

# **Investigation of Static Friction in Ball Screw Driven System**

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**ABSTRACT:** Ball screw actuator has an important application in the field of ultra-precision machines. In work machines Ball screws deliver high precision motion where both high rigidity and positioning accuracy is required. In these machines friction is one of the most significant sources of disturbance. Hence an accurate identification and compensation of friction is required to alleviate the positioning errors. In this work Coulomb and Tustin models are developed for the investigation of static friction.

**KEYWORDS:** Ball screw actuator, Friction, Coulomb model, Tustin model

## **I. INTRODUCTION**

There is an increasing demand for machine tools with high precision in the fabrication of optical parts, precision dies and moulds, Micro-Electro-Mechanical Systems (MEMS), etc. It is necessary to measure or manipulate surfaces on the atomic level with extremely high resolution in the field of micro positioning. Actuators are used to produce the desired motion in the positioning system. It creates physical movement by converting different forms of energy into linear or rotary motion [1].

For micro positioning applications Piezoelectric Actuators (PAs) are used. Due to its high precision performance it is widely used in data storage, medical and MEMS. PA is suitable for applications where the travel range is short and immense precision is expected. The limitations of PAs include nonlinearities like hysteresis and creep, high-cost and it is unsuitable for macro positioning [2-3].

The Electro Mechanical Actuator (EMA) systems are widely used in many applications because of reduced number of parts, rapid production requires less maintenance and reduced weight and cost. This brings the motivation for this work [4]. In an EMA system the electrical part consists of motor and the mechanical part consists of Ball screw. The mechanical actuator which converts the rotational motion into linear motion is a Ball screw. The actuator is driven by servo motor. Servo motor ensures precise control of angular or linear position. Therefore better positioning accuracy can be achieved at high speed [5].

The paper is organized as follows, section II discusses on the different static friction models, section III describes the verification of the Coulomb and Tustin friction model.

## **II. MODELING**

Friction is a nonlinear phenomenon observed in most of the Ball screw actuators. The investigation of friction between the contact surfaces of Ball screw driven mechanisms is closely related with the design and application of precise motion control systems. The force resisting the motion of an object moving relative to another is termed as friction. It causes an opposition to the objects sliding down a sloped surface. The object can move when a force is applied to overcome friction [6-7].

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For high precision mechanical motion friction deteriorates the performance of the system. To minimize the influence of friction in motion control, it should be compensated. It is essential to describe the friction behavior in order to compensate the effects of friction. The exact formula for friction is not available, it is usually described using empirical model. The accurate modeling of friction is necessary with increasing demand of precision engineering. Static friction models are dependent on velocity [8]. The various static friction models are discussed below.

### STICTION

Stiction force exists when an object is at rest i.e. velocity is equal to zero. The model describes the static dependence of the object on velocity. The breakaway force is defined as the force essential to overcome stiction and initiate motion. The model is formulated as given in (1),

$$F = \begin{cases} F_{app} & \text{if } \dot{x} = 0, F_{app} < F_s \\ F_s \text{sign}(F_{app}) & \text{if } \dot{x} = 0, F_{app} > F_s \end{cases} \quad (1)$$

where  $F_{app}$  is the applied force on the body,  $F_s$  is the stiction force,  $\dot{x}$  is the sliding speed.

The discontinuity at zero velocity is the main drawback of the model. The lack of continuity makes the simulation of stiction model tedious [9].

### COULOMB FRICTION MODEL

The Coulomb friction model is used to study dry contacts, boundary and mixed lubricated contacts. The friction behavior in mechanical contacts where dynamic effects are not considered is described by this model. The Coulomb friction force is less than the stiction force for the same materials. The Coulomb model is unsuitable for micro motion systems [9].

### VISCOUS FRICTION MODEL

The problems encountered in the simulation of Coulomb friction model are simplified in the viscous friction model. In the viscous frictional model the friction force is defined to vary linearly with the sliding speed [10].

### STRIBECK EFFECT

When liquid or solid oil is used for the contact surfaces of moving mechanical parts Stribeck effect is a kind of friction which occurs. Stribeck effect is the decrease in the friction force as the sliding speed increases.

The friction force decreases until the Stribeck velocity  $\dot{x}_s$  is reached. From this velocity the moving machine subparts are affected by the viscous friction.

### EXPONENTIAL MODEL

The combined model comprising of Coulomb friction, viscous friction and the Stribeck effect is called the exponential friction model. It is given by (2).

$$F = F_c \text{sgn}(\dot{x}) + (F_s - F_c) e^{-\left(\frac{\dot{x}}{\dot{x}_s}\right)^\delta} + k_v \dot{x} \quad (2)$$

where  $F$  is the friction force,  $\dot{x}$  is the sliding speed,  $F_c$  is the Coulomb friction force,  $F_s$  is the stiction friction force,  $\dot{x}_s$  is the Stribeck velocity,  $k_v$  is the viscous friction coefficient. Different friction models can be implemented by choosing different values of  $\delta$ . The range of values of  $\delta$  varies largely. Gaussian model is obtained from the exponential model by taking the value of  $\delta = 2$ . The Gaussian model is similar to the Lorentz model. With  $\delta = 1$  gives Tustin model [11-12]. The friction force near zero speed is described best by Tustin model. A model with negative viscous friction (Stribeck effect) was first described by Tustin. The oscillation at low speed was predicted. Experimental works shows that this model can approximate the real friction with high precision [13-14].

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### III. VERIFICATION OF COULOMB AND TUSTIN FRICTION MODEL

Friction is a natural occurrence that affects almost all objects in motion. To describe the friction phenomenon for contact problems modeling is frequently used.

#### VERIFICATION OF COULOMB FRICTION MODEL

Coulomb friction model is the commonly used friction model it is formulated as given in (3).

$$F = \begin{cases} F_c \text{sgn}(\dot{x}) & \text{if } \dot{x} \neq 0 \\ F_{app} & \text{if } \dot{x} = 0 \end{cases} \quad (3)$$

where  $F$  is the friction force,  $\dot{x}$  the sliding speed and  $F_{app}$  the applied force on the body.

The Coulomb friction force  $F_c$  is defined as given in (3).

$$F_c = \mu F_N \quad (4)$$

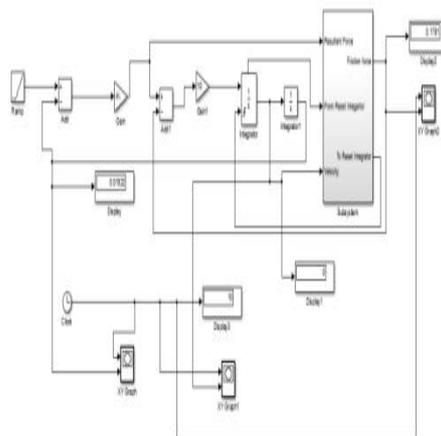
where  $\mu$  is the coefficient of friction and  $F_N$  the normal load between the two contact surfaces.

There is no sliding (i.e.  $\dot{x} = 0$ ) between two contact surfaces when  $F_{app} < F_c$ , and the Coulomb friction can take any value from zero up to  $F_c$ . Coulomb friction takes  $F_c$  or  $-F_c$  depending on the direction of sliding if  $\dot{x} \neq 0$ .

To verify the Coulomb friction model a case study is considered. Using this model the frictional force generated on a box sliding on the floor when an external force is applied is observed. The values of parameters used in simulation of the model are given in Table 1.

**Table 1: Model parameters used in simulation**

Description	Values
Mass( $m$ )	0.1kg
elasticity( $k$ )	100N/m
velocity of the drive system ( $V_0$ )	0.002m/s.
$F_c$	0.25N



**Figure 1: Test bench for Coulomb friction model.**

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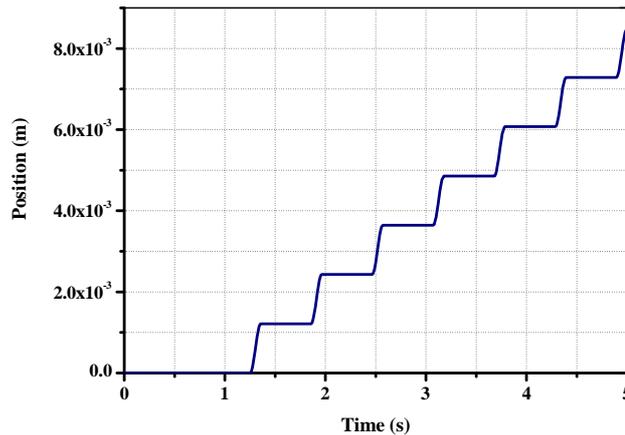


Figure 2: Plot of position v/s time.

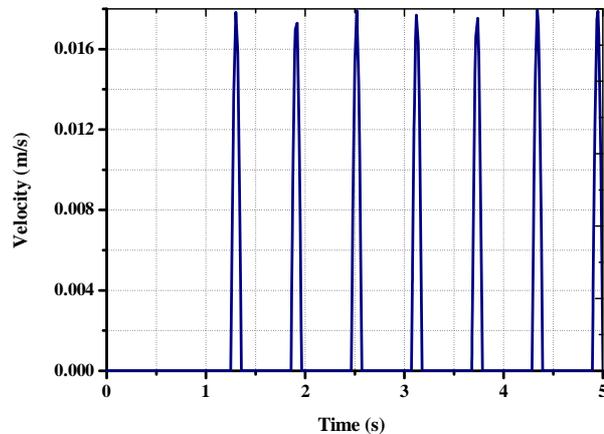


Figure 3: Plot of velocity v/s time.

The test bench to verify Coulomb friction model is as shown in Figure 1. The Plot of displacement of the box with time is as shown in Figure 2 and the plot of velocity with time is as shown in Figure 3. It is observed clearly that as the velocity increase the object moves and retains that state as velocity is decreased to zero. The output plot of frictional force is as shown in Figure 4. The frictional force is equal to the external force when velocity is zero, corresponding to no motion and no tendency for motion, this phenomenon is defined as sticking. When the velocity increases from zero slipping takes place. In the case of slipping, Coulomb friction model states that the friction force is proportional to the magnitude of the normal contact force.

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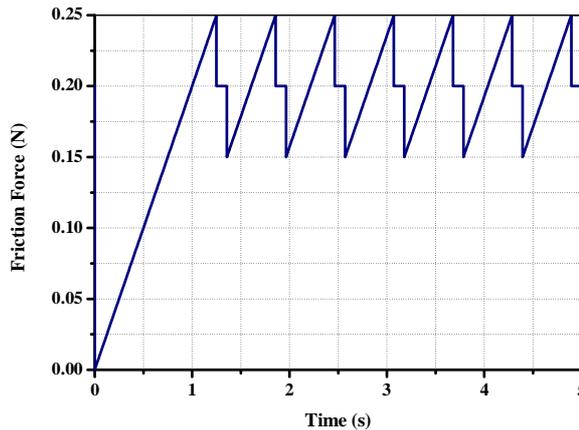


Figure 4: Plot of Friction force v/s time.

### VERIFICATION OF TUSTIN MODEL

In the static friction phase the nonlinear friction is mainly reflected. The Tustin model estimates the friction force accurately, the parameters of the model are few and easy to get. This model is a special case exponential model and is given by (4).

$$F = F_c \text{sgn}(\dot{x}) + (F_s - F_c) e^{-\left(\frac{\dot{x}}{v_s}\right)} + k_v \dot{x} \quad (4)$$

where  $F$  is friction force,  $\dot{x}$  is sliding speed,  $F_c$  is Coulomb friction force,  $F_s$  is the static friction force,  $v_s$  is the Stribeck velocity,  $k_v$  is the viscous friction coefficient. The friction force at zero speed is described best by this model. The friction model includes a decaying exponential term which explains the microscopic limit cycle behavior. This model can approximate real friction force with a precision of 90%.

A test bench is used to test friction behavior of the developed model which is shown in Figure 5. The test bench model is based on Newton's law. Using this model the frictional force generated on a box sliding on a table when an external force is applied is observed. The values of the parameter used in simulation of the model are given in Table 2

Table 2: Model parameters used in simulation

Description	Values
Mass( $m$ )	1kg
$F_c$	1 N
$v_s$	0.10 m/s
$F_v$	0.05N
$F_s$	1.20 N

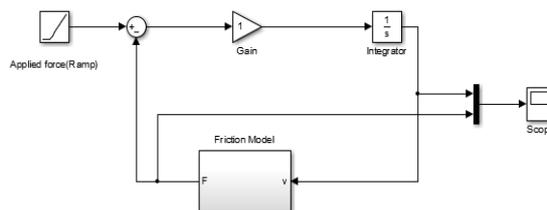


Figure 5: Test bench for Tustin friction model.

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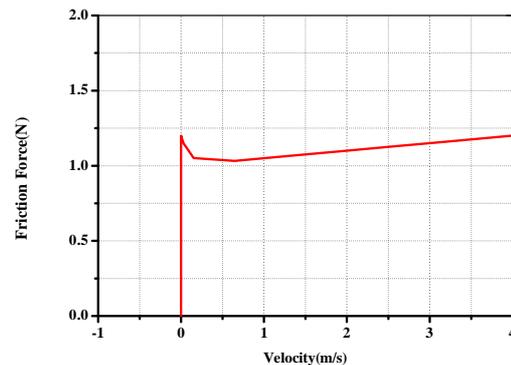


Figure 6: Output plot of velocity v/s friction force.

The output plot of Tustin model is as shown in Figure 6. Stribeck effect is clearly visible from the output waveform.

## IV. CONCLUSION

The effect of static friction behavior like Coulomb friction, viscous friction and the Stribeck effect are studied using the developed model. The simulation was performed using MATLAB/Simulink. The friction force described by Tustin model is found to be better than Coulomb friction model from the results obtained.

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