Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-05-0259

Linear Regression-based Parameter Identification of Machine Tool Feed Drive

Jong-Min Lim[1] and Byung-Kwon Min[1,#]

1 School of Mechanical Engineering, Yonsei University, 50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea
Corresponding Author / Email: bkmin@yonsei.ac.kr, TEL: +82-2-2123-6611

KEYWORDS: Curve fitting, Conservative, Sliding friction, Stribeck curve

Feed drive model is essential for simulating the behavior of machine tools. For establishing the model, it is required to identify equivalent mass and friction coefficients of a feed drive. The dominant friction behavior is the Stribeck effect, which is linear at high speed and exponentially nonlinear at low speed. The algorithms for identifying these parameters can be categorized as online estimation and global optimization. The online identification algorithms have merits in high memory efficiency and low computational load. However, the nonlinearity in the model causes an inaccuracy of identification and difficulty of implementation. On the other hand, the global optimization methods can be used with high accuracy regardless of model linearity, while it requires a considerable amount of process time and high computational load. Thus, the algorithm has a limitation in the application of machine tools to achieve sufficient accuracy. For overcoming these problems, this study proposed a parameter identification method by using linear regression analysis-based approach. Measured system data were classified into positive and negative velocity sections based on the feed direction. The feed drive model was modified by multiplying a common term according to each model parameter. Each term of the equation can be divided into conservative and nonconservative with respect to velocity after integrating the modified model about each velocity section. From this, a linear equation with the slope of each model parameter can be derived. The parameter is identified by calculating the corresponding slope using linear regression analysis. Stribeck velocity, which cannot be represented as a slope of a linear equation, was calculated using a gradient descent-based method to make the corresponding linearity of other friction parameters maximum. The proposed identification method can significantly reduce the computational load and required time compared to global optimization methods. In the experiment, the feed drive model parameters of the testbed were identified. The computation time and the identification accuracy were compared to the genetic algorithm to validate the proposed method.

NOMENCLATURE

F_f = Friction force
m_{eq} = equivalent mass of the feed drive
$\sigma_{+/-}$ = viscous friction coefficient about PVS and NVS
$F_{C+/-}$ = Coulomb friction force about PVS and NVS
$F_{S+/-}$ = break-away friction force about PVS and NVS
$v_{S+/-}$ = Stribeck velocity about PVS and NVS
$\dot{x}$ = velocity of the feed drive

1. Introduction

Machine tool models give us cost and time efficiency by simulating and improving the machine performance without operation [1-2]. Feed drive is the mechanical component of a machine tool thus, its model is used for predicting the actual driving performance caused by control force. The dominant characteristic of the feed drive can be explained with a rigid-body model which contains an equivalent mass and friction force.

Friction force in the sliding region linearly increases as velocity increases if the velocity has a high value. On the other hand, the force has an exponential form in the low-velocity region. The Stribeck curve can contain all these properties. Thus, a feed drive model with the friction curve can explain the system dynamics with high accuracy. However, the model parameter identification requires an amount of computation time or complex process steps due to its nonlinearity. Identification using the work-energy principle [3] and two-step recursive least square [4] reduced the identification complexity. However, they have limitations to be implemented into conventional machine tools since they cannot automatically identify model parameters without user intervention.

This paper proposed an offline identification method using linear regression analysis, which reduces the proportion of an iteration optimization and improves the identification performance in terms of computation time and load. The proposed method identifies each coefficient of the feed drive model by deriving a linear equation whose slope is the corresponding parameter. An iteration process is only applied to Stribeck velocity identification. The proposed method was validated by comparing the identification result of the genetic algorithm (GA) which is the general method for identifying model parameters. From the experiment, the computation time was significantly reduced with similar identification accuracy to GA.

2. Linear Regression-based Identification Process

Feed drive for each axis was modeled as a rigid body with Stribeck curve. In addition, coefficients of the friction curve can have different values according to the driving direction. Thus, the model contains 9 parameters: equivalent mass, m_{eq}, and friction-related coefficients which are viscous friction coefficient, σ, Coulomb friction, F_C, break-away friction, F_S, and Stribeck velocity, v_S, about each driving direction.

In the feed drive model, equivalent mass is multiplied by acceleration, and the friction model is a function of velocity. To make the time integral results about friction-related terms be a function of velocity, the multiplication of acceleration by the model should be done first. Then, friction-related terms become conservative with respect to velocity and the others are nonconservative. To eliminate conservative terms, positive and negative velocity section (PVS and NVS) are defined as durations from driving start to end in the positive direction and vice versa, respectively. Since the velocity at the start and end of each velocity section is zero, the conservative terms are eliminated by integrating them about PVS and NVS. Thus, the equation becomes a linear equation whose slope is m_{eq}.

Linear equations whose slopes are friction coefficients can be derived with the same method. A function of velocity is multiplied on the model for making the integral result about m_{eq}-related term be a conservative with respect to velocity. By eliminating the conservative term by integrating them about PVS or NVS, linear equations with a slope of each friction coefficient are derived.

The parameters are identified by calculating the corresponding slope of linear equations using linear regression analysis. By using the method, the coefficients of the feed drive model can be calculated. However, Stribeck velocity is contained in an exponential term, therefore the linear equation whose slope is equal to the parameter cannot be derived. Thus, an iteration optimization method is used to find v_S which makes the square error between the measured and predicted control force minimum.

3. Experimental Setup

The proposed method was applied to the testbed driven by Yaskawa servo motors and drives. The reference position data transmission and system data acquisition were produced by using a real-time PC. The feed drive was driven along a reciprocating trajectory with a velocity range from low to high speed. For the model identification, reference position, actual position, actual velocity, and applied force were acquired.

To validate the method, the identification result was compared to the result of a GA in terms of computation time. The identification accuracy was analyzed by calculating R-squared (R^2) between the real and predicted friction curve, which is a factor of curve fitting.

4. Result

The identification results of feed drive model are shown in Table 1. The proposed method is reduced the computation time compared to GA. On the other hand, the identified value of each parameter does not have large difference between two algorithms. The identified friction curve from each algorithm and real Stribeck curve were represented in Fig. 1. For a quantitative comparison of identification accuracy, R^2 about the friction curve was calculated. As a result, the accuracy of proposed method was similar to GA as shown in Table 1.

Table 1 Comparison of Identification Result

Identification Result		Proposed method	Genetic algorithm
Feed Drive Model Parameter	$m_{eq}\ (kg)$	98.99	102.46
	$\sigma_+\ (Ns/m)$	705.05	689.34
	$F_{C+}\ (N)$	25.79	25.77
	$F_{S+}\ (N)$	7.48	7.52
	$v_{S+}\ (m/s)$	1.44×10^{-4}	1.42×10^{-4}
	$\sigma_-\ (Ns/m)$	759.82	727.70
	$F_{C-}\ (N)$	26.96	26.91
	$F_{S-}\ (N)$	7.59	6.86
	$v_{S-}\ (m/s)$	1.43×10^{-4}	1.30×10^{-4}
Computation time (s)		3.54	5114.49
R^2 w.r.t Friction Curve		0.9983	0.9986

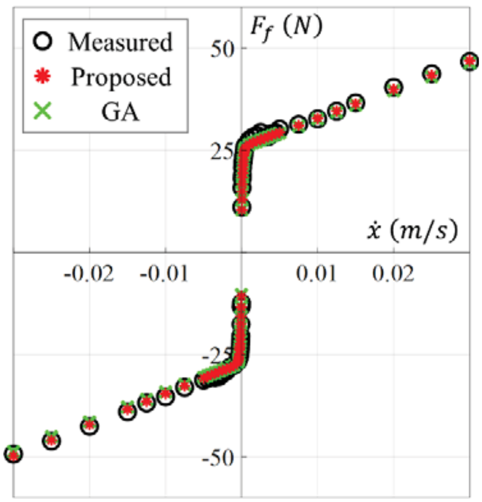

Fig. 1 Identified Stribeck Curve

5. Conclusion

In this paper, a linear regression-based method for identifying a feed drive model was proposed. Since the Stribeck friction curve has nonlinearity, the identification requires considerable computational load and time when using global optimization methods. In addition, recursive algorithms do not guarantee identification accuracy. The proposed method reduced the iteration computation by deriving linear equations which have slopes of model parameters. These slopes were calculated by using linear regression analysis. The proposed method experimentally showed that the computation time was reduced while keeping similar identification accuracy compared to GA.

REFERENCES

1. Le Flohic, J., Paccot, F., Bouton, N. and Chanal, H., "Model-based method for feed drive tuning applied to serial machine tool," Int. J. Adv. Manuf. Technol., Vol. 95, No. 1, pp. 735-745, 2018.
2. Bui, B. D., Uchiyama, N. and Simba, K. R., "Contouring control for three-axis machine tools based on nonlinear friction compensation for lead screws," Int. J. Mach. Tools Manuf., Vol. 108, pp. 95-105, 2016.
3. Vakil, M., Fotouhi, R. and Nikiforuk, P. N., "Energy-based approach for friction identification of robotic joints," Mechatronics, Vol. 21, No. 3, pp. 614-624, 2011.
4. Lee, C. Y., Hwang, S. H., Nam, E. and Min, B. K., "Identification of mass and sliding friction parameters of machine tool feed drive using recursive least squares method," Int. J. Adv. Manuf. Technol., Vol. 109, No. 9, pp. 2831-2844, 2020.