別紙４（課程博士）

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Abstract

論文内容の要旨　(博士)

Title of Thesis 博士学位論文名	Nonlinear Friction Modeling and Adaptive Compensation for Precision Contouring Control of Industrial Machines (産業機械の高精度輪郭制御のための非線形摩擦のモデル化と適応補償)

(Approx. 800 words)

(要旨　1,200 字程度)

Industrial machines have highly contributed to the development of manufacturing and productivity. Machine tool is essential industrial machine for the reason that it facilitated the manufacturing of more production machines for manufacturing in other industries. In addition, it enables ability to reproduce itself. Machine tools have developed notably over time in order to adapt to the increasing requirements for speed, precision and productivity. This development needs various intense researches on structure design, sensor, material and controller method. This thesis mainly focuses on precision motion controller for feed drive systems in machine tool by addressing friction nonlinear behavior, designing an adaptive friction compensation model and a sliding mode contouring controller.

Friction is the main disturbance in mechanical systems especially in computerized numerical control (CNC) machine tools with high precision, speed, and performance requirements. Much recent research have proven that a controller with friction compensation provides better performance. Some classical friction models such as the Coulomb–viscous–Stribeck friction model, the Lugre model, and the Generalized Maxwell Slip (GMS) model have been proposed to compensate for frictional effects, reduce the contour error and improve the surface quality. However, most of the conventional friction models focus on nonlinear frictional properties in pre-sliding region and low velocity sliding region. These models do not fully describe and compensate for friction in machine tool systems in case of high speed motion or insufcient lubrication. This thesis proposed two nonlinear friction model for feed drive systems in machine tool in chapter 2. One called "static friction model include nonlinear component" is proposed based on assumption about various friction sources with nonlinear properties in ball-screw feed drive system. It includes a nominal conventional static friction model and a number of nonlinear friction sources represented by Gaussian functions. The other model called "static friction model include eccentric friction" is the combination of the conventional static friction model and a nonlinear sinusoidal component for fully describing the eccentric friction induced by eccentric phenomenon in lead-screw feed drive systems. Identifcation method for parameters of two proposed model and conventional static friction model are presented in chapter 3 and 5. Different friction model compensation is added to existing feedback controllers in order to improve accuracy in single ball-screw feed drive, bi-axial table and three-axis machine tool motion control.

In single ball-screw feed drive systems control, frst, generalized ballscrew feed drive dynamic with conventional static friction model is presented. Non-bias lead squares techniques [1] and constant velocity operation [2] are used to identify model parameters. The performance of the two estimation algorithms have been compared by using simple control input excited patterns. However, this verifcation method did not show mismatch between estimated friction model and actual friction value. We proposed an sinusoidal signal tracking experiment to show the imperfection of conventional friction model. Distinct deviation between conventional static friction model and actual friction value confrms the presence of various friction sources with

nonlinear properties in ball-screw feed drive system. Static friction model include nonlinear component in chapter 2 are selected to model this kind of ball-screw feed drive system. A Matlab program use the Nelder–Mead downhill simplex method [3] to identify nonlinear friction parameters. Finally, a tracking controller design with friction feedforward compensation is proposed. Simulation and experimental results on a single ball-screw feed drive systems show a clearly performance improvement by adding proposed nonlinear friction model for feedforward compensation.

In bi-axial table control, identifed method in chapter 3 is applied to each axis. Tracking controller design with nonlinear friction compensation is proposed. Simulation and experimental results show the effective of proposed model. In multi-axis motion, beside tracking errors, there are contour errors defned as the normal deviation from the desired tool-path. It direct represents contour performance and is an importance factor in surface machining. Therefore, we design a contouring controller with nonlinear friction compensation for bi-axial table based on two-dimensional contour error estimation. Comparative experiments with several different friction compensations at low and high velocities motion are conducted, and it has shown that the proposed controller performance is effective at high velocity desire motion, where the maximum contour error is reduced by 58% compare to the controller use conventional static friction model. This can be explained from the nonlinear friction model's ability to accurately describe the friction nonlinear properties at high velocity motion.

In three-axis machine tool control, frst, three lead-screw feed drive dynamic with conventional static friction are identifed as in chapter 3 by conventional identifcation methods. Second, sinusoidal signal tracking experiment are conducted and show the imperfection of conventional friction model. However, the deviation between conventional static friction model and actual friction in three-axis machine tool experimental setup show a repetitive properties. This phenomenon confrms assumption about the dominant eccentric friction induced by eccentric lead-screw feed drive systems in chapter 2. Therefore, static friction model include eccentric friction in chapter 2 are chosen to describe this friction phenomenon. A Matlab program uses the Nelder–Mead downhill simplex method [3] and "fminsearch" function is designed to identify eccentric friction parameters. Finally, a contouring controller design with eccentric friction compensation is proposed. Simulations and experiments with out cutting were conducted based on a circular and a non-circular reference contours. Comparative experiments with different controller confgurations shows that the proposed method is more effective than the contouring controller without friction compensation and with the conventional friction compensation. In the average, the mean and the maximum contour error in proposed controller were reduced by about 26% and 9.3% in circular trajectories in comparison with the contouring controller that uses the conventional friction model, respectively. In addition, a robust sliding mode contouring controller with adaptive friction compensation is proposed to deal with parameters uncertainty, nonlinear friction and other unknown disturbances. We proposed a nonlinear switching gain and an adaptive friction model in controller to improve contouring performance of three-axis machine tool. It is shown that the proposed controller is effective in reducing contour error by about 28.6% and power consumption by about 7.1% in circular contour tracking experiment.

This thesis presents advanced research about friction models in feed drive systems. Two model are proposed to describe nonlinear friction components depend on particular feed drive system. Tracking controller and contouring controller design with different friction compensation technique is proposed to achieve accurate motion. Both simulation and experiment are conducted in single ball-screw feed drive, bia-axial table and three-axis machine tool. Comparison results show that the performance can be improved by adding proposed nonlinear friction model. However, further studies are desired to acquire adaptive nonlinear friction and cutting forces estimation. This will ensure a robust friction compensation approach to changing friction behavior and properties over time due to the influence of lubrication, wear, vibration and etc. In addition, this will enable extension to more complex system such as fve-axis machine tool and conduct cutting experiments.