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Finite Element Modelling of Stick-Slip Principle Based Inertial Slider

S. Shashikanth, B. K. Karthik, V. Shrikanth
Department of Mechanical Engineering, PES University, Bengaluru, Karnataka, India

ABSTRACT

Inertial sliders are positioning devices and are used to a position with a resolution ranging from few hundred nanometres to few millimeters. The inertial sliders are used in microprobe applications as they allow precise positioning, high resolution, practically unlimited travel range and can be made very compact. This work presents a finite element model to study the displacement due to friction model on stick-slip principle. In this work, finite element analysis involves mechanical and electro-mechanical coupled model. FEA of Lead Zirconium Titanate (PZT) plate is carried out under the mechanical model. The maximum displacement obtained for exponential input waveform. Finite element modeling of inertial slider subjected to different input waveforms such as linear, quadratic, cubic and exponential waveforms is carried out under the electro-mechanical coupled model and the results obtained are compared with semi-analytical results obtained by solving the differential equations derived from the lumped model, the results are directly compared to obtain good agreement.

Keywords: Inertial slider, Piezoelectric actuator and Stick-slip

I. INTRODUCTION

The positioning with sub-micrometer accuracy over distances of several millimeters is very important in many applications such as scanning tunneling microscopy and scanning probe microscopy, where the demand is on high precision, very large travel speed and minimization. Precision manufacturing and engineering require increased accuracy for the production of devices. This has resulted in miniaturization and subsequent development of nanotechnology. Miniaturization enables devices to be developed for new functions and applications. Assembly and machining of very small parts starting from a few millimeters to a few microns require very precise handling of the tools.

Piezoelectric devices provide extremely small displacement which is the range of few picometers made of lead zirconium titanate (PZT) [1]. The piezomaterial can be operated over millions of cycle without any deterioration. The advantages are microsecond response, very high force generation and practically no wear and tear.

The precision positioning systems generally incorporate the stick-slip effect. Long displacement range with a very high resolution, simple in construction, very compact and high stiffness are the advantages of stick-slip actuators [2]. The piezoelectric actuator used the inertial slider in friction drive mechanism to process exchanging periods of sliding and sticking between piezoelectric actuator and slider to produce steps during the movement and the input waveforms control the step size.

Pohl [3] designed a piezoelectric fine positioning device which utilizes the principle of inertial sliding, in order to create translation motion, sawtooth waveforms are applied to the piezoelectric actuator. The positioning device provides step size of 40-200 nm. Renner et al. [4] developed a linear translation device using piezoelectric induced stick-slip motion for low-temperature application in scanning tunneling microscope (STM). To obtained vertical motion used cycloidal waveform instead of the sawtooth signal to activate the motion. Niedermannet al. [5] voltage are applied to the piezoelectric plate to drive a stage with the utilization of stick-slip effect to produce the shear deformation. C N Woodburn et al. [6] developed a linear inertial slider to accomplish miniaturized in any direction and it is mainly for SPM cryogenic and ultra-high vacuum environment.

Erlandsson and Olsson [7] developed a three-axis micro-positioner using the inertial slider principle for the use of atomic force microscope. The device works reliably in an ultrahigh vacuum system and permits positioning with submicron precision.

From the detailed review of the literature, the precision positioning devices mainly incorporate the stick-slip effect induced friction drive stage, it can be concluded that the conventional mechanical systems are often less suitable for this application as they tend to be complex, have a problem with backlash. The inertial sliders have many advantages such as precise positioning, very compact and provide fine resolution with relatively large travel speed.

II. INERTIAL SLIDER

Inertial sliders are positioning device used to position an object in the desired direction with a resolutionranging from few hundred nanometres to few millimeters.The inertial slider is as shown in Fig.(1).A shear piezoelectric plate (PZT-5A) of area 5×5 mm^2 and 0.75 mm thickness is bonded between copper beryllium (Cu-Be) electrode plate of area 5×6 mm and thickness 0.25 mm with the help of silver epoxy resin. A steel ball is placed above the Cu-Be plate. The bottom plate is fixed to the mounting block with cyanoacrylate glue.

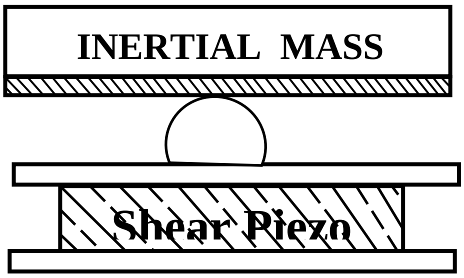

Figure 1. Sectioned view of inertial slider

A. Working principle

The stick-slip principle is used to design the inertial slider. The fine motion of the slider is possible by proper management of inertia and frictional forces. The piezoelectric actuator utilized the inertial slider to process exchanging periods of sliding and sticking between actuator and slider to produce steps during the movement. A ramp during which the slow rise of the input voltage and then rapid drop to zero. During the slow rise of voltage, the inertial mass follows the piezoelectric material movement due to friction sticking occurs ($a < \mu g$), but due to slipping ($a > \mu g$) that occurs during the sudden drop of voltage, the inertial mass cannot follow the piezoelectric movement. The input waveforms control the step size. Hence due to gradual deformation followed by a sudden drop of voltage results in a stepping motion of the inertial mass with respect to the piezoelectric actuator.Those single step movement of the slider is controlled by stick-slip principle.

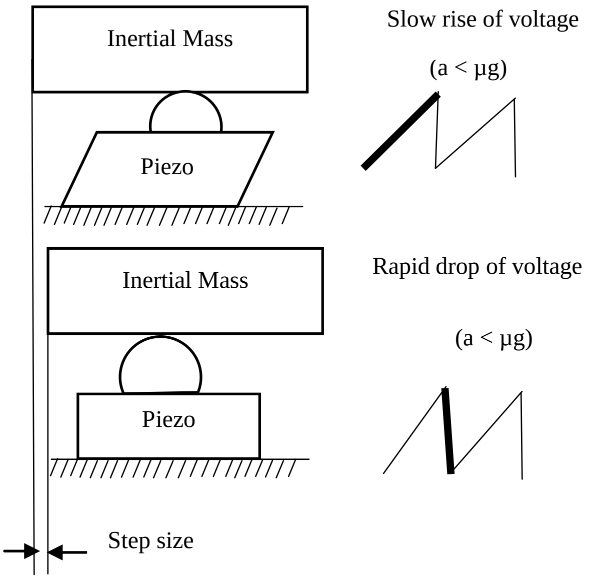

Figure 2. Working principle of inertial slider

B. Friction models

Friction is the primary factor in the inertialslider since the surface characteristics directly influence the step size of the slider. A comprehensive friction model that captures all the phenomena related to friction in a mechanical system, such as Stribeck effect, pre-sliding motion, stick-slip motion, hysteresis etc. However, Karnopp model and Luger friction model are used in this work to study the effect of static friction and then the effect of kinetic friction on the performance of the slider.

1) Coulomb friction model

$$\mathrm{F} = \begin{cases} \mathrm{F_c}.\,\mathrm{sgn}(\dot{\mathrm{x}}), & \text{if } x \neq 0 \\ \mathrm{F_a}, & \text{if } x \neq 0 \ and\ \mathrm{F_a} < \mathrm{F_c} \end{cases} \quad (1)$$

$$\mathrm{F_c} = \mu\, \mathrm{F_n} \quad (2)$$

Where F is a frictional force, $\dot{\mathrm{x}}$ is sliding speed. $\mathrm{F_a}$ is applied force. $\mathrm{F_c}$ is coulomb friction force

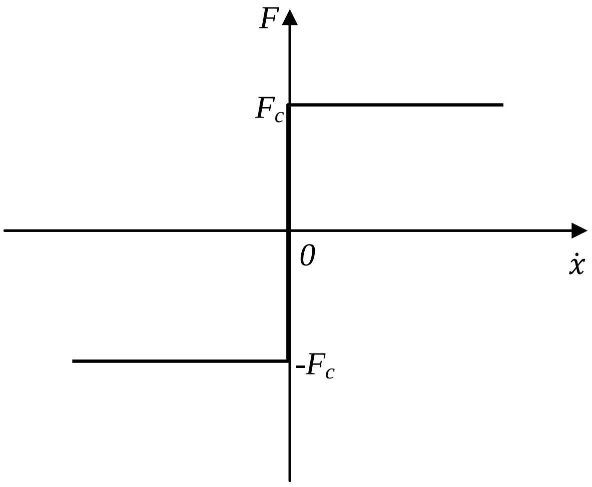

Figure 3. Coulomb friction model

There is no sliding between the contact surface when the Coulomb friction force is more than the applied force. Coulomb friction value varies from 0 to $\mathrm{F_c}$and depending on the direction of sliding it may be positive or negative value.

2) Stribeck friction model

Stribeck friction is represented by

$$\mathrm{F} = \left(\mathrm{F_c} + (\mathrm{F_s} - \mathrm{F_c})e^{-(|\dot{\mathrm{x}}/\mathrm{v_s}|)^{i}}\right)\mathrm{sgn}(\dot{\mathrm{x}}) + \mathrm{k_v}\dot{\mathrm{x}} \quad (3)$$

where F is a frictional force, $\mathrm{F_c}$ is coulmb friction force, $\dot{\mathrm{x}}$ sliding speed, $\mathrm{F_s}$ the static friction force,$\mathrm{k_v}$ the viscous friction coefficient ,$\mathrm{v_s}$ stribeck velocity, Strobeck friction force takes $\mathrm{F_c}$ and $\mathrm{F_s}$ as lower and upper limit respectively.

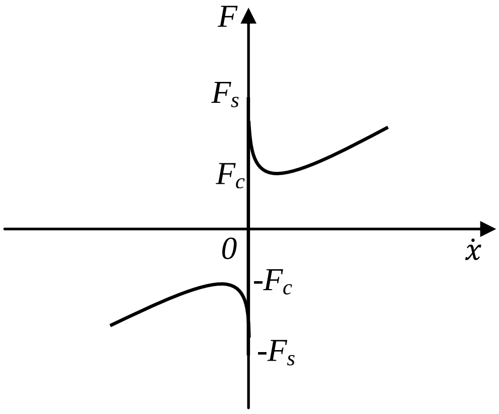

Figure 4: Stribeck friction model

3) Karnopp friction model.

Karnopp model [8] proposed the frictional force occurs in the stick-slip effect is

$$F = \operatorname{sgn}(v)[\mu_k \lambda(v) + \mu_s(1 - \lambda(v))]N \qquad (4)$$

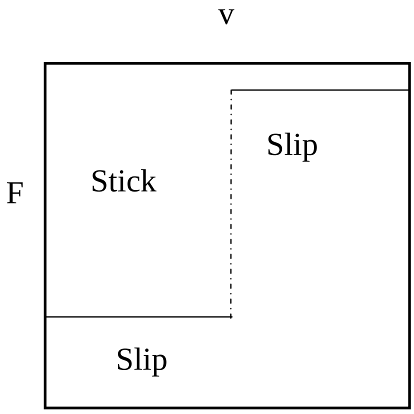

Figure 5. Karnopp friction model

Where μ_s and μ_k are static and kinetic friction coefficients, v is the velocity and N is the normal load, where $N = (m_1 + m_2)\, g$, $\lambda(v) = 0$ when $|v| \sim 0$ and $\lambda(v) = 1$ when $|v| > 0$.

4) Luger friction model

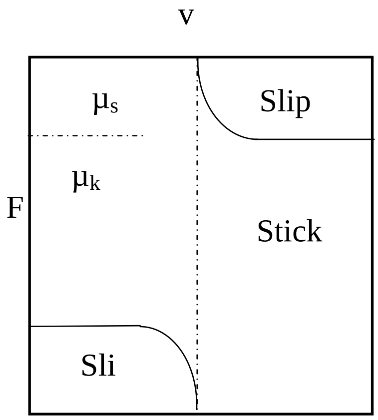

Figure 6. Lugre friction model

Canudas et al. [9] proposed the Lugre model by combining Dahl model with steady-state friction.

$$F = \operatorname{sgn}(v)[F_k + (F_s - F_k)e^{-(v/v_s)^2}] \qquad (5)$$

F_s and F_k are static and dynamic friction forces, v_s is the stribeck velocity.

III. PROBLEM FORMULATION

A. Mechanical model

FEA of single PZT is carried out under the mechanical model. PZT of area 5×5 mm^2 and 0.75 mm thickness. PZT material type used in the analysis is PZT 5A

The meshed model of PZT is shown in Fig.7 is a hexahedron mesh consists of 20000 elements with an element size 0.0001m.

The analysis has been carried out in ANSYS software. The bottom face of the PZT plate is fixed and the force equivalent to voltage is applied to the top face of the bottom PZT plate.

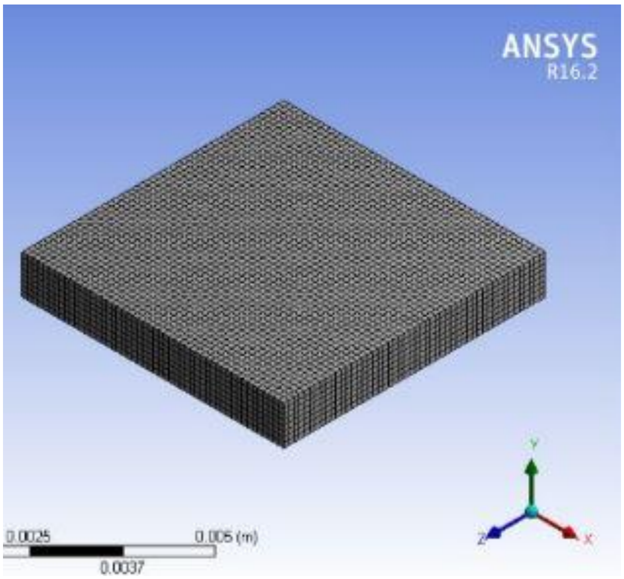

Figure 7. Meshed model of PZT Plate

B. Electro-Mechanical coupling model

FEA of the inertial slider is carried out under Electro-Mechanical coupling model. The inertial slider is designed based on the stick-slip principle. A shear piezoelectric plate (PZT-5A) of volume 5×5 mm^2 and 0.75 mm is bonded between copper beryllium (Cu-Be) electrode plate of area 5×6 mm^2 and thickness 0.25 mm by means of conducting silver epoxy resin. The two steel balls are positioned on the top of Cu-Be plate. These balls help to increase the stiffness of the drive. The base plate is fixed to the mounting obstruct with a thin layer of cyanoacrylate glue.

The meshed model of the inertial slider is shown in Fig.8 is a hexahedron mesh consists of 218337 elements with an element size 0.0001m.

The stick-slip principle is used to design the inertial slider. The voltage is applied to the top face of the piezoelectric actuator due to its indirect effect it undergoes shear deformation and mounting block is fixed. During the slow rise of voltage, the inertial mass follows the piezoelectric material movement because of friction sticking occurs ($a < \mu g$), whereas it can't take after a sudden piezoelectric withdrawal because of its inertia, hence slipping occurs ($a > \mu g$), due to the sudden drop of voltage. For the electrical boundary condition, the **bottom** surface of the PZT plate should be grounded in order to create a potential difference.

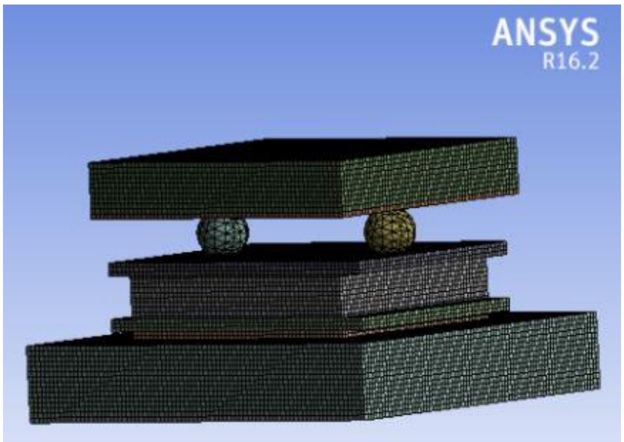

Figure 8. Meshed model of inertial slider

C. Lumped model of the inertial slider

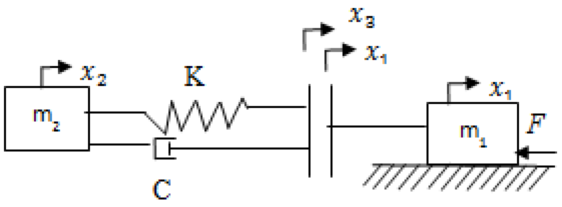

Figure 9. Lumped model of theinertialslider

$$\begin{aligned} m_1\ddot{x}_1+c(\dot{x}_3-\dot{x}_2)+k(x_3-x_2)+F=0 \\ m_2x_2-c(\dot{x}_3-\dot{x}_2)-k(x_3-x_2)=0 \end{aligned} \quad (6)$$

Where $\mathbf{m_1}$ is inertial mass and $\mathbf{m_2}$ is the mass of piezoelectric actuator respectively. C is the damping co-efficient of the piezoelectric material. K is the stiffness of the piezo material. $\mathbf{x_1}$is the displacements of the inertial mass and$\mathbf{x_2}$ is the displacement of the piezoelectric actuator respectively. F is the frictional force involved in the motion of the inertial mass. $\mathbf{x_3 = x_1 - s}$. Where $\mathbf{s = d_{15}}$ V and $\mathbf{d_{15}}$ are the applied displacement and charge constant of the piezo material and V is the input voltage.

Linear waveform $\quad \mathbf{V(t) = V_0\left(\frac{t}{t_p}\right)}$

Quadratic waveform $\quad \mathbf{V(t) = V_0\left(\frac{t^2}{t_p^2}\right)}$

Cubic waveform $\quad \mathbf{V(t) = V_0\left(\frac{t^3}{t_p^3}\right)}$ **and**

Exponential $\quad \mathbf{V(t) = (\frac{V_0}{2^{15}})(e^{10.39(t/t_p)} - 1)} \quad$ **(7)**

The applied input waveforms for linear, quadratic, cubic and exponential waveforms as shown in Fig.10. The applied input voltage is changed into a displacement as per the relation $\mathbf{s = d_{15}}$ .The maximum displacement obtained when the applied input waveform is exponential. The quadratic and cubic waveforms gives a displacement slightly higher than that for a linear input waveform.

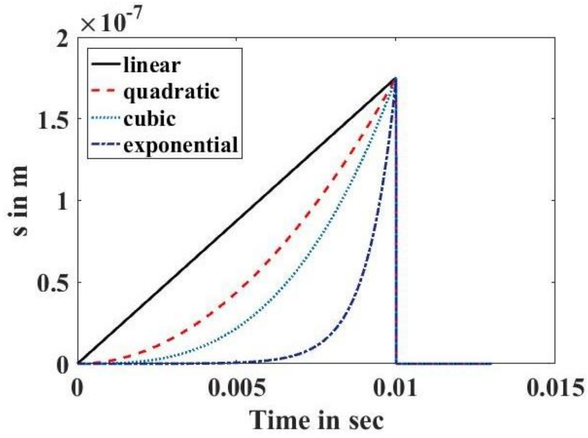

Figure 10. Input waveforms

The time parameters of the linear input signal are shown in Fig.11. A ramp during which the slow rise of the input voltage and then suddenly drop to zero voltage. During the slow ramp of input voltage or rise time (t_r), the inertial mass follows the piezoelectric movement because of friction sticking occurs. The slipping of the piezo leg is determine by drop time (t_d)

of the input signal. The delay time (t_D) is the time during which the piezo is at rest. t_p is the total time period of the input signal. The time period of the input signal is $t_p = t_r + t_d + t_D$.

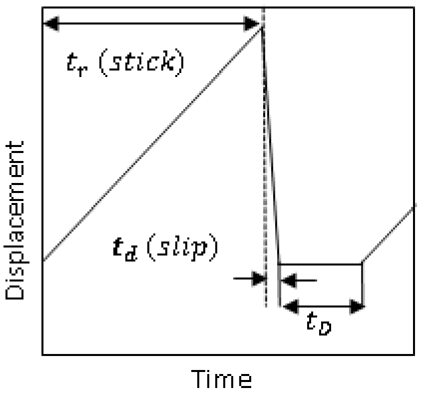

Figure. 11. Time parameters of the input signal

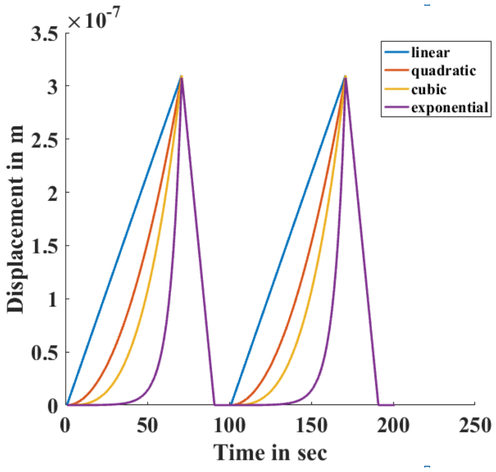

Figure.12 (a). Simulation result of PZT Plate

IV. RESULTS AND DISCUSSIONS

A. Simulation results of the mechanical model

1) Displacement of single PZT plate

Figure 12 (a) shows the simulation result of PZT plate. The analysis has been carried out in ANSYS software. Simulation is carried out for the following condition: the bottom face of the PZT plate is fixed and the force magnitude of 140N equivalent to 300V is applied to the top face of the PZT plate. The time parameters t_r , t_d and t_D are 12ms, 4μs and 3ms respectively. Displacement of plate the the is 322.13nm obtained in Ansys.

Figure 12 (b) shows the semi-analytical results of PZT plate obtained by solving the equation of motion. In both the cases the maximum displacements of PZT plate obtained are in good agreement

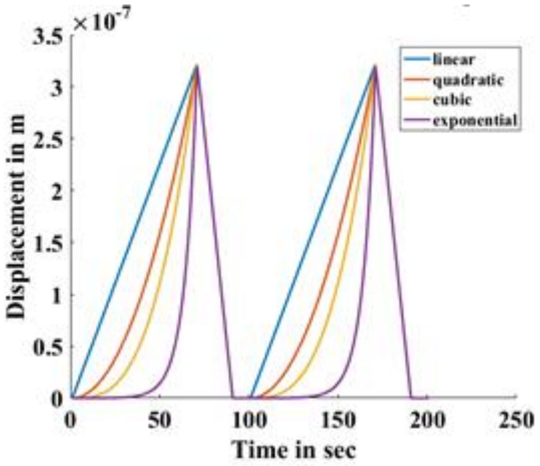

Figure.12 (b). Semi-analytical result of PZT Plate

B. Simulation results of Electro-Mechanical coupled model

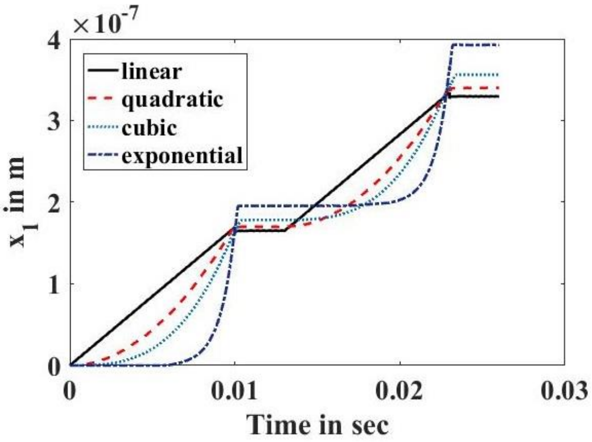

Figure.13 (a). Simulation result of inertial slider

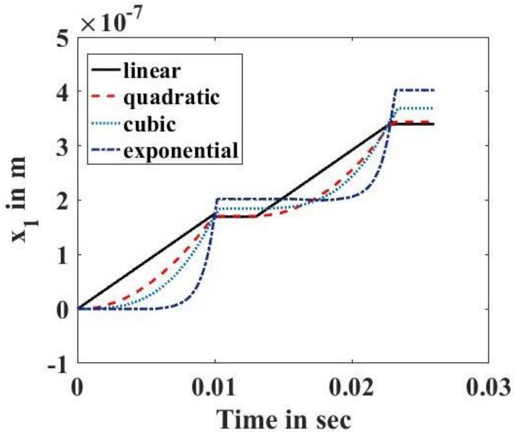

Figure.13 (b). Semi-analytical result of inertial slider

Figure 13 (a) shows the simulation result of inertial slider. Simulation is carried out for the following condition: the voltage is applied to the top face of the piezoelectric actuator and mounting block is fixed. Due to exponential drop during the slipping phase, the slider experiences a backward movement and the net displacement is not as much as the applied displacement. When compared with the linear, quadratic and cubic waveform, slider gets the highest velocity and acceleration when the exponential waveform is applied.

Figure 13 (b) shows the semi-analytical results of inertial slider obtained by solving the equation of motion. The maximum displacement of the slider when the input waveform is exponential. The quadratic and cubic waveform gives a displacement slightly higher than that for a linear input. The displacement obtained by the finite element method are very close to the Semi-analytical results.

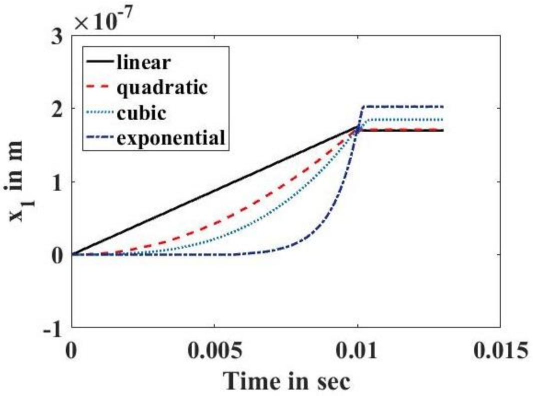

Figure. 14. Displacement of the slider x_1

From the above results, it is found that the Step size of the inertial slider varies for the different input waveforms is shown in Fig.14. During sticking phase input waveforms such as linear, quadratic, cubic and exponential waveforms move the slider, by the same amount but during the slipping phase there is an exponential drop as a result in the backward motion of the slider and the net displacement of the slider is less than the applied displacement. The size of the slider is reliant on the velocity just before the beginning of the slip, because of which the slider has the maximum velocity and acceleration when the exponential waveform is applied. Higher the velocity and acceleration, larger step size, Hence, when the exponential signal is applied the step size is much larger than the other input signal. The maximum displacement of the slider when the input waveform is exponential followed by cubic, quadratic and linear input waveform.

V. CONCLUSIONS

FEA of mechanical and electromechanical coupled model has been carried out. Both mechanical model and electro-mechanical subjected to different input waveforms. Any periodic waveforms can move the slider when input amplitude is slowly increased and then suddenly dropped to zero. The displacement of the slider is maximum when exponential ramp input is applied. The FEM results obtained are compared with semi-analytical results obtained by solving the differential equations, both the results are in good agreement.

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