

# Nonlinear Friction Behavior of Discontinuity at Stroke End in a Ball Guide Way

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**Abstract:** In this paper, the non-linear behavior of friction is modeled with a dynamic system. The non-linear behavior model being proposed here can be used for modeling Coulomb friction, viscous friction, Stribeck effect and can also be used to study the non-linear behavior of elastic deformation. The frictional force does not cause disturbance in the accelerated motion, instead, it lends a support. The proposed model is not symmetrical about the zero-speed of motion. The simulation result demonstrates that the proposed model is more accurate than conventional ones. In order to verify the validity of the proposed model, experimental results are provided. A linear slider is used to perform the friction force compensation experiment to compare the proposed model with a conventional model. The tracking error is seen to have reduced by more than 50% compared to the case when friction compensation is not used. Further, the value of the positive error was sufficiently suppressed compared with conventional models that use compensation.

**Keywords:** ball guide way, friction compensation, non-linear behavior

## 1. Introduction

The need for high precision and fast response in NC machines for use in the machine tool industry, especially in the manufacturing of semiconductors, is rapidly growing. In order to achieve high levels of performance, frictional effects have to be addressed. However, only a few methods that address frictional effects have been reported thus far. These methods have failed to consider the dynamic behavior of friction. The non-linear nature of friction gives rise to tracking errors and causes stick-slip motion at low speeds. Friction is a natural phenomenon that is quite hard to model, and it is not yet completely understood. Typical examples of friction are different combinations of Coulomb friction, viscous friction, and Stribeck effect [1,2]. In this paper, the non-linear behavior of friction is modeled with a dynamic system. The non-linear behavior is studied using a one-axis stage that is driven by an AC linear motor and guided by a rolling ball guide [3]. It is shown that simulation results based on the proposed model agree well with experimental results.

## 2. Nonlinear Frictional Behavior

### 2.1 Experimental System

The experimental system shown in Fig.1 consists of the following: (i) a one-axis stage mechanism consisting of an AC linear coreless motor which has no cogging and no attraction magnet force, (ii) a rolling guide mechanism (iii) a position-sensor (1pulse=10nm), (iv) two current amplifiers, and (v) a personal computer with the controller, a D/A board and a counter board. Figure 2 shows a block diagram of the control system, which consists of a P controller ( $K_p$ ), a PI controller ( $K_v, T_i$ ), a force filter ( $T_f$ ), a constant gain ( $K$ ) and a mass ( $M$ ).  $FF$  is Velocity feed-forward gain,  $CF_r$  is friction compensation force and  $F_l$  is the actual frictional force. The controller is tuned using the normal procedure and the force is calculated by eqn.(1), where  $V_r$  is velocity reference, and  $V_{fb}$  is velocity response.  $FF$  gain is set to zero.

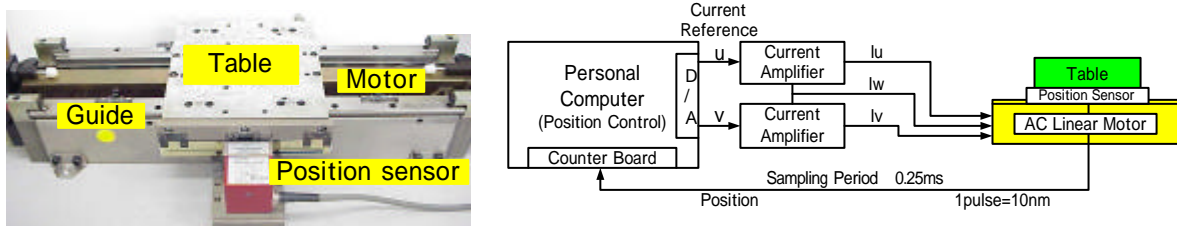


Fig.1: Experimental system.

## 2.2 Experimental Results and Discussions

In applications requiring high precision positioning and low velocity tracking, the conventional control methods are not always satisfactory. In particular, the tracking error is large at the end of stroke. The major disturbance source is friction. It is common to regard the friction force as a static function of velocity although more complex friction phenomena using complex models have been proposed and reported. Experiments have shown that there is a deflection or relative movement in the pre-sliding region, indicating that the relationship between the deflection and the applied force resembles a non-linear spring with a hysteretic behavior [4,5].

Thus, the present study focuses on the non-linear behavior at the stroke end during changes in velocity as shown in Fig.3. In Figs 3 and 4, the signals of  $V_{r1}$ ,  $V_{r2}$ , and  $V_{r3}$  are velocity references with constant acceleration-deceleration profiles of 2.5mm/s, 5.0mm/s, and 10mm/s, respectively.  $V_1$ ,  $V_2$ , and  $V_3$  are velocity responses and  $F_1$ ,  $F_2$ , and  $F_3$  are output forces. The forces in the actual experiment are calculated values and not the values mechanically measured. From Fig. 3, it is seen that the output forces are different at zero velocity for different deceleration profiles. When the velocities are decreasing, output forces have not decreased and when the velocities are increasing, output forces have not increased. Further, it was found that the direction of forces changed. Next, the region of decreasing velocities and zero velocities are studied as shown in Fig. 4. In Fig. 4, the output forces decrease when decelerating, and the output forces to keep zero velocities are about 5.3N.

Next, the output forces are set to zero. This causes spring-like behavior in the motion, as shown in Fig. 5. Fig. 5 shows position responses when the output forces are set to zero and the command velocities are 2.5mm/s, 5.0mm/s, and 10mm/s, respectively. At values of low command velocities, the spring-like behaviors produce large displacement (2000pulse=20  $\mu$ m). The displacement, which exceeds 15  $\mu$ m can negatively influence precision point to point control. The frequency of vibration was observed to be 40Hz. The natural frequency does not depend on the magnitude of the frictional forces at zero velocity. The spring-like characteristic behavior is thought to be due to the elastic deformation between balls and rails in the ball guide-way [6].

## 3. Modeling of Nonlinear Frictional Behavior

### 3.1 Proposed Friction Model

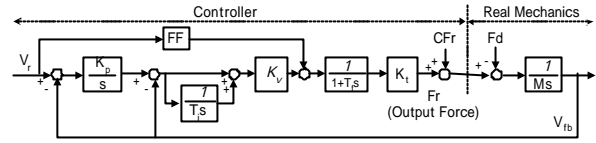


Fig.2: Block diagram of control system.

$$F_r = \frac{K_t}{1 + T_f s} \left\{ K_v \left( 1 + \frac{1}{T_i s} \right) \left( \frac{K_p}{s} (V_r - V_{fb}) - V_{fb} \right) + FF V_r \right\} \quad (1)$$

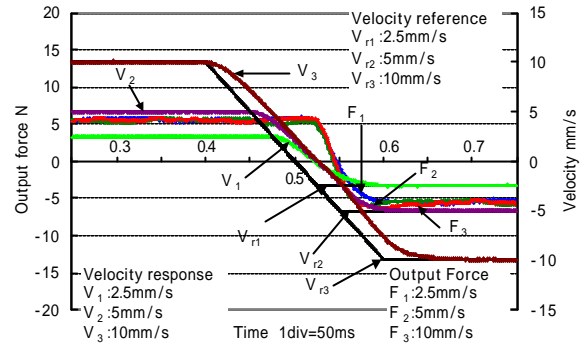


Fig.3: Experimental results at stroke end.

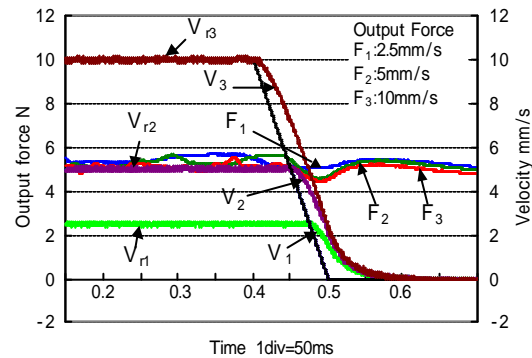


Fig.4: Experimental results at zero velocity.

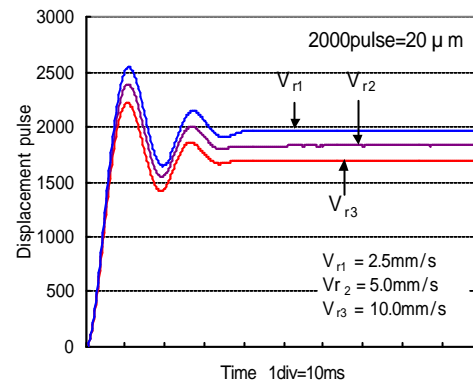


Fig.5: Spring-like behavior when output-forces are set to zero.

Based on the results of these experiments, a new friction model is developed. The model includes a linear term (viscous friction), a non-linear term (Coulomb friction), which is nearly constant but whose sign depends on the direction of velocity, and an extra component at low velocities (Stribeck effect). During deceleration, the magnitude of the frictional force at zero velocity increases due to Stribeck effect which means the influence of friction increase by direct contact of balls and rails in the mixed lubrication mode at low velocity. When the direction changes and the mass accelerates, the frictional force exhibits spring-like characteristics. The frictional force does not hinder the accelerated motion and in fact lends a support. In this operating region, the present model differs from conventional models, as described below. The curve of friction in the deceleration area and in the acceleration area is not symmetrical about the zero velocity point. It is continuous and is an exponential function, as shown in Fig. 6. Equations are as follows:

$$C_s(t) = -C_1 - C_e \exp((t - t_z)/t_1) - D_s V_{fb} \quad t \leq t_z \quad (2)$$

$$C_s(t) = C_2 - (C_e + C_1 + C_2) \exp((t_z - t)/t_2) + D_s V_{fb} \quad t \geq t_z \quad (3)$$

$C_1$  and  $C_2$  are Coulomb friction,  $C_s(t_z)$  is state force at zero velocity.  $t_z$  is the time of zero velocity. The property of the friction model is determined when three parameters,  $t_1$ ,  $t_2$  and  $C_s(t_z)$  are given.

### 3.2 Conventional Friction Model

The conventional description of friction is a static relation between velocity and friction force. Tustin's model consists of Coulomb and viscous friction. The inclusion of the Stribeck effect with one or more break points gives a better approximation at low velocities, as shown Fig. 7. Equations for the conventional model areas as follows:

$$C_s(t) = -C_1 - C_e \exp((t - t_z)/t_1) - D_s V_{fb} \quad t \leq t_z \quad (4)$$

$$C_s(t) = C_2 + C_e \exp((t_z - t)/t_1) + D_s V_{fb} \quad t \geq t_z \quad (5)$$

The curve has an exponential characteristic and is symmetric about the zero velocity time-axis ( $t_z$ ). However, it is difficult to define these parameters using linear estimation techniques because of the nonlinear behavior of friction. The three parameters cited above are estimated using GA (Genetic Algorithm) [7]. The proposed friction model's response, the conventional friction model's response and the response obtained experimentally are compared to determine the accuracy of the proposed model, as shown Fig. 8. When the velocity is greater than zero, the estimated force using proposed model is the same as that in conventional model and the real (output) force. When the velocity is changing direction, the force given by conventional model is far from the real force, while the force given by the proposed model is the same as the real force. The proposed model is judged to have good accuracy. Figure 9 shows the estimated frictional force curves as function of velocity. The estimated frictional force curves show that the exponential and continuous curve improves the accuracy of the proposed model. The friction curve during the change in the direction of velocity works as an acceleration force.

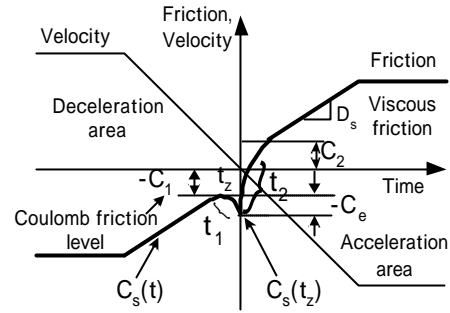


Fig.6: Proposed Friction Model.

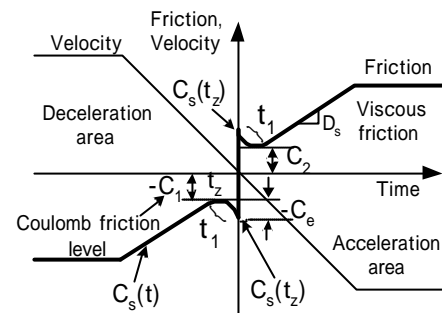


Fig.7: Conventional Friction Model.

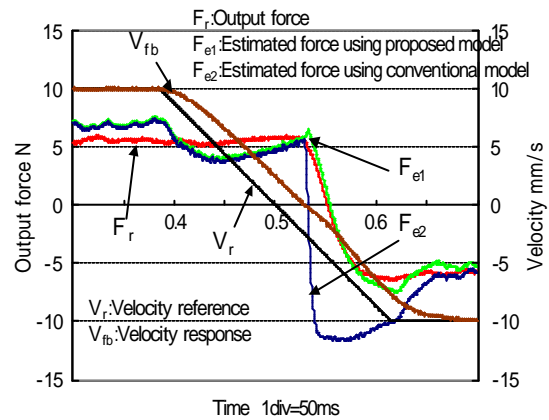


Fig.8: Performance comparison between i. real (output) force, ii. estimated force using proposed model, and iii. estimated force using conventional model at 10mm/s.

#### 4. Compensation of Frictional Behavior

A linear slider is used to perform the friction force compensation experiment using the proposed model and the conventional model. A motion in which the velocity is reversed was used to carry out the experiment. In Fig.10,  $V_r$  is velocity reference, while  $V_1$ ,  $V_2$ , and  $V_3$  are velocity responses. To reduce the tracking error,  $FF$  gain is assumed to be one.  $P_d$  is position error without compensation,  $P_{e2}$  is position error with compensation using proposed model, and  $P_{e3}$  is position error with compensation using conventional model, respectively. The tracking error was reduced to less than a half of that when friction compensation is not used ( $-4.7\mu\text{m}$  -  $2.4\mu\text{m}$ ). When position errors  $P_{e2}$  and  $P_{e3}$  are compared, positive error occurs in the case of  $P_{e3}$  using conventional model ( $+1.5\mu\text{m}$ ). In NC machines, positive error is undesirable, since this would mean that a work piece is excessively cut. Thus, the proposed model is judged to have better performance accuracy.

#### 5. Conclusion

The non-linear behavior of friction is modeled with a dynamic system. Based on simulation and experimental results, the following are the conclusions:

- (1) The non-linear behavior model being proposed here can be used for modeling Coulomb friction, viscous friction, Stribeck effect and can also be used to study the non-linear behavior of elastic deformation. The frictional force does not cause disturbance in the accelerated motion, but lends as a support.
- (2) The simulation demonstrates that the proposed model is much more accurate than conventional ones.
- (3) A linear slider is used to perform the friction force compensation experiment using the proposed method. The tracking error by proposed model was reduced to less than a half of that when friction compensation is not used, and the positive error was sufficiently suppressed compared with conventional model with compensation.

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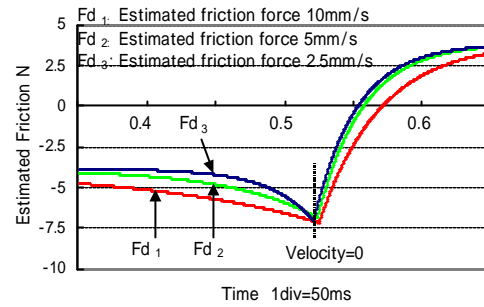


Fig.9: Simulation results of estimated frictional force curves using proposed model.

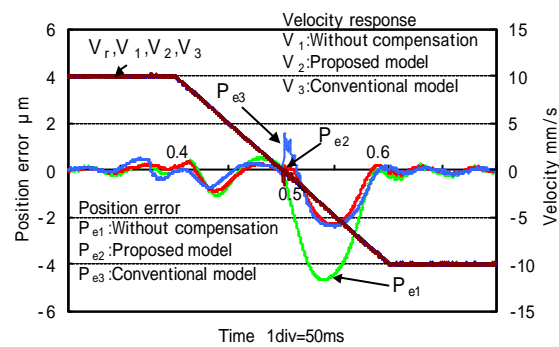


Fig.10: Experimental results obtained for i. Case without friction compensation, ii. Case with compensation using proposed model, and iii. Case with compensation using conventional model at 10mm/s.