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# Adaptive two-degree-of-freedom control of feed drive systems

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**Abstract**

Feed drive systems are widely used in industrial applications, and many efforts for improving their precision control have been made thus far. One of the basic approaches for improving the control accuracy of feed drive systems is to design a controller based on the internal model principle, which states that for a control system to track a reference signal without a steady state error, it needs to include a generator of the reference signal. Feed-forward controllers, such as the zero phase error tracking controller (ZPETC) proposed by Tomizuka, are also employed for improving control performance. However, prior knowledge of plant dynamics and/or reference signal properties is required for both the internal model principle and the feed-forward controller based designs. For precision control, plant dynamics should be identified in real time because feed drive dynamics are affected by varying conditions, such as frictional and thermal effects. This paper presents a new type of adaptive control for arbitrary reference tracking, which requires neither plant dynamics nor reference signal properties for controller design. This type of controller can also reduce the effect of unknown disturbances. The control system is designed using a discrete-time plant model and consists of adaptive feed-forward and feedback controllers. This design is then applied to a feed drive system with a ball screw drive. The effectiveness of the proposed design is demonstrated by simulation and experimental results, which was obtained by applying the proposed control system to an unknown reference signal whose property is varied during control.


*Keywords:* Feed drive system; Motion control; Discrete-time system; Adaptive control

## 1. Introduction

For improving the tracking accuracy of the feed drive systems of machine tools, two fundamental approaches are known to be effective. First is a controller design based on the internal model principle, which states that for a control system to track a reference signal without a steady state error, it needs to include a generator of the reference signal. For designing the control system with this reference signal generator, the reference signal properties must be known in advance. The other approach involves using a feed-forward controller that is widely applied in the control of machine tool feed drives; however, plant dynamics must be known prior to its design.

The zero phase error tracking controller (ZPETC) proposed by Tomizuka [1] is one of the most effective feed-forward controller designs and has been extensively studied in many researches. ZPETC is also used in the design of contouring controllers, which aim to reduce deviations in cutter location from the desired contour paths of CNC machine tools. For example, Chen et al. [2] proposed a hybrid control structure, which combined the feed-forward and cross-coupling controllers with the ZPETC. Erkorkmaz and Altintas [3] presented a controller with a disturbance estimator, friction compensator and a ZPETC, and demonstrated its effectiveness by verifying contouring accuracy. However, since the ZPETC design is based on the cancellation of all the poles and well-damped zeros of feedback loop systems, plant dynamics must be known in advance. In addition, the design is sensitive to plant modelling errors and only achieves a DC gain response of unity. For achieving good tracking performance of high frequency reference signals, the control system gain should be unity not only at zero frequency but also at higher frequency ranges.

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For applying a ZPETC to plants with unknown dynamics, some adaptive versions have been presented. Tsao and Tomizuka [4] proposed an adaptive ZPETC design, which requires a controller that can stabilise the feedback control system for cancelling the feedback loop poles. This controller can also only achieve a DC gain frequency response of unity. Yeh and Hsu [5] proposed an optimal and adaptive ZPETC design, which requires feedback loop stability during adaptive processing.

Non-adaptive extensions of the ZPETC design have also been widely studied. Torfs et al. [6] proposed a design with a feed-forward controller added to a ZPETC, which improved the frequency response over a wider range. Guo and Tomizuka [7] developed an optimal hybrid controller with $\delta$ operators, which can handle undesirable right half-plane zeros. However, plant dynamics must be known in advance for both of these designs.

In this paper, a new approach to improve the control accuracy of feed drive systems with both feed-forward and feedback adaptive controllers is presented. Because plant dynamics are often varied by changing the objects on the feed drive table and are also affected by disturbances, feedback controller parameters should be adjusted in real time. The proposed feed-forward controller is also adjusted to improve the tracking accuracy of reference signals without cancelling the feedback loop poles and zeros. Fourth-order dynamics with consideration of the compliance of lead screw drives are employed in the design of feed drive system controllers.

In Section 2, the fourth-order dynamics of feed drive systems are explained and converted to a discrete-time model that is useful for the proposed controller design. In Section 3, the controller design problem dealt with in this paper is formulated. In Section 4, we present the new control system design having adaptive feed-forward and feedback controllers, which requires neither the plant dynamics nor the reference signal properties to be known. The proposed controller can also reduce the effect of unknown disturbances. In Section 5, simulation and experimental verifications of the effectiveness of the proposed design are described. Concluding remarks are given in Section 6. The stability of the proposed control system is analysed in the Appendix.

## 2. Dynamics of feed drive systems

Although many methods for modelling feed drive dynamics are available, second- and fourth-order dynamics are commonly used for controller design in many researches [8,9]. In this research, the fourth-order model, which considers the compliance of the lead screw drive, is employed for controller design to achieve better control performance.

Fig. 1 shows a schematic fourth-order model of the feed drive dynamics, and its mathematical representation is given as follows:

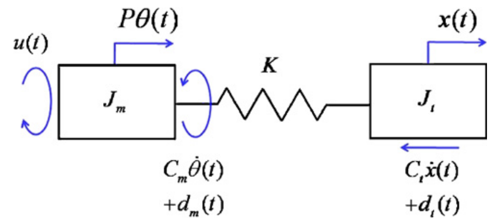


Fig. 1. Schematic model of feed drive dynamics.

$$J_t\ddot{x} + C_t\dot{x} + K(x - P\theta) + d_t = 0, \tag{1}$$

$$J_m\ddot{\theta} + C_m\dot{\theta} + KP(P\theta - x) + d_m = u, \tag{2}$$

where $J_t$ and $C_t$ are the table mass and viscous friction coefficient acting on the table, respectively. $K$ and $P$ are lead screw stiffness (in its axial direction) and pitch divided by $2\pi$, respectively. $J_m$ and $C_m$ are motor and lead screw inertia, and viscous friction coefficient acting on the motor, respectively. $d_t$ and $d_m$ are disturbances including non-linear frictions, acting on the table and the motor, respectively. $u$ denotes a control input torque.

Since the electric time constant is generally much smaller than the mechanical time constant, electric motor dynamics are neglected in this paper. In fact, the electric time constant of the motor utilised in the experiment is much smaller than the sampling period as shown in Section 5.

The relationship between input torque $u$ and position $x$ in the complex frequency domain is

$$(h_1 s + h_2 s^2 + h_3 s^3 + h_4 s^4)X(s) = U(s) + W(s), \tag{3}$$

$$W(s) = -D_m(s) - \frac{(J_m s^2 + C_m s + KP^2)}{KP}D_t(s), \tag{4}$$

where $X(s)$, $U(s)$, $D_m(s)$ and $D_t(s)$ are the Laplace transformations of $x$, $u$ and the disturbance terms, respectively, and $s$ is the variable of the Laplace transformation. The coefficients of the left-hand side of Eq. (3) are $h_1 = (C_mK + C_tKP^2)/(KP)$, $h_2 = (J_mK + J_tKP^2 + C_tC_m)/(KP)$, $h_3 = (J_mC_t + J_tC_m)/(KP)$ and $h_4 = (J_mJ_t)/(KP)$. The discrete-time representation of Eq. (3) with zero-order hold and sampler is

$$\begin{aligned} &A(z^{-1})x(k) = z^{-1}B(z^{-1})u(k) + w(k),\\ &A(z^{-1}) = 1 + a_1z^{-1} + a_2z^{-2} + a_3z^{-3} + a_4z^{-4},\\ &B(z^{-1}) = b_0 + b_1z^{-1} + b_2z^{-2} + b_3z^{-3}, \end{aligned} \tag{5}$$

where $z^{-1}$ is the one-step delay operator, $a_i$'s and $b_i$'s ($b_0 \neq 0$) are coefficients of the pulse-transfer function, and $x(k), u(k)$ and $w(k)$ are the values of $x$, $u$ and the disturbance terms at sampling instant $k$, respectively.

Note that the pulse-transfer function Eq. (5) has three plant zeros, whereas there are no zeros in Eq. (3). It is known that the three zeros in Eq. (5) converge to the zeros of the following polynomial when sampling period $T$