Technical note

Cross-coupling position command shaping control in a multi-axis motion system

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ABSTRACT

A new structure of a cross-coupling position command shaping controller (CPCSC) for precise tracking in multi-axis motion control is proposed in this paper. This controller feedforwards the cross-coupling terms, based on the geometrical relationship between the tracking and contouring errors, to compensate for the contouring error in real-time. Compared with the conventional multi-axis cross-coupling control (CCC) system, this new structure has the advantage that its compensators in CCC have a simpler design process than conventional ones, as does its stability analysis. The proposed controller is evaluated and compared experimentally with a traditional uncoupled and a conventional CCC controller on a multi-axis positioning system controlled by microcomputer. The experimental results show that the new structure remarkably reduces contour error. In addition, this new controller can be implemented easily on most current systems by reprogramming the reference position command subroutine.

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1. Introduction

Accurate contour control is a fundamental requirement for modern manufacturing systems, especially for multi-axis CNC machine tools. Any single axial positioning accuracy can be improved by applying various control strategies such as a large P gain controller, a feed-forward controller [1,2] or a ZPETC (zero phase error tracking controller) [3]. However, good tracking performance for each individual axis does not guarantee the reduction of the contour error for multi-axis motion [4]. The term "contour error" representing, for example, the deviation of the cutter location from the desired contour path in a CNC machine, is defined as the error component orthogonal to the desired trajectory. Chiu and Tomizuka [5] viewed the contouring performance as a regulation problem in a moving task coordinate frame to attach the desired contour. Xi [6] developed a contouring error model, which can predict the contour error in each of the instantaneous reference commands, which are projected to each driving axis and fed into the control loop of each driving axis. Another method to reduce the contour error is the cross-coupling control, and Koren [7] introduced a symmetrical structure of cross-coupling controller to improve the contour accuracy. In this approach, the whole system was considered as a single unit, instead of individual loops, thereby reducing the influences of load disturbances and axis mismatch on system performance.

A typical cross-coupling controller essentially consists of an algorithm to calculate the contour error and a control law to eliminate the contour error. Many control laws such as traditional PID [8] control, optimal control [9], adaptive control [10], fuzzy logic control [11], iterative learning control [12] and robust control [13–15] have been proposed to implement the CCC.

The traditional multi-axis cross-coupling control system in the literature is shown in Fig. 1, where the CCC output is generated to modify the feed drive (velocity command type). In this figure, $\boldsymbol{P_d} = [P_{dx} \quad P_{dy} \quad P_{dz}]^T$ represents the desired axial positions and $\boldsymbol{P_a} = [P_{ax} \quad P_{ay} \quad P_{az}]^T$ represents the actual axial positions; $\boldsymbol{Q} = [Q_x \quad Q_y \quad Q_z]^T$ represents the position loop controller for each axis; $\boldsymbol{e} = [e_x \quad e_y \quad e_z]^T$ represents the tracking errors; $\boldsymbol{G} = [G_x \quad G_y \quad G_z]^T$ represents the plant including the velocity inner loop and the integrator for each axis; $\hat{\boldsymbol{\varepsilon}} = [\varepsilon_x \quad \varepsilon_y \quad \varepsilon_z]^T$ represents the contour errors calculated by geometric relationship; and w is the CCC controller. In the design of this type of CCC, the CCC outputs are decomposed and then injected into the inner loops in order to reduce the contour error. However, the fed loop, induced by the CCC controller, will affect the stability of the whole system. Therefore, a complicated stability analysis should be used to design the CCC controller.

The servo drives currently used in industry can be classified into three types of control mode: position mode, velocity mode, and torque mode; each of which has its own merits and applicability. This is why most suppliers provide these three control modes for application engineers to choose from. Although various control modes are available, the classical CCC, which is intended to modify the command of the velocity-mode feed drive, can not cope with systems using the position-mode feed drive. In order to apply this advanced control scheme, we need a more generalized CCC structure, as proposed in this paper. Since the contour error is a function of axial tracking errors, we believe that modifying the position

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