year month day
2013 8 7

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A b s t r a c t

Title	Nonlinear Control for High Precision Motion and Energy Saving in Multi-Axis Industrial Systems

(800 words)

High-precision machining of complex-shaped such as dies, molds, and aerospace parts with sculptured surfaces requires multi-axis feed drive systems to accurately follow specified contours. In addition, because computer numerical controlled (CNC) machines are widely used night and day in manufacturing all over the world, not only high-speed and high-precision control but consumed energy control is required. In practice, the tool motion deviates from the desired trajectory due to the limited bandwidth of the servo drives as well as disturbances originating from cutting forces and guide-way friction. For machining, reduction of contour error is an important issue. Contour error is defined as the component orthogonal to the desired contour curve, and it represents better indicator of precision machining. In addition, it is too difficult to calculate the contour error in real time because it requires solving nonlinear equations in real time. In order to improve tracking/contouring performance for multi-axis feed drive systems, this thesis presents several approaches for the following feed drive systems:

(1) Single-axis feed drive system: We presented a novel sliding mode controller with a non-linear sliding surface to improve the machining accuracy of ball-screw feed drive systems. Unlike the conventional sliding mode control design, the proposed non-linear sliding surface varies according to the output (controlled variable) so that the closed loop system simultaneously achieves low overshoot and a small settling time, resulting in a smaller error and small energy consumption. The consumed energy and control input variation were reduced by about 12.9% and 19.1%, respectively.

(2) Biaxial feed drive system: We proposed a novel sliding mode contouring controller with a nonlinear sliding surface to improve the machining accuracy and reduce the consumed energy of the biaxial feed drive systems. The advantage of including the contour error in the proposed sliding surface is that the damping ratio of the system changes from its initial low value to its final high value as the contour error changes from high value to small value and vice versa. The proposed approach reduced the control input variance and consumed energy on average by about 41.2% and 14.9% (for x and y-axis, respectively) and 23.6% and 5.5% (for x and y-axis, respectively), respectively.

(3) Three-axis feed drive systems: We presented a new contour error estimation model for three dimensional machining tasks. The model is based on estimation of the instantaneous curvature of the reference trajectory and a coordinate transformation approach. This algorithm is based on an iterative desired contour curve approximation by circular curves. We extended the approach of sliding mode contouring controller for biaxial feed drive system to the three-axis case. In this approach, the normal and bi-normal error components are given more importance than the tangential component. By using the proposed method, simulation and experimental results for a desktop three-axis machine show a significant performance improvement in terms of the contour error.

(4) Five-axis machines: Conventionally, five-axis machines do its control efforts to minimize the error components along the driving axis independently. Although many effective controllers have been applied to the individual axis control loops, elimination of the tracking errors of each individual axis in multi-axis feed drive systems may not guarantee the desired contouring accuracy. Even if the tool tip contour error and tool orientation contour error are very small, a mismatch between the observed tool tip position and tool orientation will cause an over-cut or undercut when these errors are treated independently. To avoid this mismatch, we present a new definition of the tool orientation contour error to consider synchronization between the tool tip contour error and tool orientation contour error. Experimental results demonstrate that the proposed tool orientation contour error reduction is more important than the reduction of the conventional tool orientation contour error. Based on the tool orientation contour error estimation method, we designed a novel sliding mode contouring controller with nonlinear sliding surface and disturbance observer for five-axis machines. The proposed controller considers the synchronization of the tool tip and orientation contour errors.