別紙４－１（課程博士（英文））

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Abstract（Doctor）

Title of Thesis	Adaptive Nonlinear Control and Friction Compensation for Precision Motion and Energy Saving of Multi-Axis Industrial Systems

Approx. 800 words

Due to the strong demand to produce very complicated industrial component s with high accuracy in large quantities, sophisticated technological equipme nt and machinery such as computer numerical controlled (CNC) machines h ave been used. These machines actually operate all day and night all over t he world in various industrial applications, consequently they are responsibl e for consuming a great amount of electrical energy consumption, therefore usage these machine leads to increase of energy problem in diverse industri es. For this reason, reducing even a small percentage of energy consumed b y CNC machines can provide a significant reduction of the manufactured wo rld energy consumption.

Control approaches that employ to manufacture industrial products using high control gains, can generally enhance motion accuracy of feed drive systems, but they cause increase of manufacturing energy consumption. Thus, energy saving of industrial machines as well as motion accuracy have to be simultaneously considered. One more challenge in CNC machine tools is friction phenomena, which cannot be negligible in case of producing high accurate products to meet high technologies required zero error. Friction adversely affects not only motion accuracy but also excessively consumes energy of the control systems. This thesis attempts to overcome these problems occurred in industrial feed drives, thereafter improvement of the control performance and energy consumption reduction is highly expected. In order to enhance the motion accuracy in terms of tracking and contouring accuracies in machine tool feed drives, this thesis proposed various approaches as follows:

- The new adaptive sliding mode contouring control (ASMCC) has been designed to reduce energy consumption and motional errors in a biaxial feed drive machine tool. The adaptation strategy allowed control gains to be adjusted relying mainly on resultant contouring errors. Once the resulted control errors are changed due to some disturbances, the control gain is simultaneously updated to generate appropriate control signal achieving a precisely track to desired motion. Therefore, the adaptive controller could largely reduce the contouring errors by 37.62% and 34.65% in computational simulation and experiments without the need to increase the consumed energy under the same control parameters, respectively. Moreover, consumed energy could be improved by 8.20% compared to non-adaptive

sliding mode control producing the same control performance, approximately.

- In order to achieve highly precision parts, an estimation process for frictional properties of a biaxial feed drive has been applied. The updated system parameters and meanwhile a disturbance observer (DOB) have been combined with the proposed adaptive controller (ASMCC) to decrease the contouring performance and the consumed energy. Experimental results confirmed that the mean and maximum contour errors were improved by 91.72% and 38.6% compared to using only ASMCC, respectively. Furthermore, energy consumption was reduced by 0.898% and 2.05% for X and Y axis, respectively.
- The previous adaptation approach has been modified and reformulated to meet high quality standards of industrial parts. A circular motion trajectory has been performed using an industrial machine tool. The new adaptive formula was able to update control gains not only through reaching phase but also during the sliding phase, therefore energy consumption reduction and motion accuracy in each feed drive axis could be significantly improved. Moreover, the suggested adaptive gains could be flexibly updated depending on the control performance. Thus, the mean and maximum tracking errors were largely enhanced by 55.98% and 31.10% on average compared to a general adaptive law used in many previous studies, respectively. In addition, energy consumption of the proposed adaptation method was significantly by 2.53%.
- The novel nonlinear friction mode was proposed to improve mechanical properties of feed drives alleviating frictional errors. The introduced model could comprise many unknown frictional sources in both low and high velocity regions. Therefore, the friction compensator was able to precisely describe actual frictional attitude in the machines, thus the proposed model with its highly precise knowledge of a nonlinear friction behavior could be effectively reduced control efforts dissipated in compensation of unknown frictional sources. The proposed model consists of four frictional sources; Coulomb friction, viscous friction, Stribeck effects, and a nonlinear friction term. The latter term is represented with the Fourier series, which can well describe any periodic signals. The proposed frictional model was able to flexibly extend for many nonlinear terms until obtaining the best description of the actual friction behavior. Experiments have been repeated five times to ensure repetitiveness and accuracy in energy and error measures. Experimental results show a significant enhancement of the proposed technique on reducing control errors and energy consumption in each feed drive axis. The mean tracking error resulted using the new friction model was lowered to less than 5 μm for each axis. The control input variance has been also improved by 7.62% compared to a conventional friction mode. Consequently, consumed energy of feed drives was significantly reduced by 12.83%.
- The final adaptive controller was combined with a nonlinear frictional model to increase energy saving. Experiment results confirmed that the presented combination could achieve significant enhancement on reducing the tracking errors and energy consumption of an industrial feed drive compared to the proposed adaptive control approach combined with a classical friction model.