Stick-Slip Tower-Shaped Piezoelectric Actuator

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(Received 9 January 2015; revised 26 January 2015; accepted 12 February 2015)

Abstract: Since stick-slip actuators present the advantage of allowing long displacements (several centimeters or even more) at a high speed with an ultra high resolution (<5 nm), a new type of stick-slip piezoelectric actuator is proposed to attain sub-nanometer positioning accuracy. The actuator is composed of a slider and a tower-shaped stator using forced bending vibration in *y-z* plane to generate tangential vibration on the top of the driving foot. When excited by the sawtooth input voltage, driving foot of the stator is able to generate a tangential asymmetrical vibration on the top, and the slider is thus pushed to move. A prototype and its testing equipment are fabricated and described. Following that, the testing of vibration mode and mechanical characteristics as well as stepping characteristics are conducted. Experimental results show that under the condition that the sawtooth input voltage is 400 V_{P-P} and the pre-pressure is 6 N. Velocity of the actuator reaches its maximum 1.2 mm/s at the frequency of 8 000 Hz and drops to its minimum 35 nm/s at the frequency of 1 Hz. When the excitation signal is the single-phase sawtooth stepping signal, the tower-shaped actuator can directionally move forward or backward step by step. And when excited by the sawtooth stepping signal with 1 Hz and 300 V_{P-P} during 1 cycle (200 ms), the actuator has a minimum stepping distance of 22 nm.

Key words: piezoelectric actuator; stick-slip; sawtooth; stepping

CLC number: TM35 **Document code**: A **Article ID**: 1005-1120(2015)02-0156-07

0 Introduction

With the rapid development of ultra-precision machining and measuring instruments, semiconductor technology, micro-assembly and biomedical engineering micro-manipulator, and other modern high-tech, linear driving technology must meet many new requirements, such as large stroke, high speed and nano-positioning accuracy, high power density, and no electromagnetic interference. The piezoelectric actuator is well-known for its obvious comprehensive advantages in overall dimension, precision, response speed, output power and power density, etc. Therefore, the key to meet the requirements above is to research and develop a novel piezoelectric linear actuator with large stroke, high speed and nano-positioning accuracy[1-6].

As we all know, it is difficult for an actuator to allow both long displacements at a high speed and a high positioning accuracy at the same time. However, stick-slip actuators present the advantage of allowing longer displacements (several centimeters or even more) at a high speed with an ultra high resolution (<5 nm). Moreover, they are simple, compact and offer a high stiffness. Therefore, they are perfectly well adapted to challenge applications, e. g. micro-manipulation[7-8].

Based on the excellent performance of stick-slip actuators as well as a wide range of applications in modern high-tech fields, we propose a new type of stick-slip piezoelectric actuator.

1 Actuator Design

1.1 Design for tower-shaped stator

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How to cite this article: Chen Qianwei, Ju Quanyong, Huang Weiqing, et al. Stick-slip tower-shaped piezoelectric actuator[J]. Trans. Nanjing U. Aero. Astro., 2015,32(2):156-162.
http://dx.doi.org/10.16356/j.1005-1120.2015.02.156

As the tower-shaped structure is good at focusing energy, it is adopted into the design of the stator, as shown in Fig. 1. The stator in Fig. 1 consists of two columnar parts, both of which have a square cross section and have two piezoelectric ceramics attached to the upper and lower surfaces. The unit also has a tower-shaped driving foot connected with these two columnar parts.

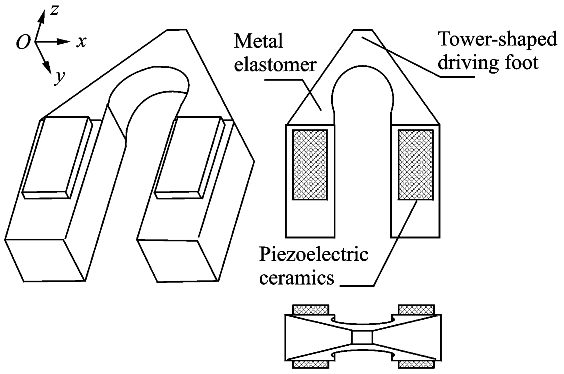


Fig. 1 Structure of tower-shaped stator

To construct the stick-slip actuator, it is necessary for the stator to generate a tangential asymmetrical vibration at its driving foot while moving in a direction parallel to that of the mover below when driven by a sawtooth wave signal. As for the tower-shaped stator in the paper, the forced bending vibration shown in Fig. 2 is designed to generate the desired tangential asymmetrical vibration in a non-resonant state.

To achieve the vibration mode for a non-resonant forced vibration as shown in Fig. 2, the polarization layout scheme is designed for the piezoelectric ceramic plates as shown in Fig. 3. The whole tower-shaped stator employes totally four plates of piezoelectric ceramics polarized in the thickness direction. The desired tangential asymmetrical vibration can be achieved by imposing a sawtooth wave signal on phase A which is formed by all four piezoelectric ceramic plates.

Fig. 4 shows the principle of how to take an advantage of the tangential asymmetrical vibration to make a stick-slip actuator. When a periodic continuing sawtooth wave signal which rises slowly at first and then drops quickly is applied to phase A of the stator, the driving foot of the stator will produce an asymmetrical vibration with the forward movement at a slow rate and the backward movement at a fast rate. It will then be able to drive the mover to go forwards. In contrast, when a reversed-phase sawtooth signal is applied, the driving foot of the stator will produce a reversed-phase asymmetrical vibration, which will then be able to drive the mover to go backwards.

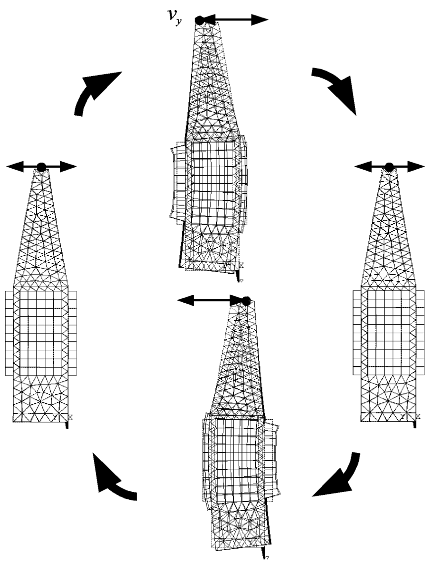


Fig. 2 Vibration type of non-resonant tangential forced vibration for tower-shaped stator

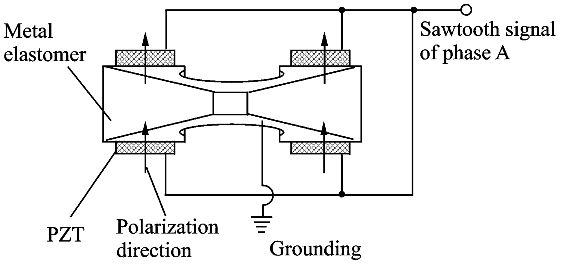


Fig. 3 Polarization layout of piezoelectric ceramics

We have fabricated a prototype of the stick-slip tower-shaped stator above, as shown in Fig. 5. The dimension of the stator prototype is 20 mm×6 mm×30 mm, with a mass of 20 g.

1.2 Overall structural design for actuator

After finishing the fabrication, it is necessary to take measures so as to build the tower-shaped actuator. This process involves: Designing and manufacturing the appropriate mover; Mounting stator and mover on a base in common; And choosing the correct pre-pressure to let the stator and mover contact with each

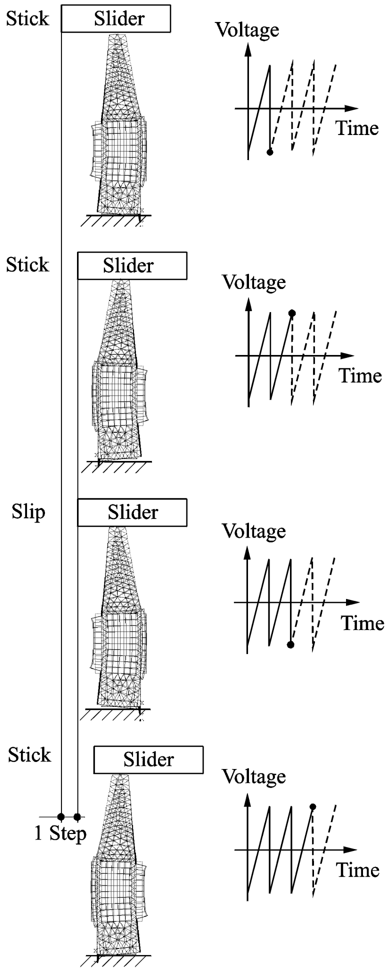


Fig. 4 Principle of stick-slip for tower-shaped stator

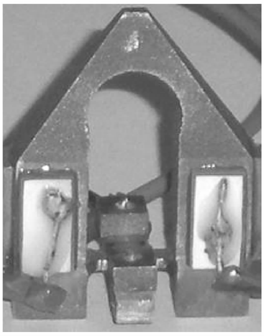


Fig. 5 Prototype of tower-shaped stator

other. All of these steps determine the overall structural design for the actuator. What is more, whether the overall structural design is reasonable or not, it will seriously affect operatiing stability and positioning accuracy of the actuator.

As it is common to purchase slider product or platform product as the mover of a linear actuator, we have to consider two major issues for the overall structural design of the actuator. The first issues the installation of the stator and mover. The second regards pre-pressure applied between stator and mover.

With reference to the overall structure of the nanomotion motor[9], we design a one-dimensional moving platform based on a three-roller structure driven by the tower-shaped stator, with a 30 mm platform stroke, as shown in Fig. 6.

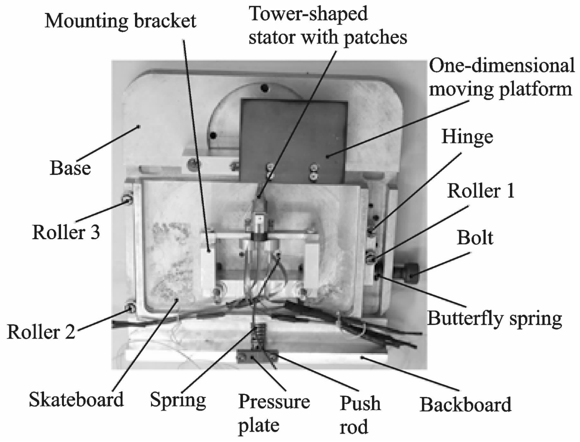


Fig. 6 One-dimensional moving platform driven by tower-shaped stator

This structure is primarily composed of three-rollers (bearings), skateboards, hinges, a common base, a pre-pressure loading mechanism, a tower-shaped stator, and a one-dimensional moving platform. As a result of using a three-roller structure as well as the effects of lateral bolts and butterfly springs, not only has the installation backlash of the stator been eliminated, but the tangential displacement stiffness is also far larger than the normal displacement stiffness from mounting clamp of the stator. This development can be very helpful to operational stability and positioning accuracy of the actuator[10].

2 Experiment

2.1 Modal experiments

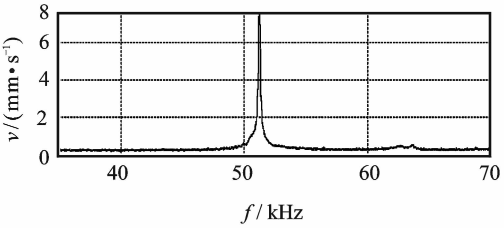
Modal experiments on the tower-shaped stator are conducted by using a PSV300F-B-type vibrometer system with a high frequency scanning laser produced by Polytec in Germany. The experimental results are shown in Fig. 7 and Table 1.

The experimental results show that:

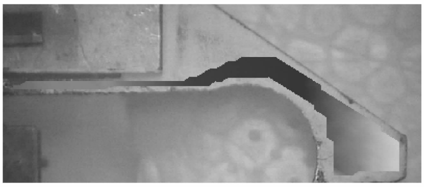
(1) Within the frequency range between 0 and 13 000 Hz, the amplitude-frequency curve for the bending vibration modal has no resonance peak. Thus, the bending vibration within the frequency range is always a non-resonant forced vibration.

Table 1 Tangential vibration amplitudes of driving foot against different excitation frequencies for tower-shaped stator with voltage of 80 V_{P-P} under non-resonant forced vibration

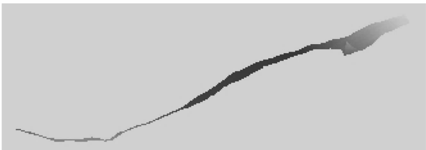
Excitation/ kHz	Tangential vibration amplitude/nm
1	50
4	40
7	40
10	30
13	30



(a) Amplitude-frequency curve for bending vibration modal in *y-z* plan



(b) Planar graph of vibration mode for forced bending vibration in range between 0 and 13 000 Hz in *y-z* plane



(c) Three-dimensional graph of vibration mode for forced bending vibration in range between 0 and 13 000 Hz in *y-z* plane

Fig. 7 Vibration type of tower-shaped stator for non-resonant forced bending vibration in *y-z* plane

(2) Within the frequency range between 0 and 13 000 Hz, the vibration mode for non-resonant forced vibration is very consistent with that of the designed one.

(3) Within the frequency range between 0 and 13 000 Hz, and under the fixed-frequency excitation voltage of 80 V_{P-P}, the vibration amplitudes of five typical sampling points for the non-resonant forced bending vibration are measured to range from 30 nm to 50 nm, which verifies the feasibility of the stick-slip principle.

2.2 Mechanical property experiments

The driving signal platform of the tower-shaped actuator is composed of a signal generator and a power amplifier. During the experiment, the signal generator sends out a single-phase sawtooth voltage signal. Then this signal is amplified by the power amplifier. The output of the voltage signal will drive the tower-shaped actuator.

Fig. 8 shows testing system of the tower-shaped actuator, which mainly consists of a one-dimensional moving platform and a Renishaw XL-80 laser interferometer, used to test the performance of the tower-shaped actuator. The Renishaw XL-80 laser interferometer system has a measuring range between 0 and 80 m, a resolution of 1 nm, a maximum measurement speed of 4 m/s, and a maximum sampling frequency of 50 kHz.

Fig. 9 shows the mechanical characteristic curves of the tower-shaped actuator. It suggests that: (1) The tower-shaped actuator can stably run in a quite wide frequency domain from 1 Hz to 14 000 Hz; In this domain a sawtooth wave is suitable for driving the

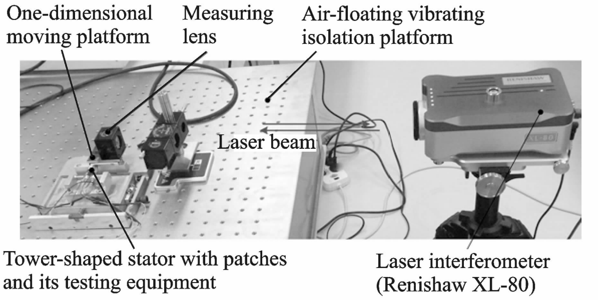
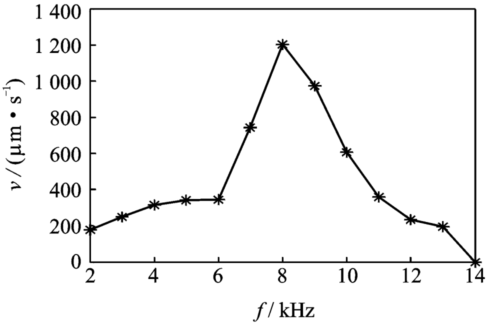
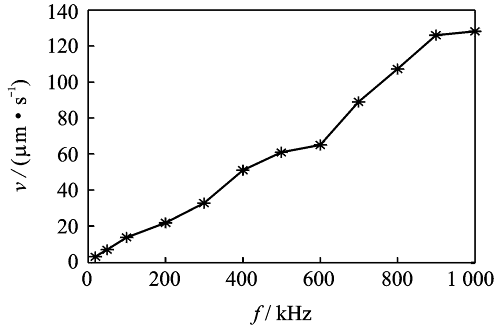


Fig. 8 Testing system of tower-shaped actuator



(a) Velocity-frequency curve from 2 000 Hz to 14 000 Hz



(b) Velocity-frequency curve from 1 Hz to 1 000 Hz

Fig. 9 Mechanical characteristics of tower-shaped actuator (sawtooth voltage: 400 $V_{p\text{-}p}$, pre-pressure: 6.0 N)

actuator forwards and backwards, with the best mechanical characteristic at 8 000 Hz. (2) Within the frequency range between 1 Hz and 8 000 Hz, velocity of the actuator increases with the increasing of the frequency of the driving signal; Within the frequency range between 8 000 Hz and 14 000 Hz, velocity of the actuator decreases with the increasing of the frequency of the driving signal. (3) Velocity of the actuator reaches its maximum 1.2 mm/s at the frequency of 8 000 Hz and reaches its minimum 35 nm/s at the frequency of 1 Hz.

2.3 Stepping property experiments

With reference to the electromagnetic working principle of stepper motor and considering its own characteristics of the tower-shaped actuator, when N ($N \geqslant$ dead zone wavenumber) cycles of the sawtooth wave signal are applied to the actuator, the actuator will directionally move a step forward or backward. Then, N cycles of the sawtooth wave signal are applied to the actuator every predetermined time, the actuator will directionally move forward or backward step by step. There fore, the excitation signal composed of N cycles of the sawtooth wave signal mentioned above is defined as a single-step sawtooth signal; N is defined as a single-step wavenumber; The frequency of the sawtooth wave signal mentioned above is defined as f_{bj}; And every predetermined time between two adjacent single-step sawtooth signal is defined as t_{bj}. Hence, the single-step sawtooth signal is called the sawtooth stepping signal with f_{bj} during N cycles (t_{bj}). When a single-step sawtooth signal is applied to the actuator, the distance the actuator directionally moving forward or backward is called as stepping distance. Fig. 10 shows the schematic diagram of the single-phase sawtooth stepping signal with f_{bj} during 3 cycles (t_{bj})[11].

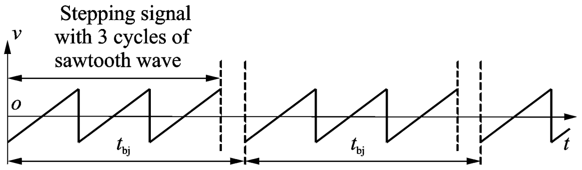
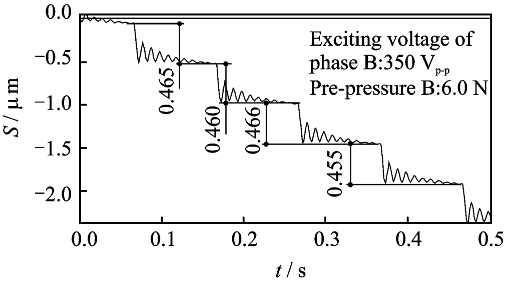
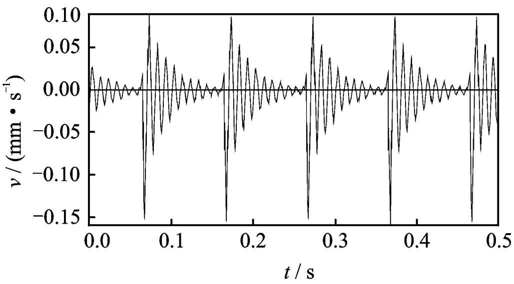


Fig. 10 Single-phase sawtooth stepping signal with f_{bj} during 3 cycles (t_{bj})



(a) Displacement-time curve

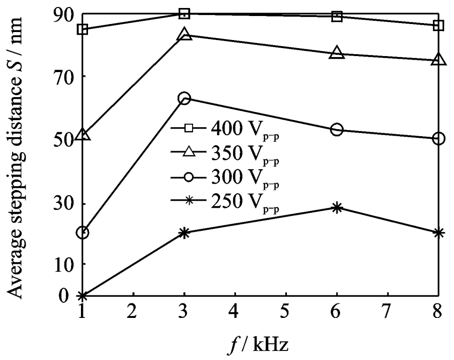


(b) Velocity-time curve

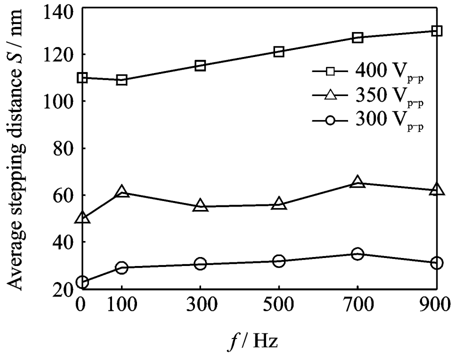
Fig. 11 Stepping characteristics of actuator excited by single-phase sawtooth stepping signal with 8 000 Hz and 350 $V_{P\text{-}P}$ during 5 cycles (100 ms)

According to working frequency domain of the actuator, the frequency of the sawtooth stepping signal applied to the actuator is selected within the frequency range between 1 Hz and 8 000 Hz. Fig. 11 shows the stepping characteristic curves of the actuator excited by the single-phase sawtooth stepping signal with 8 000 Hz and 350 $V_{P\text{-}P}$ during 5 cycles (100 ms). It suggests that: (1) When the actuator is moving step by step, its velocity fluctuates between −0. 15 mm/s and 0. 08 mm/s. (2) When the actuator is moving step by step, its stepping distance fluctuates between 0. 455 μm and 0. 466 μm.

In order to get the value of the minimum stepping distance of the actuator as well as the characteristic of that distance, the sawtooth stepping signal with 1 cycle (200 ms) is selected as the exciting signal. The exciting frequency is selected within a frequency range between 1 Hz and 8 000 Hz. Therefore, the characteristic curve of the actuator is shown in Fig. 12. It suggests that: (1) Within the frequency range between 1 Hz and 8 000 Hz, its average stepping distance is proportional to the exciting frequency or the exciting voltage applied to the actuator. (2) When excited by the sawtooth stepping signal with 1 Hz and 300 $V_{P\text{-}P}$ during 1 cycle (200 ms), the actuator has a minimum stepping distance of 22 nm.



(a) Displacement-frequency curves from 1 000 Hz to 8 000 Hz



(b) Displacement-frequency curves from 1 Hz to 9 00 Hz

Fig. 12 Average stepping distance characteristics of actuator excited by single-phase sawtooth stepping signal with 1 cycle (200 ms)

3 Conclusions

(1) We propose a new type of stick-slip piezoelectric actuator. The actuator is composed of a tower-shaped stator and a slider. The stator uses forced bending vibration in *y-z* plane to excite tangential vibration of the driving tip. When excited with the saw-shaped input voltage, the saw-shaped tangential vibration take place on driving tip of the stator, so the slider is pushed to move.

(2) The tower-shaped actuator can stably run in a considerably wide frequency domain from 1 Hz to 14 000 Hz; In this domain a sawtooth wave is suitable for driving the actuator forwards and backwards; Velocity of the actuator can reach its maximum 1. 2 mm/s at the frequency of 8 000 Hz and reach its minimum 35 nm/s at the frequency of 1 Hz.

(3) When excited by the single-phase sawtooth stepping signal with f_{bj} during N($N \geq$dead zone wave-number) cycles(t_{bj}), the tower-shaped actuator can directionally move forward or backward step by step; And within the frequency range between 1 Hz and 8 000 Hz, average stepping distance of the actuator is proportional to the exciting frequency or the exciting voltage applied to the actuator; And when excited by the sawtooth stepping signal with 1 Hz and 300 $V_{P\text{-}P}$ during 1 cycle (200 ms), the actuator has a minimum stepping distance of 22 nm.

Acknowledgements

This work was supported by the Natural Science Foundation of China (Nos. 51375224, 51275235), the Research Fund for Young Teachers of Jinling Institute of Technology (No. Jit-b-201318).

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(Executive editor: Xu Chengting)