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Identification of Friction Models for Precise Positioning System in Machine Tools

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Abstract

This paper focuses on friction identification and numerical validation on ball-screw driven XY milling table. Two friction models namely; static friction model and Generalized Maxwell-slip (GMS) model are identified and validated numerically. Static friction model is identified by measuring the control command signals of various constant velocities while friction-position behavior during sliding and pre-sliding regimes is determined to identify GMS model. Parameters of static friction model are estimated using heuristic approach while application of piecewise linear functions and theory of superposition in virgin curve are used in approximating the parameters of GMS model. Based on obtained parameters, the models are generated in simulation using MATLAB/Simulink to verify the friction models and glitches formed during motion of low velocity. Simulation results showed that GMS model produced clearer and larger glitches compared to static friction model during low velocity motion. GMS model is capable of characterizing the friction behavior during pre-sliding.

Keywords: identification; machine tools; motion control; precision.

1. Introduction

High accuracy and precision is crucial in machining process due to the sky-rocketing development of technologies. However, the presence of disturbance forces in machining system often leads to inaccuracy in tracking and positioning. One of the disturbance forces that greatly affect the tracking performance is friction. It is an undesirable and nonlinear phenomenon that caused many control problems such as limit cycles and stick-slip. One of the famous effects of friction is the formation of quadrant glitches that can be found during machining especially milling process [1]. It is the uneven milled surface or “spikes” during milling process in circular motion and it is formed due to the near zero velocity or motion reversal on each axis of motion system [1], [2].

As the quadrant glitches affected the accuracy and precision of tracking and positioning of the system, compensation of friction is a must and the friction behavior must firstly be characterized. In literature, friction behavior has been studied extensively and recorded. Basically, friction consists of two categories namely; pre-sliding regime and sliding regime [2]. In pre-sliding regime, the friction force is predominantly dependent on displacement while friction force is predominantly dependent on velocity during sliding regime [3]. In order to represent the behavior and characteristic of friction in both

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regimes, many models are suggested and recorded in literatures.

One of the classic models is Coulomb friction model and it is further developed into static friction model that comprised of Coulomb, viscous and Stribeck friction [1]. It is a static map between friction force and velocity and it only described the behavior of friction during sliding regime. One of the early attempts in describing the characteristic of friction in pre-sliding regime is known as Dahl model. The development of Dahl model motivated the further advancement in models such as LuGre friction model [4], Leuven model [5], [6] and Generalized Maxwell-slip (GMS) model [7], [8].

LuGre model is an extension of Dahl model by averaging the deformation of contact asperities and included other friction behavior such as break-away force. Details of this model can be found in [4]. Reference [5] proposed the Leuven model which is an extension of LuGre model that included the hysteresis behavior of non-local memory in pre-sliding regime. Based on Leuven model, reference [6] is then further improved this model and lead to the development of GMS model.

Generalized Maxwell-slip (GMS) model is basically the integration between LuGre model and Maxwell-slip model that applied in Leuven model. This model is capable in capturing the hysteresis behavior of non-local memory in pre-sliding regime, frictional memory in sliding regime, and the Stribeck curve for constant velocities. Deeper information can be found in [7] and [8].

Many methods of friction model identification had been suggested and demonstrated in literatures. Reference [9] applied and compared different approaches in approximating the friction model such as white box and black box approaches. Piecewise linear function is applied by [1] in estimating GMS model. Details procedures in friction identification process can be found in [1] and [10].

In this paper, the static friction model is identified using heuristic method while GMS model is identified using piecewise linear function which similar to the methods presented in literatures. The effect of friction represented by the models identified is validated through simulation using MATLAB/Simulink.

2. Experimental Setup

The considered test setup is a ball-screw driven XY milling table as shown in Fig. 1. The XY milling table consists of two axes namely x and y axes which are driven by a Panasonic MSMD 022G1U AC servomotor and equipped with an incremental encoder with resolution of 0.0005 millimeter/ pulse respectively.

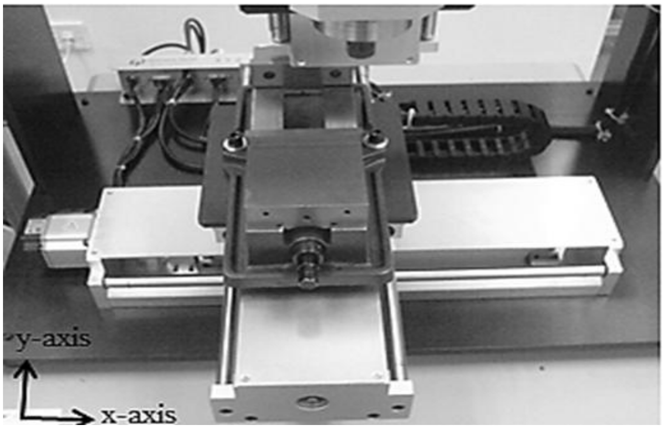

Fig. 1. Ball-screw driven XY milling table.

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Fig. 2 shows the schematic diagram of overall experimental setup.

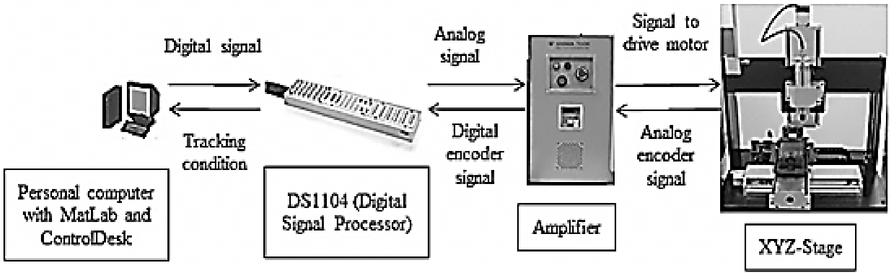

Fig. 2. Schematic diagram of overall experimental setup.

The XY milling table is powered by servo amplifier and it is connected to dSPACE DS1104 Digital Signal Processor (DSP) board. The DSP board is linked to personal computer equipped with ControlDesk and MATLAB software. The host computer used to monitor the motion control of axes and data collected. DSP board uploaded the commands from computer to the drives and received tracking signals from encoder. The signal that sent out from host computer is amplified by a factor of 10 when out from DSP board.

The considered system dynamics can be described using two single-input-single-output (SISO) models and estimated using frequency domain identification approach. Based on the input and output measurements obtained using band-limited random excitation signals, the SISO frequency response functions (FRFs) of the system shown in Fig. 3 are approximated using H1 estimator [11]. Nonlinear least square frequency domain identification method [11] is applied to fit the parametric models on FRFs, producing second order transfer function with delay of 0.00129 seconds as shown in (1).

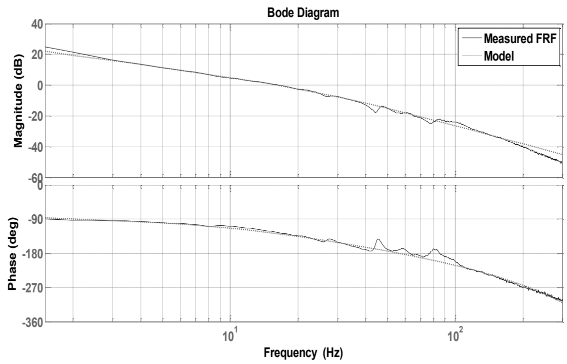

Fig. 3. FRF measurement and estimated model.

$$\frac{Y(s)}{U(s)} = \frac{A}{s^2 + Bs + C} \tag{1}$$

with A = 19.85 mm/V.s^2, B = 168.4 V/s and C = 176.8 V/s^2, where Y is the output position in unit of millimeter while U is the input voltage to the drive in the unit of volt.

3. Friction Model Identification

Two friction models, namely; static friction model and GMS model are considered and identified in this paper.

3.1. Static Friction Model

Static friction model is one of the famous models that characterized the friction behavior in sliding regime which is predominantly dependent on velocity, v. This model comprise of Coulomb, viscous and Stribeck friction, yielding (2).

$$F(v) = \left\{ F_c + (F_s - F_c) \cdot \exp\left(-\left| \frac{v}{V_s} \right|^{\delta} \right) + \sigma \cdot |v| \right\} \cdot sign(v) \tag{2}$$

F_c, F_s, and σ denoted Coulomb, static and viscous friction force coefficient respectively. V_s represented the Stribeck velocity while δ is the Stribeck shape factor.

In static friction identification process, excitation signal, that is, a ramp input signal is used to excite the closed loop system with a manually tuned PID controller to enforce constant velocity as the motor force is equal to the friction force during constant velocity [1], [12]. Measurement of input voltages during constant velocities of 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.2, 0.3, 0.4, 0.5, 0.8, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 25, and 30 mm/s are captured and recorded. The input voltage is averaged for each velocity as shown in Fig. 4. The calculated mean voltage is converted into friction force by multiplying motor constant [1]. Heuristic approach is used to estimate the parameters of the model by fitting the approximated model with the measured friction force-velocity mapping as shown in Fig. 5. The identified parameters are tabulated in table I.

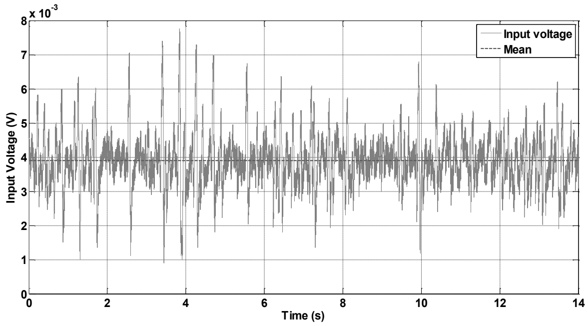

Fig. 4. Input voltage at constant velocity of 0.4 mm/s.

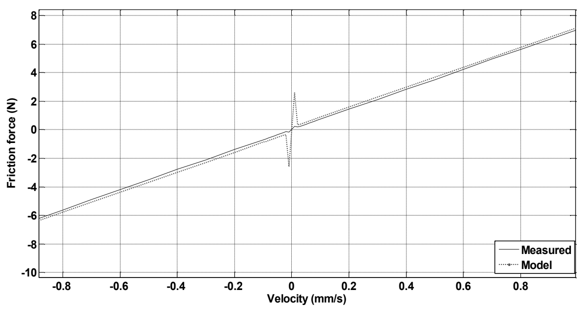

Fig. 5. Measured friction force-velocity mapping and manually fitted static friction model.

Table 1. Parameters Of Static Friction Model

Parameters	Values
F_c	0.1826 N
F_s	210 N
V_s	450 mm/s
σ	6.9846 Ns/mm
δ	1

Based on Fig. 5, although the results of measured friction force-velocity mapping during low velocities are in ambiguous due to the limitation of machine and encoder, the parameters with best fit model is identified using heuristic approach.

3.2. GMS Model

GMS friction model applied the concept of Maxwell-slip model which consists of *N* different elementary slip-blocks and springs in parallel connection. The dynamic behavior of an elementary slip-block during slipping and sticking are characterized as a spring model that shown in (3) and (4).

$$\frac{dF_i}{dt} = k_i v \tag{3}$$

$$\frac{dF_i}{dt} = sign(v) C \cdot \left(\alpha_i - \frac{F_i}{s(v)} \right) \tag{4}$$

During velocity reversal, that is, sticking, friction acted as a spring model with stiffness, k_i. Slipping is occurred when the elementary friction force, F_i equals to a maximum value of elementary Coulomb force, $W_i = \alpha_i s(v)$. α_i is the normalized sustainable maximum friction force of each element during sticking and $s(v)$ is the Stribeck curve. C is equals to $1/V_s$ in (2) and it is a constant parameter that denoted the rate of friction force followed the Stribeck effect in sliding. The total friction force can be obtained by summing up all output of elementary models and viscous constant σ (if presence) as shown in (5).

$$F_f(t) = \sum_{i=1}^{N} F_i(t) + \sigma \cdot v(t) \tag{5}$$

For this considered system, a GMS model with four elementary slip-blocks is selected and each slip-block consists of two parameters, namely; α_i and k_i. Measurements are obtained from sinusoidal signal of small excitation amplitude and larger excitation amplitude but in same frequency to generate virgin curve [1]. Fig. 6 shows the measured friction force and position when sinusoidal excitation signal with amplitude of 0.0001 millimeter and 0.1 Hertz is used.

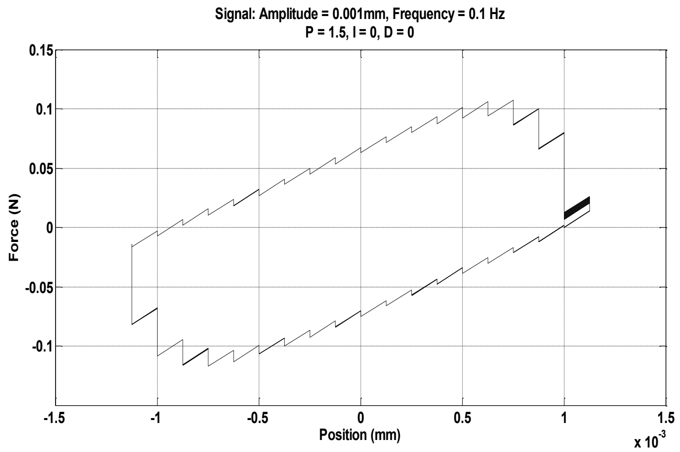

Fig. 6. Measured friction force and position using sinusoidal signal of 0.1 Hertz in frequency and 0.001 millimeter in amplitude.

The two measurements from small and larger excitation amplitudes but with same frequency are combined, reduced by a factor of 2, and shifted to origin in order to produce the virgin curve [1]. From the virgin curve, four knots and slopes are selected manually to estimate the parameters, α_i's and k_i's using piecewise linear function as shown in Fig. 7.

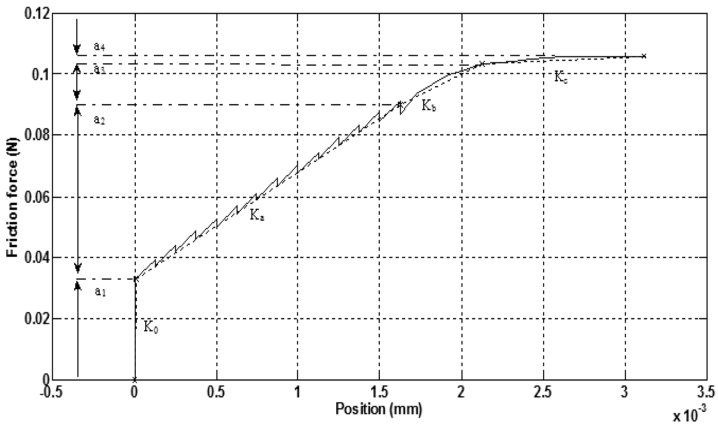

Fig. 7. Virgin curve with selected knots and slopes.

Based on Fig. 7, the slopes, K_0, K_a, K_b, K_c, and α_1, α_2, α_3, α_4 are firstly estimated. By using theory of superposition and (6) the values of k_1, k_2, k_3, and k_4 are calculated. Fig. 8 summarizes the relationship between K_0, K_a, K_b, K_c, α_1, α_2, α_3, α_4, k_1, k_2, k_3, and k_4 and the identified parameters of GMS model is tabulated in table 2.

$$\begin{aligned}
&\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = \sum W_i \\
&k_1 + k_2 + k_3 + k_4 = K_0 \\
&k_2 + k_3 + k_4 = K_a \\
&k_3 + k_4 = K_b \\
&k_4 = K_c
\end{aligned} \tag{6}$$

where $\sum W_i$ is the friction force at the moment of breakaway.

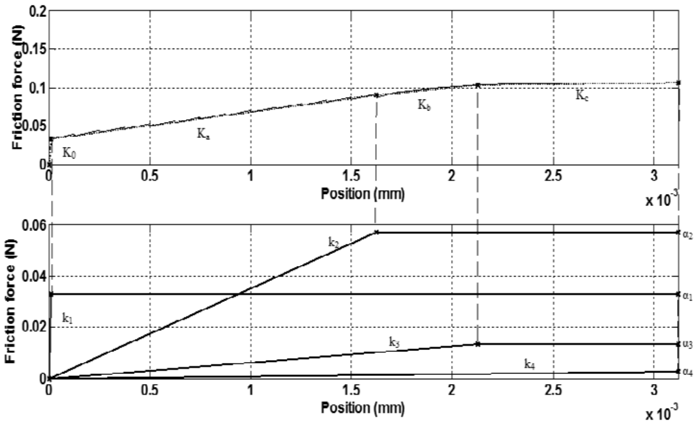

Fig. 8. GMS model parameters identification.

Table 2. GMS Slip-Blocks Model Parameters

α_i	Values (N)	k_i	Values (N/mm)
α_1	0.0330	k_1	3264.7059
α_2	0.0570	k_2	8.8941
α_3	0.0132	k_3	23.7869
α_4	0.0026	k_4	2.6131

4. Friction Model Verification

Two identified models are verified numerically using MATLAB/Simulink software. Two main steps involved in numerically verification are namely; revision of system transfer function parameters and simulation of friction.

4.1. Revision of System Transfer Function Parameters

In order to describe the friction behavior in the system, the friction model is inserted into the system transfer function. Fig. 9 shows the general schematic diagram of system transfer function with friction model to characterize the friction behavior in system. The second order parameters (A, B and C in (1)) are revised manually so that the FRF of this combined model fitted into original model and FRF of actual measurement. The band-limited white noise is used to excite the combined model and approximating the FRF based on simulated input and output signals using H1 estimator [1], [11]. Results of FRF are plotted in Bode diagram as shown in Fig. 10 and Fig. 11.

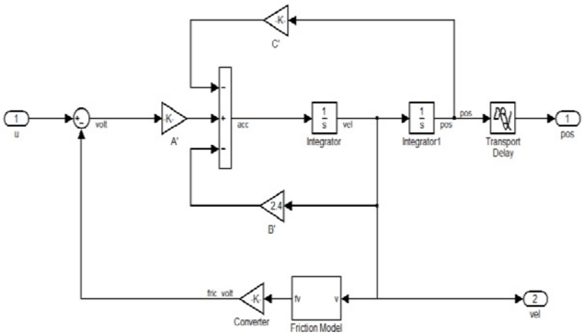

Fig. 9. Schematic diagram of system transfer function with friction model.

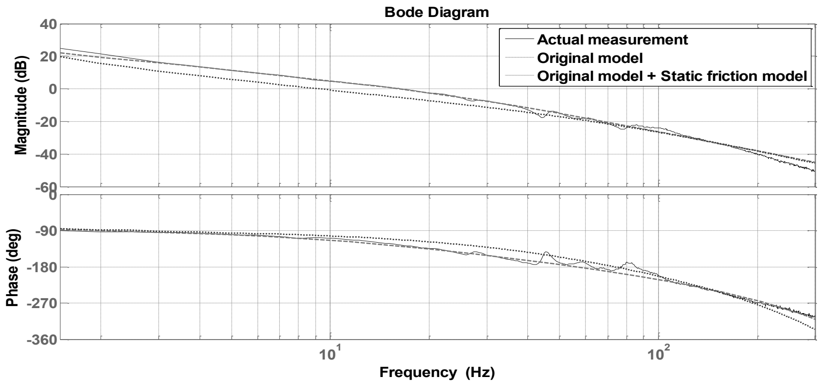

Fig. 10. FRF of actual measurement, original model and combined model of static friction model.

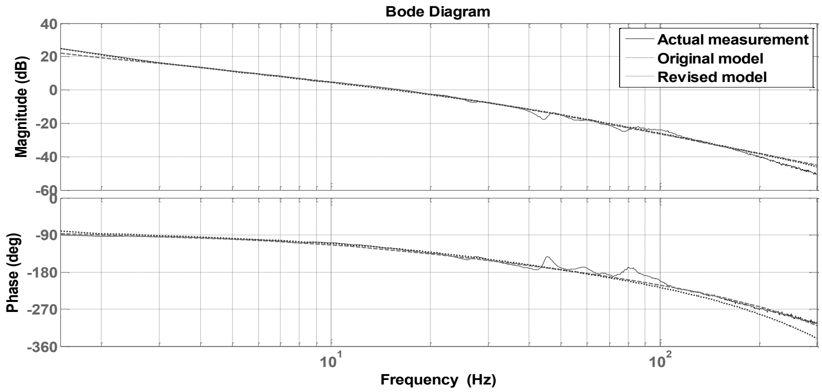

Fig. 11. FRF of actual measurement, original model and revised model with static friction model.

Based on Fig. 10, it is clearly showed differences in magnitude and phase diagram between FRF of models. In order to improve the correspondences between FRF of models, parameters A, B and C in original model (1) are revised manually. Fig. 11 shows that the revised model has better correspondences with actual and original models. Same procedures are repeated for GMS model and the FRF results are showed in Fig. 12 and Fig. 13.

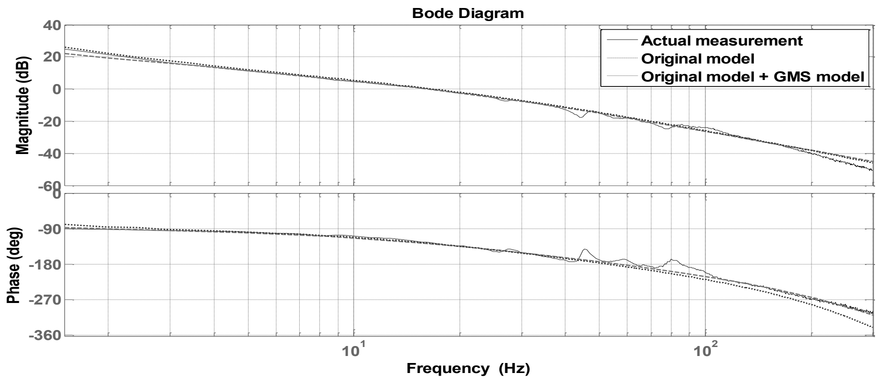

Fig. 12. FRF of actual measurement, original model and combined model of GMS friction model.

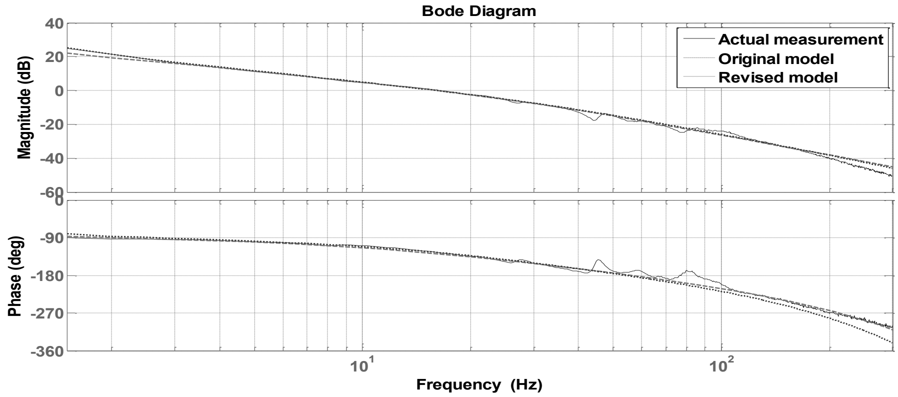

Fig. 13. FRF of actual measurement, original model and revised model with GMS friction model.

Based on Fig. 12, the main difference between FRF of combined model with GMS friction model and other models is the phase diagram in low frequency regions. The revised parameters of system transfer function improved the correspondences of FRF as shown in Fig. 13 and these parameters for both friction models are tabulated in table 3.

Table. 3. Original and Revised System Transfer Function Parameters

Parameters	Type of friction model	
	Static friction model	GMS model
A' (mm/V.s^2)	19.85	19.85
A (mm/V.s^2)	19.85	19.85
B' (V/s)	2.40	180.40
B (V/s)	168.40	168.40
C'(V/s^2)	176.80	176.80
C (V/s^2)	176.80	176.80

4.2. Simulation of friction

By filling up the revised parameters, the friction model is completed. Sinusoidal signals with low frequencies are used to excite the system shown in Fig. 9. Sinusoidal reference signal of 10 millimeters in amplitude and 0.01 Hertz in frequency is used to simulate friction in both friction models. Fig. 14 compared the tracking errors between system without friction model and system with friction models.

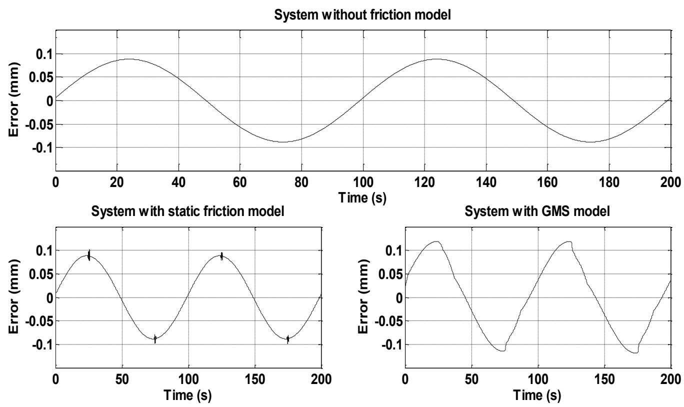

Fig. 14. Tracking errors of system without and with friction models.

Based on Fig. 14, it is clearly showed that GMS model provided larger glitches and errors compared to static friction model. This is compliance with theory that GMS model incorporated more friction behavior compared to static friction model. In addition, this also proven GMS model capable and better in characterized the friction behavior in low frequency regions which considered as pre-sliding regime.

5. Conclusion

In overall, this paper identified two friction model namely; static friction model and GMS friction model in ball-screw driven system. Identification methods for both models are demonstrated and parameters are obtained. GMS model that covered friction behavior in pre-sliding and sliding regimes is identified using piecewise linear function while static friction model that incorporated Coulomb, viscous and Stribeck friction is identified using heuristic approach. Both friction models are simulated and the simulation results showed that GMS model provided clearer glitches and better friction behavior compared to static friction model although with low frequency excitation signal. As future work, both friction models can be validated experimentally and applied in feedforward compensation approaches in friction compensation to improve tracking and positioning performance of machine tools.

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