Large Thrust Trans-scale Precision Positioning Stage Based on Inertial Stick-Slip Driving

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Abstract: For the smaller thrust, it is difficult to achieve 3D trans-scale precision positioning based on previous stick-slip driving. A large thrust trans-scale precision positioning stage is studied based on the inertial stick-slip driving. The process of the movement is divided into two steps, i.e., the "sliding" phase and the "stickness" phase. In the whole process, the kinematics model of the inertial stick-slip driving is established, and it reveals some factors affecting the velocity of inertial stick-slip driving. Furthermore, a simulation of movement is preformed by Matlab-Simulink software, and the whole process of the inertial stick-slip driving is displayed. After one experimental prototype is designed, the back and forth velocity is tested. Finally, the simulation verifies the accuracy of the kinematics model.

Key words: PZT actuator; inertial stick-slip driving; trans-scale; precision positioning

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0 Introduction

Micro-driving system, which is widely approved in technology and industry, is a very important part of micro electro mechanical system (MEMS). Because of the advantages of the high displacement positioning accuracy, fast response, large driving force, low driving power and the wide working frequency, etc, the piezoelectric ceramic actuators have been comprehensively utilized in precision machinery. Usually, majority of positioning and operation are driven directly by PZT in precision positioning technology. However, the devices of PZT actuator work in lower micron range, or even in sub-micron range. At present, the large trans-scale precision positioning technology, with not only nanometer positioning accuracy, but also millimeter moving range even greater movement scale, has become crucial technical issues in the field of nanotechnology. For the sake of micro-operation and observation in the limited space, some scholars extend the moving range to tens of millimeter by means of accumulating deformation of piezoelectric ceramics. Some typical trans-scale precision positioning technologies have been further studied for now, such as macro-micro hybrid driving, piezoelectric ultrasonic motor driving, piezoelectric inchworm driving, stick-slip driving, and so on. Inertial stick-slip driving technology, which has better flexibility and higher integration, also satisfies the above requirement. It has an extensive application prospect in the field of nanotechnology, such as cell operation, burning disks, assembly and packaging of MEMS device, etc[1-2].

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1 Principle of Inertial Stick-Slip Driving

Specifically, the driving is divided into stepping-mode and scanning-mode[3-5]. In the stepping-mode, the sawtooth wave and the principle of an inertial stick-slip driving are shown in Fig. 1(a). Driving the step signal from ① to ②, the power drives the piezoelectric ceramic in great acceleration motion. Meanwhile, slider and inertial mass generate different micro displacement in two opposite directions. The sum of the displacement of slider and inertial mass is equal to the deformation of piezoelectric ceramic. When the driving signal applied on the piezoelectric ceramic is from ② to ③, the slider holds its position under the effect of friction force, but the inertial mass walks toward the slider. As a result, the model of inertial stick-slip driving fulfills a cycle of displacement ΔX_i. Repeating the process of movement, the model will achieve the accumulation of displacement step by step. The aim of large trans-scale movement accomplishes.

The total displacement of such a macro/micro arrangement is written as

$$X(t)=X_{\text{step}}+X_{\text{scan}}=\sum_i \Delta X_i+f(V(t)) \quad (1)$$

where the displacement of the stepping-mode X_{step} is replaced by a sum of steps ΔX_i, which have previously been performed, and X_{scan} the displacement of the scanning-mode. There is function relationship between voltage values $V(t)$ and X_{scan}. Approximately, the displacement of the seanning-mode X_{scan} is linear with input voltage $V(t)$.

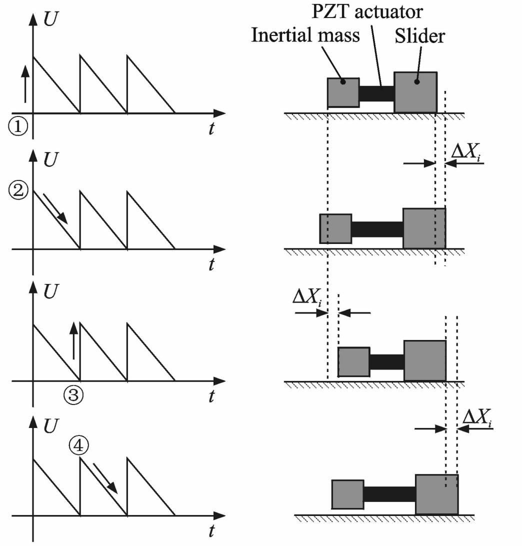

Fig. 1 Principle of inertial motion

2 Model of Inertial Stick-Slip Driving

Actually, the model of inertial stick-slip driving can be described as two degrees of freedom system. As shown in Fig. 2.

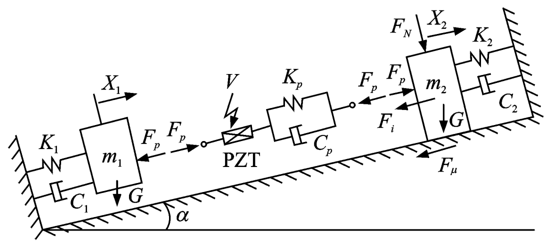

Fig. 2 Kinematics model of inertial stick-slip driving

Under the action of external electric field, PZT actuator will produce the accumulation of charges which is called polarization. PZT produces strain under the both action of outer and inner electric field[6]. PZT can be considered as a big capacitance in electric field. According to the capacitance charge-discharge formula, the voltage on both ends of PZT actuator $V(t)$ can be expressed as

$$V(t)=V_0+(V_1-V_0)\times[1-\mathrm{e}^{(-\frac{t}{RC})}] \quad (2)$$

where V_0 is initial voltage, V_1 the voltage of external electric field, R the resistance of Charge-discharge circuits, and C the equivalent capacitance of PZT.

Apparently, the deformation of PZT can be described as

$$X_p=n\cdot d_{33}\cdot V(t)=n\cdot d_{33}\cdot \{V_0+(V_1-V_0)\cdot[1-\mathrm{e}^{(-\frac{t}{RC})}]\} \quad (3)$$

where $V_0=0$, V_1 is the output value of the driving power, and $V_1=V$. Therefore, the Eq. (3) can be simplified as

$$X_p=n\cdot d_{33}\cdot\{V\times[1-\mathrm{e}^{(-\frac{t}{RC})}]\} \quad (4)$$

Otherwise, according to the piezoelectric equation

$$\varepsilon=S_{33}\cdot\sigma+d_{33}\cdot\frac{V_{\text{in}}}{t_p} \quad (5)$$

where ε is the strain of piezoelectric in the direction of axis $\mathrm{d}l/l = X_p/(nt_p)$, S_{33} the modulus of elasticity of piezoelectric, σ the stress of piezoelectric in the direction of axis, d_{33} the piezoelectric constant, V_{in} the voltage of driving, and t_p the thickness of piezoelectric.

$$\frac{X_p}{nt_p} = S_{33}\cdot\sigma + d_{33}\cdot\frac{V_{\mathrm{in}}}{t_p} = S_{33}\cdot\frac{-F_p}{A} + d_{33}\cdot\frac{V_{\mathrm{in}}}{t_p} \tag{6}$$

where F_p is generated by PZT and imposed on slider and inertial mass. F_p can be observed as

$$F_p = \frac{d_{33}A}{S_{33}t_p}V_{\mathrm{in}} - \frac{X_pA}{nt_pS_{33}} \tag{7}$$

Like the two degrees of freedom system, the motion of the inertial stick-slip driving can be described by differential equation. The equation of motion can be written as

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \end{bmatrix} + \begin{bmatrix} C_1+C_p & -C_p \\ -C_p & C_p+C_3 \end{bmatrix}\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} + \begin{bmatrix} K_1+K_p & -K_p \\ -K_p & K_p+K_3 \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} -F_p - m_1 g\sin\alpha \\ F_p - F_l - \mathrm{sgn}(\dot{X}_2)F_\mu - m_2 g\sin\alpha \end{bmatrix} \tag{8}$$

When the inertial stick-slip driving system is in horizontal plane, i. e. $\alpha=0$, stiffness damping coefficients $C_1=0$, $K_1=0$, $C_3=0$, $K_3=0$, and the external load $F_l=0$, $F_N=0$, Eq. (8) can be simplified as

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \end{bmatrix} + \begin{bmatrix} C_p & -C_p \\ -C_p & C_p \end{bmatrix}\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} + \begin{bmatrix} K_p & -K_p \\ -K_p & K_p \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} -F_p \\ F_p - \mathrm{sgn}(\dot{X}_2)F_\mu \end{bmatrix} \tag{9}$$

Eq. (9) is the form of second-order matrix. More simplified form is shown as

$$m_1\ddot{X}_1 + m_2\ddot{X}_2 = -\mathrm{sgn}(\dot{X}_2)F_\mu \tag{10}$$

We can approximate displacement X_2 with $X_p + X_1$ of m_2 in Eq. (10) to obtain the equation of motion in its simplified form as

$$\ddot{X}_2 = \frac{-\mathrm{sgn}(\dot{X}_2)F_\mu + m_1\ddot{X}_p}{m_1+m_2} \tag{11}$$

Specifically, F_μ is the friction between the substrate and slider. Coulomb friction model is used to calculate the friction force[7].

$$F_\mu = \begin{cases} 0 & \dot{X}_2 = 0 \\ -\mathrm{sgn}(\dot{X}_2)\cdot F_f & \dot{X}_2 \neq 0 \end{cases} \tag{12}$$

where $F_f = (m_1+m_2)g\mu$, μ is the friction coefficient between the slider and the environment ground.

Based on the driving principle and the kinematics model of the inertial stick-slip driving system, the process of the movement will be executed by Matlab-Simulink software. The aim is to understand the principle of inertial stick-slip driving, and obtain displacement and velocity curves. Intuitively, the effect of the friction force and the mass of slider and inertial part on the movement have been discovered in theory.

Fig. 3 is the simulation process diagram of inertial stick-slip driving system. The parameters used in simulation are shown in Table 1.

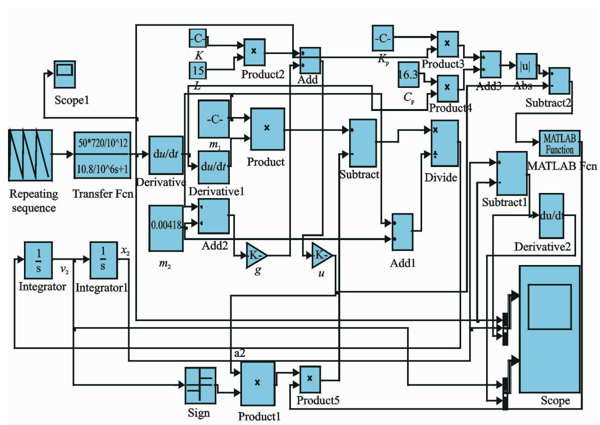

Fig. 3 Simulation diagram in Matlab-Simulink

Table 1 Parameters in dynamic model simulation

Parameter	Symbol	Value
Piezoelectric coefficient/(m · V)	d_{33}	720×10^{-12}
Number of layers	n	50
Equivalent capacitance/μF	C	0. 18
Resistance/Ω	R	60
Charge-discharge time constant/μs	τ_{RC}	10. 8
Step voltage/V	V	150
Mass/kg	m_1	0. 003 14
Mass/kg	m_2	0. 004 18
Coefficient of friction	μ	0. 3

According to the parameters given in Table 1 and the simulation model shown in Fig. 3, the displacement curves of PZT, inertial mass, slider and the instantaneous velocity curves of inertial mass, slider can be obtained, as shown in Fig. 4.

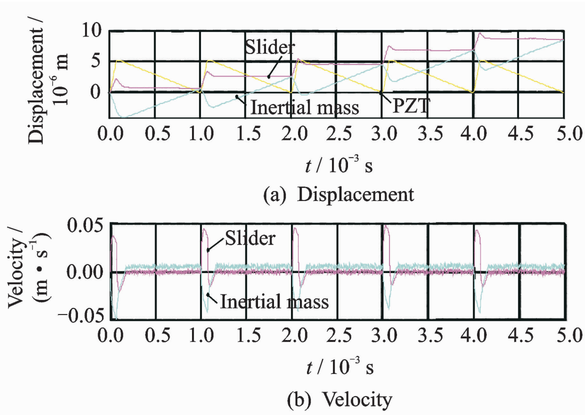

Fig. 4 Displacement and instantaneous velocity

In Fig. 4, the PZT actuator is driven by the sharply rising signal from ① to ②. The slider walks toward the positive direction, while the inertial mass goes toward the negative direction. The sum of the displacement of slider and inertial mass is equal to the deformation of piezoelectric ceramic, i. e. $|X_2 - X_1| = |X_p|$.

When PZT shortens slowly, i. e. "stick" phase, corresponding to ② and ③ in Fig. 1(a), the state of motion of slider can be described as $\dot{X}_2 = 0$, $\ddot{X}_2 = 0$. In the sticking phase, F_μ is static friction, which is be concerned with F_p, as shown in Eq. (13).

$$|F_\mu| = |F_p - m_2 \ddot{X}_2| \leqslant (m_1 + m_2) g\mu \quad (13)$$

Repeating the process of the movement, the inertial stick-slip driving model achieves accumulating the displacement of every single step. Commonly, we call it the stepping-mode movement.

3 Design and Experiment

3.1 Structure design

According to the inertial stick-slip driving principle, a large thrust trans-scale precision positioning platform has been designed, which is driven by PZT stack actuator (5 mm×5 mm×6 mm). The maximum deformation of PZT is 5.34 μm under 150 V. The friction between the axle and the V-groove can be adjusted by the spring. The length of the spring is 30 mm and the stiffness of the spring is 0.38 N/mm. The mass of slider and inertial part will be transformed by means of increasing or reducing the number of copper billet on each side. The movement range of the prototype is 20 mm along the direction of the PZT deformation. The thrust of the prototype will reach 8 N. Each part of the thrust trans-scale inertial stick-slip driving platform is shown in Fig. 5.

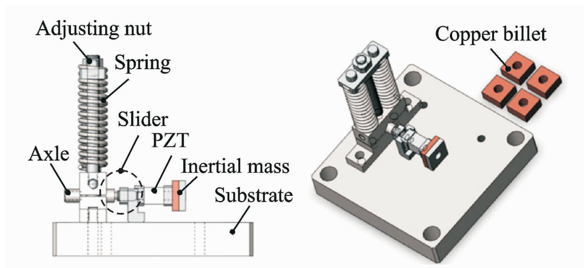

Fig. 5 3D model of inertial stick-slip driving

3.2 Prototype experiment

A prototype of novel trans-scale precision positioning stage based on the inertial stick-slip effect is processed and the prototype will be tested by the equipments shown in Fig. 6.

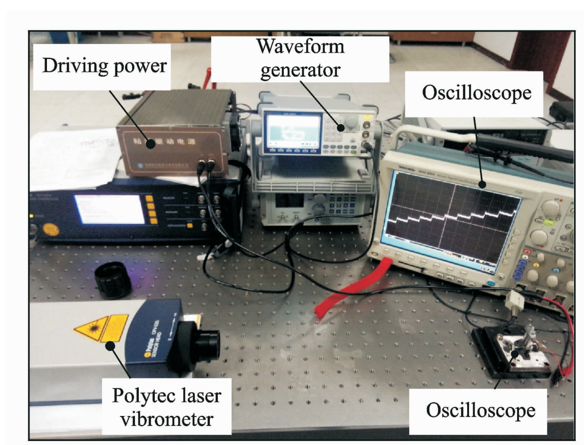

Fig. 6 Experimental equipments in prototype testing

Referring to the Eq. (11) and the result of simulation of inertial stick-slip movement, the characteristics of kinematics of inertial stick-slip driving system relates to the mass of slider and inertial part, friction, the frequency of the input voltage, etc.

In the experiment, the form of wave is generated by waveform generator. To test the forward and the backward velocity, two types of sawtooth wave are inputted, respectively. Moreover, the external step voltage is applied to inertial stick-slip stage by the PZT driving power. Polytec laser vibrometer records the displacement of the prototype, and the actual forward displacement curve in Fig. 7 is similar to the simulation result in Fig. 4(a). The forward and the backward velocities are as follows

$$v_+ = \frac{X_+}{V_+} \tag{14}$$

$$v_- = \frac{X_-}{V_-} \tag{15}$$

where v_+ is the forward velocity, v_- the backward velocity, X_+ the forward displacement, X_- the backward displacement, T_+ the time taken by the forward walking, and T_- the time taken by the backward walking.

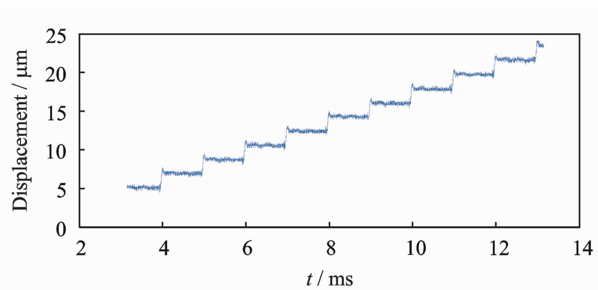

Fig. 7 Forward displacement curve of prototype

As discussing the mass of inertial part effect on the velocity of the inertial stick-slip driving stage, the friction F_μ, the frequency of the input voltage f and the amplitude the input voltage U are considered as constant. The mass of slider m_2 is 3.12 g. The mass of inertial part m_1 is independent variable, and the velocity of the stage V is induced variable. Increasing or decreasing the mass of inertial part is available by adding or taking down the copper billet from the stage. The result is shown as Fig. 8.

In Fig. 8, the bigger the mass of inertial part is, the faster the stage work. In other word, the stage walks more quickly along with the mass of inertial part increasing. Besides, the forward velocity comes closer to the reverse one when the mass of inertial part increases. The rule shown in Fig. 8 matches the Eq. (11) in the kinetics model.

Moreover, in Eq. (11), the characteristics of

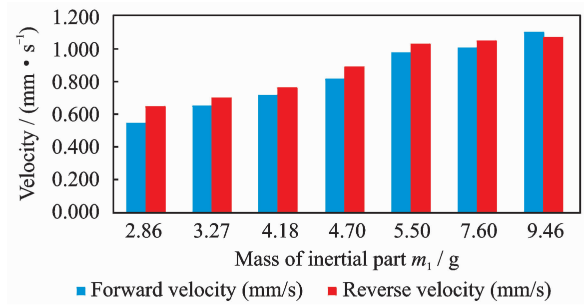

Fig. 8 Mass of inertial part m_1 affecting velocity

kinematics of inertial stick-slip driving system is related to F_μ. To study the friction impact on the process of the movement, the adjusting nut is screwed to compress or loosen the spring. Different length of spring supply different pressure on the axle, and that means different friction on the contact interface. Obviously, the larger the deformation of the spring is, the larger the friction is. Some data have been sorted as shown in Fig. 9.

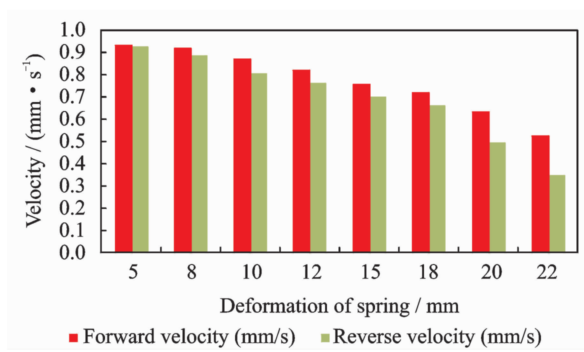

Fig. 9 Deformation of spring affecting velocity

In the experiment, the mass of the slider $m_2 = 3.12$ g, the mass of inertial part $m_1 = 4.18$ g, the frequency of the input voltage $f = 1$ kHz, the amplitude of the input voltage $U = 90$ V. All in all, it is concluded that the stage walks more slowly along with the friction on the contact interface increasing. In addition, there is more difference between the forward and the reverse velocities. The experimental result is corresponding to the above kinetics model.

4 Conclusions

The background and the principle of inertial stick-slip driving are introduced. An initial approach in movement modeling of inertial stick-slip driving stage is put forward. The process of the movement is divided into two steps, the "sliding" phase and the "stickness" phase. The movement of the inertial stick-slip driving is simulated by Matlab-Simulink software. Furthermore, a large thrust trans-scale precision positioning platform is designed. Some experiments are conducted on the platform to verify the accuracy of the kinetics model. Obviously, there is a close relationship between the velocity and some system parameters, the mass of slider and the friction on the surface. Roughly, the larger the mass of inertial part is, the faster does the prototype work. But the prototype walks more slowly along with the friction increasing. It is different between the forward velocity and the reverse velocity. Two reasons are taken into account: (1) PZT responses differently in two types of input signal, which are sharp rising and sharp dropping. (2) The friction between the slider and the substrate is different in the forward direction and the reverse direction.

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