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The Integrated Linear and Nonlinear Motion Control Design for Precise CNC Machine Tools

Zheng-Hong Tsai, Syh-Shiuh Yeh, Pau-Lo Hsu, *Member, IEEE*

***Abstract* - The error resources of precise motion control systems are basically categorized into linear and nonlinear effects. To pursue motion precision of industrial CNC machine tools, this paper proposes an integrated control structure with modular algorithms including both the linear control and the nonlinear compensation. In linear control design, this paper applies three algorithms: (1) the feedforward control to deal with the tracking error, (2) the cross-coupled control (CCC) to reduce the contouring error, and (3) the digital disturbance observer (DDOB) to lessen the effects of modeling error and disturbance in real applications. Results indicate that the linear motion controller achieves both greatly improved tracking and contouring accuracy by reducing the servo lags and mismatched dynamics of different axes. However, the slip-stick effect due to friction still exists and cannot be removed by applying the linear motion controller only. This paper further integrates the nonlinear compensator and develops friction estimation and compensation rules for CNC machine tools. The DSP microprocessors are suitable to implement all linear and nonlinear algorithms and the proposed controllers have been successfully applied to industrial CNC machine tools. Experimental results in various speed commands indicate that the proposed integrated controller reliably achieve 7 *um* contouring accuracy in CNC motion control.**

I. Introduction

Because the computation speed increases and the cost decreases as the microprocessors were developed rapidly in the past two decades, motion control design for CNC machine tools with high precision operated under high speed are pursued. In addition to the defects of mechanical structure, system including the improper control loop gains, incompatible dynamic response among axes, servo lags, nonlinear command path, loading and external disturbance all play important roles of motion error which can be overcome by applying suitable control design [1]. In addition to the above motion errors caused by linear factors, the nonlinear friction also plays an important role in precise motion control. If mealy linear design is used to the motion controller, the desirable motion control performance cannot be achieved. Hence, in this paper, we propose an integrated controller design including both the linear motion controller and the nonlinear compensator. By implementing all the proposed control and compensation algorithms on a DSP microprocessor, the precision and robustness of the motion system are thus greatly improved.

In general, feedforward controllers are effective to improve the tracking accuracy. Its design concept basically applies the pole-zero cancellation to shape the dynamic characteristics of servo systems. However, for systems with unstable and lightly-damped zeros, they cannot be cancelled directly [2] and the zero phase error tracking control (ZPETC) was proposed by Tomizuka [3]. Because ZPETC is a model-based design, the tracking ability is sensitive to all modeling error, plant parameter variation, and the external disturbance which includes friction, inertia, cutting force, measurement noise and torque ripple. In other words, the tracking accuracy is affected easily by system uncertainty and disturbance so some auxiliary control design is desired for feedforward controller design.

Moreover, Koren and Lo further proposed the variable-gain CCC which improves the contouring accuracy significantly [1]. Houng and Hsu proposed the concept of integrated control that including ZPETC and CCC to improve both the tracking performance and the contouring accuracy [4]. Furthermore, Yeh and Hsu proposed the method of estimation of contouring error vector for multi-axis CCC controlled systems [5].

In real applications, the system uncertainty and the external disturbance affect robustness of precise motion systems. Ohnishi proposed the structure of disturbance observer (DOB) in order to suppress disturbance and increase the robustness of systems [6]. Umeno and Hori further proposed the DOB that including all the system uncertainty, external disturbance, friction, and change of loading as unknown disturbance torque. The DOB estimation and compensation eliminate external

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Z. H. Tsai is with the Department of Electrical and Control Engineering, Chiao-Tung University, Hsinchu, Taiwan, 300 (E-mail: gaggery.ece91g@nctu.edu.tw).

S. S. Yeh is with the Department of Numerical Control Technology, Mechnical Industry Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan, 300 (E-mail: ssyeh@itri.org.tw).

P. L. Hsu is with the Department of Electrical and Control Engineering, Chiao-Tung University, Hsinchu, Taiwan, 300 (Phone: 886-3-5712121 ext.54362; E-mail: plhsu@cc.nctu.edu.tw).

disturbance in the low frequency range and the noise effect in high frequency is also effectively suppressed. Moreover, design of digital disturbance observer (DDOB) was developed in the discrete-time domain in practice [7]. Therefore, feedforward controllers improve the tracking ability of system, CCC improves the contouring accuracy of path of motion, DDOB suppresses the modeling error and disturbance effects. In this paper, we will integrate all the linear controllers of ZPETC、CCC and DDOB into CNC machine tools to results in both good tracking and contouring accuracy in real applications.

In addition, friction is a dominant factor that limits the motion precision of CNC motion. However, friction in CNC control is usually neglected or dealt with general linear controllers. Since friction is non-causal, identification of the friction model is not reliable. In this paper, motion error is eliminated to some extent by applying the linear controllers. Then, identification of the friction model is achieved by constructing the relationship between the velocity and the friction torque. Since there is an evident discontinuity near the zero velocity, the inadequate compensation may easily cause oscillatory system [8-9]. In this paper, we will develop the technique of the frictional identification. Then, a numerical friction model is built. The frictional compensation is applied to eliminate the slip-stick phenomenon. Three linear control algorithms and one nonlinear compensation algorithm will be suitably implemented on the TI TMS320C32 floating-point DSP microprocessor on a Leadwell CNC machine. The experimental results show that the maximum contouring error is reduced 135% in average under different feedrates. Moreover, measurements of maximum contouring error from the double ball-bar (DBB) also show the reduction of 120% by applying the present integrated control and 7 *um* maximum contouring precision is achieved.

II. Design of linear controllers

In order to cope with motion error caused by the servo lag, mismatched dynamics among axes, and external disturbance, this paper adopts three controllers: (1) the feedforward controller, (2) the cross-coupled controller (CCC), and (3) the digital disturbance observer (DDOB) to effectively solve the problems of tracking error, contouring error, and disturbance effects, respectively.

A. Design of the feedforward controller

In order to provide good tracking ability in the position loop of servo systems, a suitable feedforward controller is located in front of the position loop to cancel all the poles and the stable zeros. However, to deal with unstable zeros, the design of ZPETC compensates for the unstable and lightly-damped zeros to achieve the zero-phase error and a unity DC gain in frequency response. The design guarantees no phase error at all frequency and no amplitude error at the DC gain only. ZPETC has been proven to be effective in real applications to reduce the tracking error in real motion applications [3].

B. Design of CCC

In order to eliminate the contouring error, the CCC is designed to coordinate the position error among axes and compensate for each axis according to their geometric components. In the integrated control structure including all feedback, feedforward, and CCC controllers, the control design for different controllers have been proven to be independent [10]. Furthermore, Yeh and Hsu [5] proposed the estimation of the contouring error vector for CCC design which can be applied to mutli-axis systems.

C. Design of DDOB

In real applications, the model-based control design causes the degradation of control performance because of the unavoidable modeling error and external disturbance. Yeh and Hsu proposed the design method of digital disturbance observer (DDOB)[11].

III. Nonlinear friction compensator

Although above three different linear controllers can improve the precision of motion effectively in the tracking, contouring, and the disturbance effects, respectively, they cannot be effectively applied to reduce the nonlinear slip-stick effects due to friction. In this section, a practical method of friction identification and compensation for CNC machine tools will be introduced.

A. Identification of the friction model

In friction compensation, the popular approach is to develop a nonlinear friction model to imitate the relationship between the velocity and friction force/torque as shown in Fig. 1.

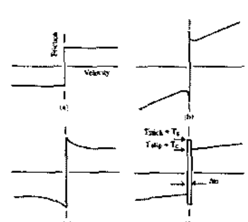

Fig. 1 The specific frictional models [8].

The general motor control block of CNC servo systems is shown in Fig. 2. The torque generated by servo motors is subtracted from friction and external disturbance to drive feed tables in real applications. Thus, the torque command is different from the actual torque that delivered by servo motors. The torque command τ_{cmd} is obtained from the velocity command ω^* through the controller in the velocity loop. The actual torque that delivered by motor is τ_{act}, measured as the current in the feedback loop and $\tau_{act}=\tau_{cmd}-\tau_{friction}-\tau_{disturbance}$. Since CNC machine tools are usually designed as sturdy enough and cutting force is usually negligible compared to the motor output, the servo system is as followed:

$$J\alpha = J\frac{d\omega}{dt} = \tau_{act} = \tau_{cmd} - \tau_{friction} \qquad (10)$$

In this paper, the control mode of servo motors is the torque mode. Let the motion operated in a steady velocity command, the τ_{cmd} then represents the $\tau_{friction}$ as in (10). The approach to identify the nonlinear friction effects here is to generate different steady velocity commands and measure the average current feedback to construct their relationship.

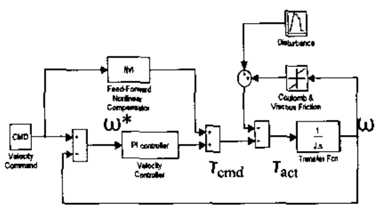

Fig. 2 The velocity loop in motor control

B. Friction compensation

Note that the dominant factor of the friction model is the Coulomb friction in the low speed and the viscous friction in the high speed. The obtained friction model is divided into 5 segments. The least square curve fitting is applied to each segment to obtain their parameters. In the low speed region, a higher-order model is used because of the discontinuity due to the static friction. In the high-speed region, a lower order models are used because the curve is more linear. The structure of compensator is shown in Fig. 2.

IV. THE DESIGN EXAMPLE

A. Linear controllers design

In the identification procedure of servo systems for linear controllers design, the pseudo random binary sequence (PRBS) commands are generated for the velocity and position. Then, the velocity models by applying the AR modeling can be obtained for X and Y axes separately as

$$V_x(z^{-1}) = \frac{0.174324z^{-3} + 0.055299z^{-4} + 0.018861z^{-5} + 0.032584z^{-6}}{\begin{aligned}&1 - 0.33354z^{-1} - 0.26079z^{-2} - 0.19207z^{-3} - 0.065409z^{-4}\\ &+ 0.002068z^{-5} + 0.007182z^{-6} + 0.124797z^{-7}\end{aligned}}$$

$$Vy(z^{-1}) = \frac{0.186132z^{-3} + 0.028259z^{-4}}{\begin{aligned}&1 - 0.391058z^{-1} - 0.363857z^{-2} - 0.115917z^{-3} + 0.033927z^{-4}\\ &+ 0.004945z^{-5} - 0.06318z^{-6} - 0.00116z^{-7} + 0.111347z^{-8}\end{aligned}}$$

Since both axes present similar DC gains, by choosing suitable gains for the position loop as K_{px}=0.035, K_{py}=0.035, their position loops are matched DC-gain and become

$$P_x(z^{-1}) = \frac{0.00477z^{-1}}{1 - 1.70318z^{-1} + 0.17889z^{-2} + 0.490335z^{-3} + 0.3870008z^{-4} - 0.350434z^{-5}}$$

$$P_y(z^{-1}) = \frac{0.0025132z^{-3}}{1 - 1.733067z^{-1} + 0.2450446z^{-2} + 0.528681z^{-3} + 0.2276909z^{-4} - 0.265799z^{-5}}$$

According to (2) and (4), the design results of ZPETC and DDOB are obtained directly as

ZPETC:

$$\begin{aligned}Z_x(z^{-1}) &= 382.78835z^3 - 651.9575z^2 + 68.477303z + 187.69478\\ &\quad + 148.13942z^{-1} - 134.1423z^{-2}\end{aligned}$$

$$\begin{aligned}Z_y(z^{-1}) &= 392.10965z^3 - 679.5523z^2 + 96.08437z + 207.30116\\ &\quad + 89.2798z^{-1} - 104.2226z^{-2}\end{aligned}$$

DDOB:

$$Q_x(z^{-1}) = \frac{LPF(z^{-1})}{1 + 0.317224z^{-1} + 0.108198z^{-2} + 0.1869207z^{-3}}$$

$$Q_y(z^{-1}) = \frac{LPF(z^{-1})}{1 + 0.1518257z^{-1}}$$

By choosing the cut-off frequency of a 3[rd]-order IIR low-pass filter LPF(z^{-1}) as 30Hz, the transfer function is

$$LPF(z^{-1}) = \frac{0.00069934 + 0.002098z^{-1} + 0.002098z^{-2} + 0.00069934z^{-3}}{1 - 2.6235518z^{-1} + 2.314682z^{-2} - 0.6855359z^{-3}}$$

In the CCC design, we choose a proper constant gain as

C=1.3.

B. Design of nonlinear friction compensator

In the design of the nonlinear compensator, applying different velocity commands to each axis from 0*RPM*~±300*RPM* and recording the current as the torque output, and the difference of the encoder output as the velocity command, the friction model can be obtained in five segments. The friction compensation pattern of X-axis is shown below.

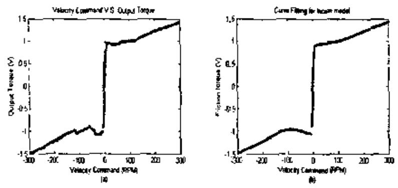

Fig. 3 Velocity v.s. friction torque (a)experiment, (b)modeling

V. Experimental Results and Discussion

A. Linear motion controllers

The experimental setup is applied to a LEADWELL MCV-OP CNC machine with 3-phase Panasonic MDDA103D1A AC servo motors. The experimental setup is a personal computer and an ITRI PMC6000 DSP-based motion control card to implement the integrated motion controller. The embedded high performance TMS320C32 DSP microprocessor is used to implement the present integrated controllers with the 1*ms* sampling time. The hardware structure is shown in Fig. 4.

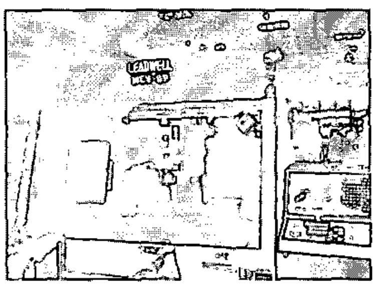

Fig. 4 The experimental hardware setup

With different linear controllers, the circular commands were provided with a radius 50 *mm* under a feedrate 3000 *mm/min* as shown in Fig. 5. The comparison between the maximum and RMS contouring error is shown in Fig. 6. In the matched DC-gain P controller only, the maximum contouring error is about 40 *um*. After adding the ZPETC, the result of tracking error is reduced besides the corner at 0、90、180 and 270 degrees. When the DDOB is added to the system, the effect of the slip-stick phenomenon is decreased and the maximum contouring error is also reduced about 50%. Although nonlinear phenomenon due to friction still cannot be eliminated completely, the system with ZPETC and CCC improves the contouring error significantly, and the maximum contouring error is reduced to 16um, the RMS contouring error is diminished obviously as shown Fig. 7 and Fig. 8. From these figures, we conclude that the system with ZPETC can improve the tracking error significantly, and the maximum tracking error is reduced by 17 times. Also, the contouring error is improved by applying the CCC and DDOB. The integrated linear controller reduces both the tracking and contouring errors. Since the velocity at zero presents a significant discontinuity to cause the slip-stick effect, the non-linear compensation is mainly applied as velocity of the motor within $\pm 5RPM$.

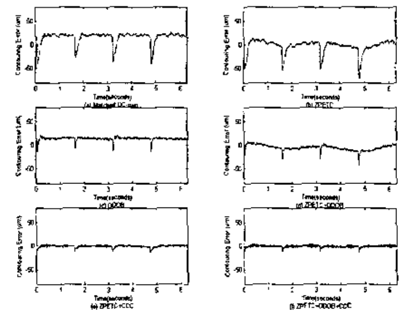

Fig. 5 The contouring error at the command F3000 R50 under different linear controllers

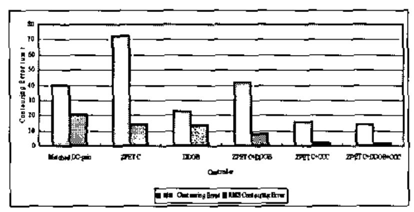

Fig. 6 The contouring error of different linear controllers

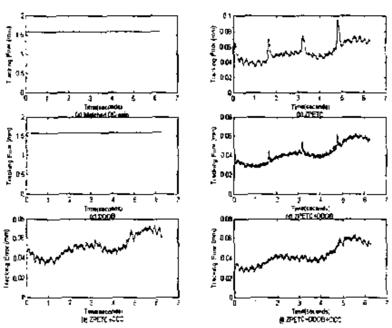

Fig. 7 The tracking error at the command F3000 R50 under different linear controllers

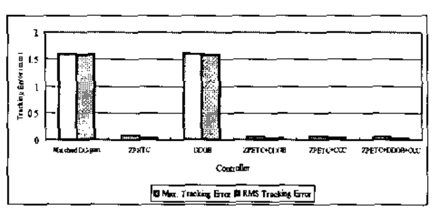

Fig. 8 The tracking error of different linear controllers

B. The Nonlinear compensator

There are four experiments for the circular commands with a radius 50 *mm* under different feedrates 1000、3000、5000 and 8000 *mm/min*, respectively. When the system consists of linear controllers only shown in Fig. 9, the maximum contouring error is dominated by the slip-stick phenomenon at position of 0、90、180 and 270 degrees. After including the nonlinear compensator, the experimental results shown in Fig. 10 indicate that the significant contouring error at the four corners have been all eliminated. Hence, the nonlinear friction compensator possesses the ability to eliminate the friction effects due to friction. The comparison between the maximum and the RMS contouring error are shown in Fig. 11 and Fig. 12, respectively. Results indicate that the system with the nonlinear compensator performs better than those controllers without the nonlinear compensator. We also applied the nonlinear compensator to cutting substitution-wood and aluminum under feedreate 1000 mm/min, the maximum contouring error of experimental result are all maintained below 7 *um*.

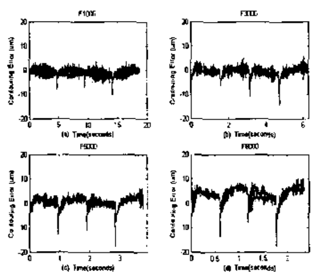

Fig. 9 The contouring error of linear controller without nonlinear compensator under different feedrates

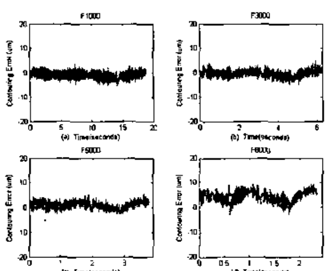

Fig. 10 The contouring error with nonlinear compensation under different feedrates

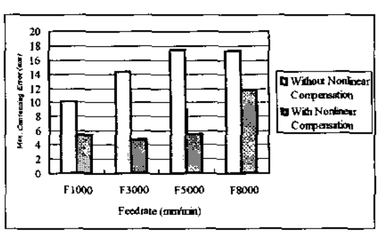

Fig. 11 Summary of Figs. 8-9 in the maximum contouring error

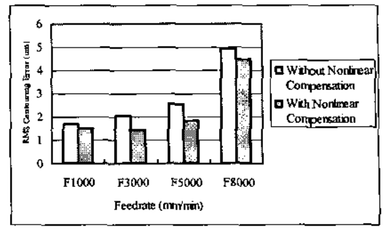

Fig. 12 Summary of Figs. 8-9 in the RMS contouring error

C. DBB measurement

We also compared the proposed integrated controller with the Panasonic industrial PID controllers. The circular commands with radius 150 *mm* under different federates were provided and the position output of the contouring error was measured by DBB as shown in Fig. 13 and the slip-stick phenomenon is significant. The contouring error of the present integrated controller is shown in Fig. 14. Results indicate that the slip-stick phenomenon is successfully removed at each corner. Compare Fig. 15 and Fig. 16, the maximum and RMS contouring errors of the Panasonic PID controllers increase as the federate, but the present integrated controller still maintains the motion precision well and has proven the robustness of the present system.

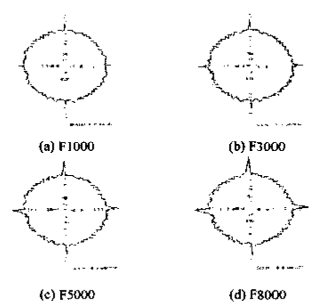

Fig. 13 The contouring error of DBB measurement of Panasonic controller

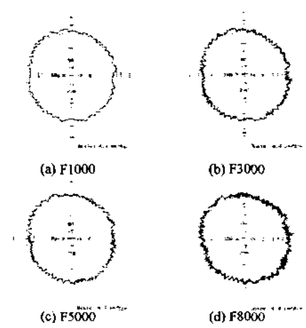

Fig. 14 The contouring error of DBB measurement of the integrated control structure

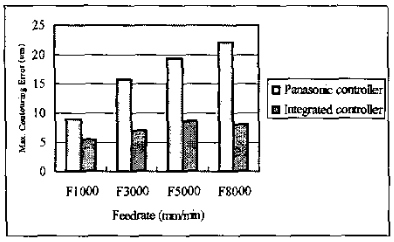

Fig. 15 The comparison of maximum contouring error

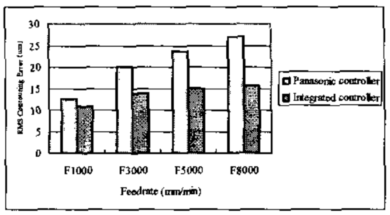

Fig. 16 The comparison of RMS contouring error

VI. CONCLUSION

In this paper, we proposed an integrated motion control structure which consists three linear controllers and one nonlinear friction compensator. The integrated controller has been successfully applied to a real CNC machine tool and experimental results show that the linear controllers can improve the tracking and contouring error significantly. However, the slip-stick phenomenon due to friction still exists. By integrating both the linear controllers and the nonlinear compensator, results indicate that the slip-stick phenomenon is removed and both good tracking and contouring due to the application of linear controllers are maintained well. Compared with industrial PID controller, the proposed integrated motion control structure achieves both motion precision and the robustness. All experimental results are concluded as in Table I to indicate the merits of different control algorithms.

TABLE I
Summary of experimental results

	Tracking	Contouring	Slip-Stick
ZPETC	••		
CCC		••	
DDOB		•	•
Nonlinear Compensation			••

- • Improvement
- •• Significant Improvment

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