別紙４－１（課程博士（英文））

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Abstract (Doctor)

Title of Thesis	Multi-Objective Optimization Approach to Energy-Saving Motion Trajectory Generation with High-Speed and High-Accuracy for Industrial Feed Drive Systems

Approx. 800 words

The ever-growing breakthroughs in science and technology perpetually pressurize the manufacturing industry to increase accuracy and production rates in processes. Such increases come at a price, the price of an enlarging carbon footprint with limited reliable energy sources. Computer numerical control (CNC) machine tools are typically used in the industry due to their accuracy and repetitive task execution speed. Due to the afore-mentioned production and energy pressures, the objectives of improving accuracy, cycle time, and energy consumption are major research drivers. Since these objectives are contradictory, Pareto optimization methods are necessary to obtain optimal operating conditions.

There are typically three possible actions for achieving the aforenamed objectives: hardware upgrades, internal software modifications, and trajectory optimizations. Hardware upgrades are usually avoided since they are relatively expensive. Most commercial CNC machine tools' internal software is inaccessible; hence trajectory optimization presents a feasible and cost-effective action. With this rationale, trajectory optimization is the study field explored in this thesis.

This thesis discusses several propositions for trajectory optimization in industrial feed drive systems: Pareto optimization of energy and tolerance in motion trajectory generation (Chapter 3), a trade-off between energy saving and cycle time reduction by Pareto-optimal corner smoothing (Chapter 4), and Pareto optimization of cycle time and motion accuracy (Chapter 5). Feed drive dynamics, energy modeling, trajectory profiling, a multi-objective optimization problem formulation, and a Pareto frontier generation algorithm are described in the preliminaries chapter (Chapter 2). The thesis is completed with a conclusion and future works chapter (Chapter 6).

A method of generating piecewise linear trajectories with smoothed corners optimizing two objectives: energy consumption and cornering tolerance for feed drive systems is proposed in Chapter 3. An energy model of an industrial biaxial feed drive system is used to formulate a bi-objective optimization problem. The linear and smooth corner segments are respectively described using jerk-limited acceleration profiles (JLAPs) and kinematic corner smoothing technique with interrupted acceleration (KCSIA). The optimization problem is formulated with the normalized normal constraints method, where sequential quadratic programming is used to solve it. A divide and conquer algorithm is utilized to generate Pareto optimal solutions recursively. The best trade-off solution is obtained as the one that minimizes both objectives. Optimization results for an industrial biaxial machine are illustrated, where the best trade-off solution achieves ~64% of the energy-saving potential with a moderate cornering tolerance of ~30μm.

Chapter 4 proposes a method of generating Pareto optimal corner smoothing trajectories that trade-off the contradicting objectives of minimizing cycle time and energy consumption. Several studies have proposed corner smoothing methods that improve cycle time for piecewise linear paths by exploiting axial limits to achieve time-optimal trajectories. Energy-saving is not considered an objective in these methods. The trajectories along linear paths and smoothed corners are respectively described using JLAPs and kinematic corner smoothing methods (i.e., KCSIA and kinematic corner smoothing with uninterrupted acceleration (KCSUA)). An energy consumption model of an industrial two-axis feed drive system is identified by least squares estimation and used in solving the bi-objective optimization problem (BOOP). A contrast and comparison are made between KCSIA, KCSUA, and point-to-point (PTP) motion profiles. The optimization results show that the KCSIA Pareto frontier is closest to the utopia point, where it is experimentally vindicated that the best trade-off trajectory achieves ~66% and ~60% of the time and energy-saving potentials, respectively. In terms of contouring performance of best trade-off trajectories, while KCSUA reduces the average error by ~7%, KCSIA decreases the maximum error by ~19% relative to PTP.

A method of Pareto optimizing the conflicting objectives of reducing cycle time and increasing cornering accuracy for piecewise linear contours is proposed in Chapter 5. It has been shown in the literature that non-zero cornering velocities deteriorate contouring performance while reducing cycle time. To resolve the set of conflicting objectives, the normalized normal constraint formulation of the BOOP is described with lower and upper cornering tolerances at each corner described as inequality constraints. This method's effectiveness is investigated with linear and smoothed corner segments, respectively, defined by JLAP and KCSIA. The optimized KCSIA is referred to as KCSIA*, where its Pareto frontier shows that the original KCSIA produces a dominated solution. Hence, KCSIA* solutions are superior compared to KCSIA. Experimental results further emphasize this point by showing that the KCSIA* had a lower contouring error than KCSIA, where the best trade-off solution reduces the maximum and average contouring errors by ~29% and ~12% while increasing cycle time by ~3% compared to KCSIA.

Concluding remarks and tentative future works of this thesis are illustrated in Chapter 6. The proposed methods can be extended to five-axis CNC machines by including tool orientation tolerances at corners. In the case of machining operations, cutting forces increase the amount of energy consumption. Hence, a cutting force model can be incorporated into the previously used energy consumption model. The proposed methods can be generalized by considering asymmetrical corner smoothing together with cornering transitions other than line-to-line ones.