and piezoelectric driving technology. Inchworm type piezoelectric actuator could obtain a large working stroke by alternate collaboration of its driving unit and clamping unit [14]–[16]. Inchworm type piezoelectric actuator has the ability to output high accuracy and load. However, it has the defects of the complicated structure and control system, which restricts its application.

The stick-slip type actuator which mainly consists of piezoelectric element, flexure hinge mechanism and mover could achieve a large working stroke via the step motion of the mover based on the inertia and friction force; its simple structure and easy control make it being a research hot direction [17]–[23]. Researchers have developed many stick-slip type actuators with stack-friction rods, and the structure of those stick-slip actuators with stack-friction rods is quite simple. Drevniok *et al.* has researched piezoelectric motors used in scanning probe microscopes [24]; Zhang *et al.* has studied a new two-degree-of-freedom piezoelectric rotary and linear actuator system, presented the conceptual design, dynamic modeling, control and prototype, and validated the feasibility by experiments [25]; Lee *et al.* has introduced a driving method that uses a single piezoelectric element to position a double slider, and applies it to a small zoom lens system [26]; Peng *et al.* has proposed a stick-slip drive method for bionic wing craft flapping mechanism [27]; Rong *et al.* has described a stick-slip accurate manipulator with a long-travel accurate positioning applied in scanning electron microscope (SEM) [28].

Besides, some researchers have investigated utilization of flexure mechanisms to achieve stick-slip motion, which makes it possible to assemble the PZT stacks vertically to the slider (high stiffness direction). The stiffness of the PZT stack in this vertical direction is much higher than that of the parallel actuators. Li *et al.* designed a piezoelectric actuator with the bridge-type flexure mechanism [12]. The parasitic motion of the bridge-type flexure mechanism has been analyzed. Cheng *et al.* explores the feasibility of the trapezoid-type flexure mechanism [29]. Zhang *et al.* talks about the application of triangle-type flexure mechanism to improve the working performance [30].

This study proposes a novel umbrella-shaped flexure mechanism to assemble the PZT stacks vertically to the slider which makes it compact and effective for the forward and backward directions. The feasibility of the application of the umbrella-shaped flexure mechanism has been investigated. Based on the stick-slip principle and the umbrella-shaped flexure mechanism, a linear piezoelectric actuator which could achieve large working stroke is obtained. The high stiffness of PZT stacks in the working direction is utilized. The structure and the motion principle are described in detail, and the FEM is used to investigate the asymmetrical deformation of the proposed umbrella-shaped flexure mechanism; furthermore, experiments are carried out to study the performance of the proposed actuator.

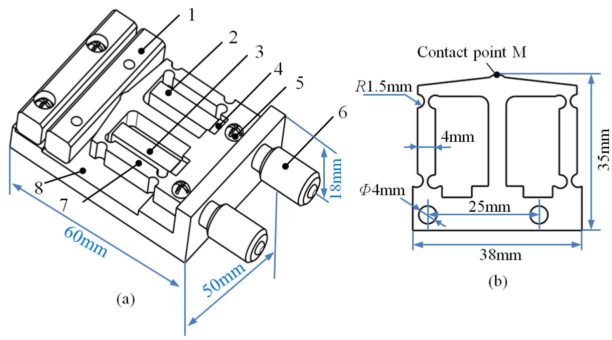


FIGURE 1. Structure of the proposed actuator: (a) overview: 1-linear slider, 2-PZT stack 1, 3-PZT stack 2, 4-wedge block, 5-screw, 6-micrometer knob, 7-umbrella-shaped flexure mechanism, 8-base; (b) size of the umbrella-shaped flexure mechanism.

II. STRUCTURE AND PRINCIPLE

A. STRUCTURE

The umbrella- shaped linear piezoelectric actuator consists of a linear slider, two PZT stacks, two pairs of wedge blocks, four screws, two micrometer knobs, an umbrella-shaped flexure mechanism and a base as Figure 1(a) showed. The linear slider and the umbrella-shaped flexure mechanism which contact with each other are fastened in the base by screws and two PZT stacks and wedge blocks are assembled inside of the umbrella-shaped flexure mechanism. Two micrometer knobs coordinating with the two fasten screws are used to control the preload force between the umbrella-shaped flexure mechanism and the linear slider. Figure 1(b) shows the dimension information of the umbrella-shaped flexure mechanism. The general size of the proposed actuator is $60\times50\times18$mm which is determined by the utilized slider and PZT stacks.

B. MOTION PRINCIPLE

Figure 2 illustrates motion principle of the umbrella-shaped flexure mechanism. M is the contact point of the umbrella-shaped flexure mechanism and the slider, and A, B, C, D, E, H denote circular flexure hinges, N is the contact point of the piezo-stack and the beam EH of the umbrella-shaped flexure mechanism. In the case that the piezo-stack gets power to extend, as Figure 2(a)(b) showed, the piezo-stack drives the umbrella-shaped flexure mechanism deformed and point M will move to the position of M', which drives the slider to move due to the friction force. The umbrella-shaped flexure mechanism is designed as a symmetrical structure; thus the

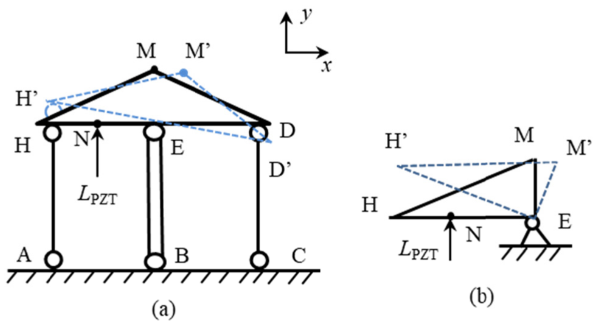


FIGURE 2. Motion principle of the umbrella-shaped flexure mechanism.

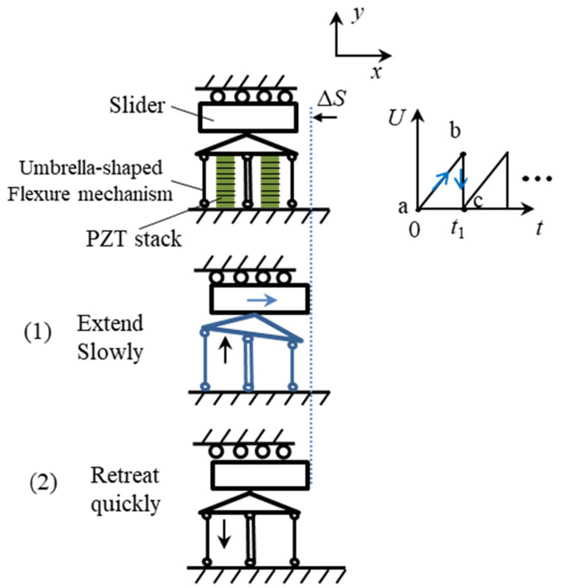


FIGURE 3. Motion principle of the proposed umbrella-shaped linear piezoelectric actuator.

slider will be driven moving reversely when the other piezo-stack gets power.

Figure 3 illustrates motion principle of the proposed umbrella-shaped linear piezoelectric actuator. In the initial, all the parts are assembled as Figure 1 showed. The saw tooth voltage applied on the PZT stack as figure 3 showed is a recycling signal. The motion process of the proposed umbrella-shaped linear piezoelectric actuator is divided into two steps. Step (1): the saw tooth voltage is growing gradually from a to b. The PZT stack gets the power to extend slowly and drives the umbrella-shaped flexure mechanism deformed, which drives the slider moving. Step (2): the saw tooth voltage drops sharply from b to c. The PZT stack retreats back quickly and the umbrella-shaped flexure mechanism retracts correspondingly. However, the slider almost keeps still because of the inertial force, which means the slider has moved a distance ΔS in x direction compared with the initial position when a cycle ended. Driving by the recycling voltage signal and repeating the step (1) and step (2), a large working stroke is obtained. The motion direction is changed by utilizing the other PZT stack.

III. SIMULATION AND DISCUSSION

To explore the performance of the proposed umbrella-shaped linear piezoelectric actuator, FEM (Finite Element Method) is utilized. The 3D model of the umbrella-shaped flexure mechanism is built up and the simulation software COMSOL is used to do the analysis. The material of the umbrella-shaped flexure mechanism is 7075 Al; two bottom fastening holes are limited with no freedom; displacement loads L_{PZT} are applied on the beam EF to simulate the PZT stack driving the umbrella-shaped flexure mechanism. Figure 4(a) shows stress of the umbrella-shaped flexure mechanism in the case of the $L_{PZT} = 10\mu$m. The contact point between the flexure mechanism and the slider marked with a red circle bears the maximum stress. The maximum stress S_{max} is 362MPa which is not beyond the yield strength of 7075 Al (the yield strength of 7075 Al = 445MPa).

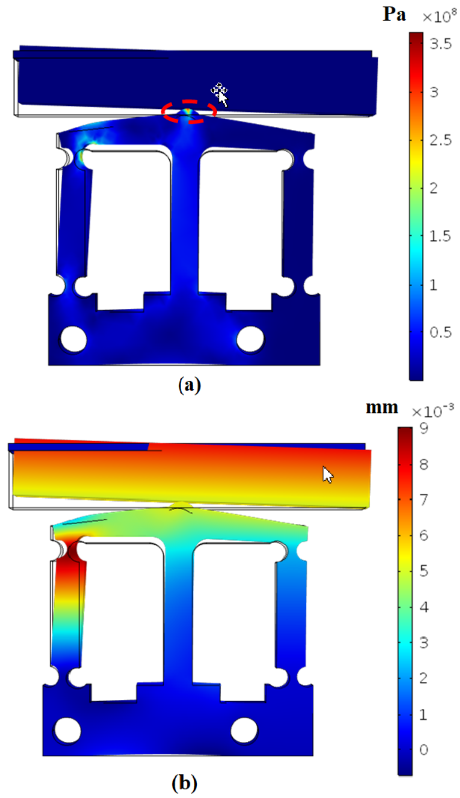


FIGURE 4. FEM results: (a) Stress distribution, (b) displacement distribution.

Figure 4(b) shows the displacement of the umbrella-shaped flexure mechanism under $L_{PZT} = 10\mu$m. The motion displacement of slider in x direction is about 7.7μm under the input of LPZT = 10μm. Additionally, the resonant frequencies of the umbrella-shaped flexure mechanism are also investigated by COMSOL. The first three resonant frequencies of the proposed umbrella-shaped flexure mechanism have also been investigated by FEM method, which are 3765.2 Hz, 4118.5 Hz and 6318.9 Hz, respectively.

IV. RESULTS

A. EXPERIMENTAL SET-UP

The prototype of the proposed actuator is machined by wire electro discharge machining (WEDM) and the experimental system is set up as is showed in Figure 5. The experimental system is made up of personal computer (PC), signal

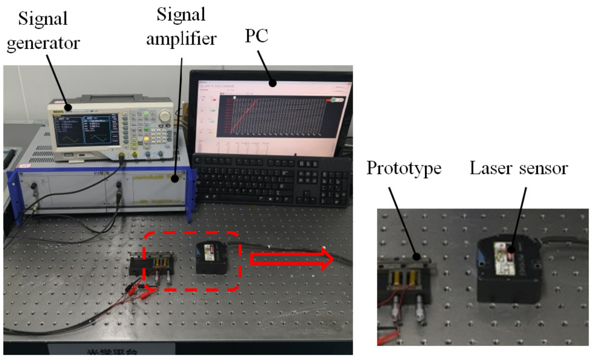


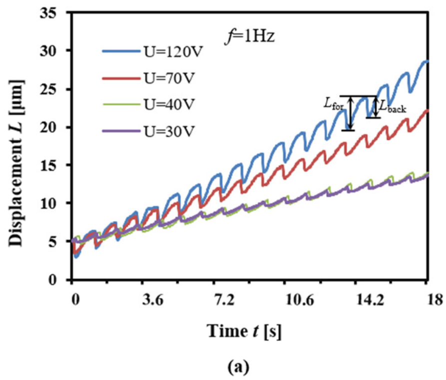
FIGURE 5. Experimental system.

generator (33522A, Agilent Ltd.), signal amplifier (9400, Tabor Electronics Ltd.), prototype of the proposed actuator and laser sensor (LK-H080, Keyence Ltd.). In the process of the experiment, the saw tooth voltage signal is generated by the signal generator and amplified by the signal amplifier. The ratio of the width for the input saw tooth voltage is set as 100%. And then the amplified saw tooth voltage signal is applied on the piezoelectric stack seated in the prototype. The laser sensor detects the displacement information while the slider is moving driven by the piezoelectric stack in the prototype indirectly. The displacement information is transmitted to and showed on the PC. Based on the experimental system, a lot of tests to investigate the performance of proposed actuator were carried out.

B. PERFORMANCES

Figure 6 shows the relationship of the input voltage and the displacement in the case of the frequency $f = 1$Hz. Figure 6(a) shows the displacement change along with the time increasing in the case of different input voltage such as $U = 120$V, 70V, 40V, 30V (a series of input voltage value has been tested, a few input voltage values showed in the Figure 6 is only for indicating the change trend). It is seen the displacement is ascending in general along with the time increasing, and the large working stroke is achieved by each step accumulating. During the extension of PZT stacks, the direct force and the contact force will increase, which lead to the nonlinear deformation of the umbrella-shaped flexure mechanism. That is thought to be the reason why the shape of the output displacement curves changes. In each step motion, it is found that periodic backward moving appears following forward moving. The backward moving is thought to be caused by the friction between the umbrella-shaped flexure mechanism and the slider. When the piezo-stack retraction along with the input voltage sharply decreasing, the umbrella-shaped flexure mechanism returns to initial correspondingly and drive the slider moving back via friction. If we use L_{for} represents forward-moving displacement and L_{back} represents the back-moving displacement, the actual stepping displacement ΔL is obtained as equation (1) showed.

$$\Delta L = L_{for} - L_{back} \tag{1}$$



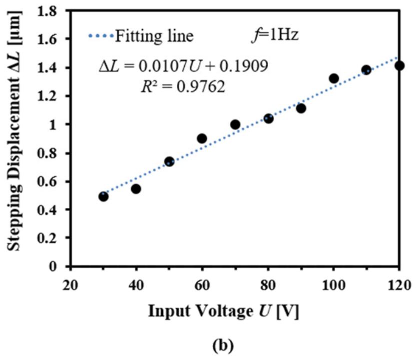


FIGURE 6. Relationship of the input voltage and the displacement in case of the frequency $f = 1$Hz. (a) Displacement under different input voltages (b) Relationship of the stepping displacement and input voltage.

Figure 6 (b) shows the relationship of the stepping displacement and the input voltage in the case of the frequency $f = 1$Hz. The stepping displacement ΔL is growing gradually from 0.495μm to 1.412μm in pace with the input voltage rise up from 30V to 120V. The correlation coefficient is $R^2 = 0.9762$, which indicates the system stability. The stepping displacement could be linearly expressed as $\Delta L = 0.0107U + 0.1909$. If the input voltage $U < 30$V or $U > 120$V, the prototype could not work stably. Thus, the maximum stepping displacement is 1.412μm when $U = 120$V. The minimum stepping displacement is 0.495μm when input voltage $U = 30$V, which is treated as the resolution of the proposed actuator.

Input frequency is a factor which has great impact on the stepping displacement. Figure 7 shows the relationship of the input frequency and the stepping displacement in the case of input voltage $U = 120$V. The stepping displacement fluctuates between 1.12μm to 1.52μm while the input frequency is upward to 100Hz and then induces to 0.882μm when the input frequency is growing to 200Hz. After that, the stepping displacement starts to climb quickly to the peak of 2.481μm when the input frequency continues upward to 400Hz and then decrease to 0.019μm till the input frequency is up to 1300Hz. This is thought to be caused by the fact that in the case the input frequency is too high, the PZT stack could not has enough time to extend to the full length, and the flexure mechanism is influenced by the inertial force to react quickly. The prototype could not keep stably if the input

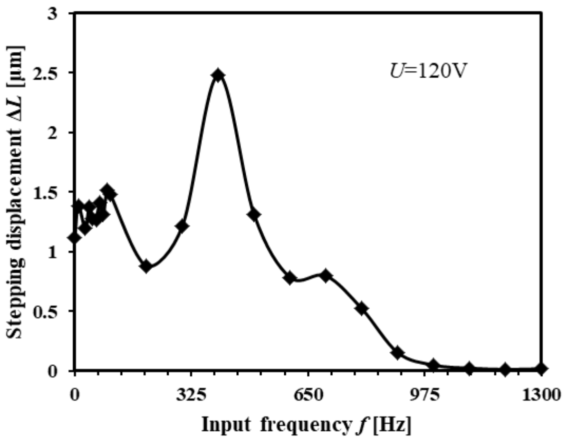


FIGURE 7. Relationship of the input frequency and the stepping displacement in the case of input voltage $U = 120$V.

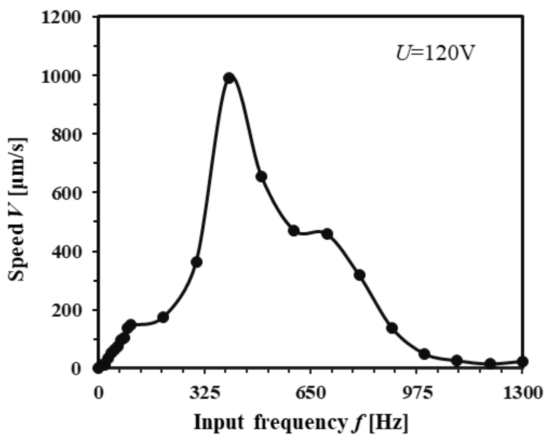


FIGURE 8. Relationship of the input frequency and the speed in the case of input voltage $U = 120$V.

frequency is over 1300Hz, which indicates the maximum stepping displacement is 2.481μm when the input frequency $f = 400$Hz and the input voltage $U = 120$V.

Speed is another important performance factor to the actuator. The speed could be obtained if the frequency multiplies by the stepping displacement, which is expressed by equation (2).

$$V = f \times \Delta L \tag{2}$$

Figure 8 illustrates relationships of the input frequency and the speed in the case of the input voltage $U = 120$V. The speed is improving while the input frequency is added to 400Hz and then starts to fall off reversely. In this process, the speed zooms up while the input frequency changes from 200Hz to 400Hz and goes down fast while the input frequency increases from 400Hz to 600Hz. When the input frequency is more than 1300Hz, the prototype of the actuator works unstably. The speed is obtained by equation (2), since the stepping displacement falls down quickly after 400 Hz, so as the speed. Thus, the maximum speed is up to 992.4μm/s when the input frequency is 400Hz and the input voltage $U = 120$V.

In order to investigate the dynamic performance of the proposed actuator, more experiments are carried out. Figure 9(a)

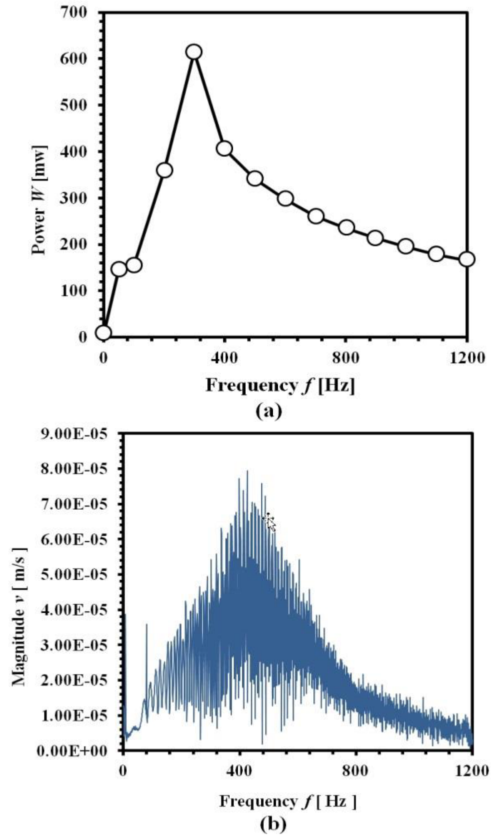


FIGURE 9. Dynamic performance: (a) power consumption, (b) vibration speed.

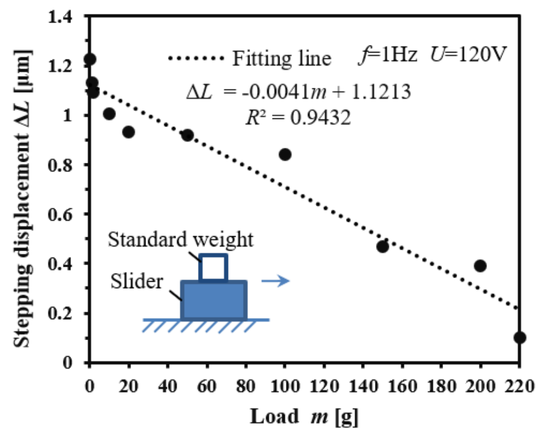


FIGURE 10. The relationship of the stepping displacement and load in the case of input voltage $U = 120$V and $f = 1$Hz.

shows the power consumption of the actuator during the experiments, which is measured by the equipment WT1802E from YOKOGAWA Company. It is seen that the largest power consumption of the actuator is 614 mw under the frequency of 300Hz, which is thought to be by the resonance phenomena. Hence, the vibration speed of the proposed actuator is carried out by PSV-500-M from POLYTEC Company. As is show in Figure 9(b), in the case that a gradual change signal is applied, the vibration speed of the slider in x direction increases first, and then falls down. The maximum vibration speed occurs in the case that the frequency is around 400 Hz, which could be utilized to explain the phenomena for the stepping displacement and the motion speed.

Figure 10 shows the relationship of the stepping displacement and load in the case of input voltage $U = 120$V and frequency $f = 1$Hz. In the test process, a series of standard weights are loaded on the slider, which is called the standard weight method. The mass of the standard weights are utilized to describe the load. It can be seen that the stepping displacement is declining linearly along with the load rising. The correlation coefficient $R^2 = 0.9432$ which indicates the system stability. The stepping displacement is expressed as $\Delta L = -0.0041m + 1.1213$. If the load $m >$220, the prototype could not work stably, which means the maximum load should be 220g when the input voltage $U = 120$V and the frequency $f = 1$Hz.

V. CONCLUSION

In this paper, an umbrella-shaped linear piezoelectric actuator is proposed and its structure and motion principle are described. FEM and experiments are performed to research the performance of the umbrella-shaped linear piezoelectric actuator. This paper indicates the proposed structure design of the umbrella-shaped linear piezoelectric actuator is feasible and it could achieve a large working stroke while high accuracy kept. The experiment results show that the minimum stepping displacement is 0.495μm when the input voltage $U = 30$V and the frequency $f = 1$Hz; the maximum stepping displacement is 2.481μm while the input frequency $f = 400$Hz and the input voltage $U = 120$V; the maximum speed is 992.4μm/s under the condition of the input frequency $f = 400$Hz and the input voltage $U = 120$V; the maximum load is 220g in the case of the input voltage $U = 120$V and the frequency $f = 1$Hz.

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