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Coupling Model and Controller Design for Four-layer Register System

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Abstract. A nonlinear and coupling model is established according to the multi-layer register system working principle in gravure printed electronic equipments, and then, the linear model of the register system is constructed based on one order Taylor formula. In order to improve the speed and accuracy of register control, a feedforward PID control algorithm is presented according to the linear model in multi-layer register system. This algorithm is unique in that it uses the PID to adjust the inputs of the register system, and feedforward compensation for the known disturbance, making the register control accuracy has been greatly improved. The simulation shows that the proposed register controller is able to realize a high precision control for the register system and endowed with better control performance than PID controller in register control.

1 Introduction

Just as the register process in traditional color printing, all parts of printed electronics can be precipitated by ink formation layer and layer correspondent to electronic materials through the method of gravure printing, and the quality of printed electronics is controlled by each layer of register accuracy. Register error, reflecting the direct index of register accuracy, comprises print-direction register and cross-direction register errors which dominated by the factors of each roller speed, web tension, web property, manufacturing and fixing errors. What's more, the cross-direction register is the key point of register system. Therefore, the thesis will discuss about it in terms of the cross-direction register, without the condition of explanation.

Kang designed his model based on the register error definition and feedforward PID controller with speed volatility of contiguous roller as the foregone interference[1,2]. But he ignore the influence of traction tension in register error. Although Li deduced detailed register model and devised feedforward controller in terms of disturbance of tension and speed, only with two layers of register system[3]. Yoshida established register error model based on web mass conservation and nonlinear control strategy, using Lyapunov's theory of stability[4]. Liu establish the relation among register error, roller speed and web tension, and design controller with method of active disturbance rejection control[5,6]. Chen put forward multi-layer register system controller strategy with the cooperation of expansion state observer and feedforward controller[7].

This thesis set up nonlinear coupling model for four-layer register system based on the working principle of cross-direction register errors and deduces the linear model of register system. On the basis of linear model, feedforward PID register controller is designed in terms of the disturbance of tension and speed. The simulation shows that the proposed register controller is endowed with better control performance than PID controller in register control.

2 Four-layer register system model and linearization

As shows in Figure 1, the register system of four-layer gravure press comprise printing unit, drying mechanism and detection section. The printing roller is compelled by servo motor and works under the model of speed. Where L^* is the nominal length in color cell, V_i is the linear speed of the roller, T_i is the tension of roller, and e_{ij} is register error between adjacent units i and j.

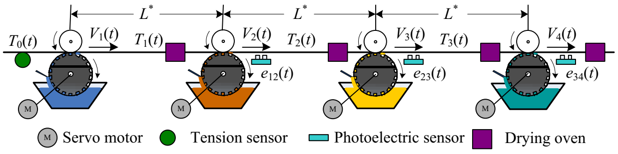

Figure 1. Structure of four-layer register system

Refer the model of double layer register system established in reference [5], the four-layer nonlinear coupling model for register system, using the relation of tension and strain, is established as Eq. 1. Where A is

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cross-sectional area of web, E is elastic modulus, t_T is delay time of the web transmission, $V_2(t)$~$V_4(t)$ are system inputs, and $e_{12}(t)$~$e_{34}(t)$ are system outputs.

$$\left.\begin{aligned}
&AE\frac{de_{12}(t)}{dt}=T_0(t-t_T)V_1(t-t_T)-T_1(t)V_1(t)+\\
&\qquad AE\big(V_2(t)-V_1(t-t_T)\big)\\
&AE\frac{de_{23}(t)}{dt}=T_1(t-t_T)V_2(t-t_T)-T_2(t)V_2(t)+\\
&\qquad AE\big(V_3(t)-V_2(t-t_T)\big)\\
&AE\frac{de_{34}(t)}{dt}=T_2(t-t_T)V_3(t-t_T)-T_3(t)V_3(t)+\\
&\qquad AE\big(V_4(t)-V_3(t-t_T)\big)\\
&L^*\frac{dT_1(t)}{dt}=T_0(t)V_1(t)-T_1(t)V_2(t)+AE\big(V_2(t)-V_1(t)\big)\\
&L^*\frac{dT_2(t)}{dt}=T_1(t)V_2(t)-T_2(t)V_3(t)+AE\big(V_3(t)-V_2(t)\big)\\
&L^*\frac{dT_3(t)}{dt}=T_2(t)V_3(t)-T_3(t)V_4(t)+AE\big(V_4(t)-V_3(t)\big)
\end{aligned}\right\}\qquad(1)$$

The four-layer nonlinear coupling model for register system is linearized with one order Taylor formula and change it with Laplace transform as Eq. 2.

$$\left.\begin{aligned}
&E_{12}(s)=G_A(s)V_2(s)+G_{D1}(s)V_1(s)+G_{E1}(s)T_0(s)\\
&E_{23}(s)=G_A(s)V_3(s)+G_B(s)V_2(s)+\\
&\qquad G_{D2}(s)V_1(s)+G_{E2}(s)T_0(s)\\
&E_{34}(s)=G_A(s)V_4(s)+G_B(s)V_3(s)+\\
&\qquad G_C(s)V_2(s)+G_{D3}(s)V_1(s)+G_{E3}(s)T_0(s)
\end{aligned}\right\}\qquad(2)$$

System input shows as Eq. 3 in terms of the expression transfer function $G_A(s)$、$G_B(s)$、$G_C(s)$.

$$\left.\begin{aligned}
&G_A(s)=\frac{V^*}{L^*s+V^*}\\
&G_B(s)=\frac{L^*}{L^*s+V^*}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)-\frac{T^*}{AEs}\\
&G_C(s)=\frac{L^*V^*}{(L^*s+V^*)^2}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)
\end{aligned}\right\}\qquad(3)$$

The transfer functions of the disturbance $V_1(t)$ to each error $G_{Di}(s)$ are shown in Eq. 4, and the transfer functions of the disturbance $T_0(t)$ to each error $G_{Ei}(s)$ are shown in Eq. 5.

$$\left.\begin{aligned}
&G_{D1}(s)=\frac{1}{s}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}-\frac{T^*}{AE}\right)\\
&G_{D2}(s)=\frac{V^*}{s(L^*s+V^*)}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\
&G_{D3}(s)=\frac{(V^*)^2}{s(L^*s+V^*)^2}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)
\end{aligned}\right\}\qquad(4)$$

$$\left.\begin{aligned}
&G_{E1}(s)=-\frac{V^*}{AEs}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\
&G_{E2}(s)=-\frac{(V^*)^2}{AEs(L^*s+V^*)}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\
&G_{E3}(s)=-\frac{(V^*)^3}{AEs(L^*s+V^*)^2}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)
\end{aligned}\right\}\qquad(5)$$

From the Eq. 2, it could read that the influence of register error e_{12}、e_{23}、e_{34} are the traction tension T_0 and the speed of first roller V_1, besides the corresponding roller speed V_2、V_3、and V_4.

3 The design of feedforward PID controller

The control of register error is attained by adjusting the speed of after-layer roller in the design of feedforward PID controller. That is to say, adjusting V_2、V_3、V_4 to change e_{12}、e_{23}、e_{34} respectively. So the transfer function $G_A(s)$ stands for the property of register error system with other factors as system disturbance. Therefore, PID is designed in terms of transfer function $G_A(s)$, and feedforward controller compensate other systematical influencing elements. Because T_0、V_1、V_2、V_3 can be measured, feedforward controller can be designed by using T_0、V_1、V_2、V_3 based on the invariance principle. What's more, feedforward controller can eliminate the effect of T_0、V_1、V_2、V_3 in register error. The structure of feedforward controller reveals as the Figure 2.

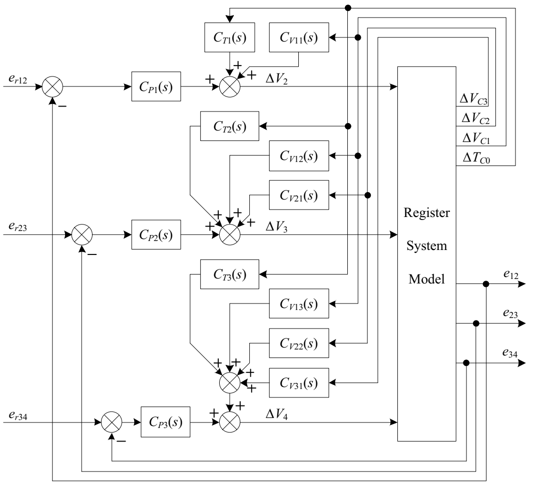


Figure 2. Block diagram of feedforward PID controller for four-layer register system

In Figure 2, Er_{12}、Er_{23}、Er_{34} are the reference inputs of register error, ΔV_{C1}、ΔV_{C2}、ΔV_{C3} are the variations of actual speed, and ΔT_{C0} is the tension of the actual traction unit. T_0 and V_1 are the disturbances for E_{12} and they have two feedforward controllers, $C_{T1}(s)$ and $C_{V11}(s)$ respectively. In a similar way, E_{23} has three feedforward controllers, $C_{T2}(s)$、$C_{V12}(s)$ and $C_{V21}(s)$ respectively. E_{34} Has four feedforward controllers, $C_{T3}(s)$、$C_{V13}(s)$、$C_{V22}(s)$ and $C_{V31}(s)$. The PID controller of each control loop are $C_{P1}(s)$、$C_{P2}(s)$ and $C_{P3}(s)$. According to the Figure 2 and the Eq. 2, the expression of $E_{12}(s)$ can be achieved as Eq. 6.

$$\begin{aligned}E_{12}(s)=&\frac{G_A(s)C_{p1}(s)}{1+G_A(s)C_{p1}(s)}E_{r12}(s)+\\&\frac{G_{D1}(s)+C_{V11}(s)G_A(s)}{1+G_A(s)C_{p1}(s)}V_{C1}(s)+\\&\frac{G_{E1}(s)+C_{T1}(s)G_A(s)}{1+G_A(s)C_{p1}(s)}T_{C0}(s)\end{aligned}\tag{6}$$

Based on the invariance principle, feedforward controller is devised in terms of T_0 and V_1 in E_{12}.

$$\left.\begin{aligned}G_{E1}(s)+C_{T1}(s)G_A(s)=0\\G_{D1}(s)+C_{V11}(s)G_A(s)=0\end{aligned}\right\}\tag{7}$$

According to Eq. 7, the feedforward controller $C_{T1}(s)$ and $C_{V11}(s)$ can be designed as Eq. 8.

$$\left.\begin{aligned}&C_{T1}(s)=-\frac{G_{E1}(s)}{G_A(s)}=\frac{V^*}{AEL^*s}\left(V^*-L^*s+V^*e^{-t_Ts}\right)\\&C_{V11}(s)=-\frac{G_{D1}(s)}{G_A(s)}\\&\quad=\frac{1}{L^*s}\left(\frac{T^*(L^*s+V^*)}{AE}+(L^*s+V^*)e^{-t_Ts}-V^*\right)\end{aligned}\right\}\tag{8}$$

Similarly, the feedforward controller $C_{T2}(s)$、$C_{V12}(s)$ and $C_{V21}(s)$ can be designed as Eq. 9, and $C_{T3}(s)$、$C_{V13}(s)$、$C_{V22}(s)$ and $C_{V31}(s)$ can be designed as Eq. 10.

$$\left.\begin{aligned}&C_{T2}(s)=-\frac{G_{E2}(s)}{G_A(s)}\\&\quad=\frac{(V^*)^2}{AEL^*s}\times\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\&C_{V12}(s)=-\frac{G_{D2}(s)}{G_A(s)}\\&\quad=-\frac{V^*}{L^*s}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\&C_{V21}(s)=-\frac{G_B(s)}{G_A(s)}\\&\quad=e^{-t_Ts}-\frac{V^*}{L^*s+V^*}+\frac{T^*(L^*s+V^*)}{AEL^*s}\end{aligned}\right\}\tag{9}$$

$$\left.\begin{aligned}&C_{T3}(s)=-\frac{G_{E3}(s)}{G_A(s)}\\&=\frac{(V^*)^3}{AEL^*s(L^*s+V^*)}\times\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\&C_{V13}(s)=-\frac{G_{D3}(s)}{G_A(s)}\\&\quad=-\frac{(V^*)^2}{L^*s\left(L^*s+V^*\right)}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\&C_{V22}(s)=-\frac{G_C(s)}{G_A(s)}\\&\quad=-\frac{V^*}{L^*s+V^*}\left(\frac{V^*}{L^*s+V^*}-e^{-t_Ts}\right)\\&C_{V31}(s)=-\frac{G_B(s)}{G_A(s)}\\&\quad=e^{-t_Ts}-\frac{V^*}{L^*s+V^*}+\frac{T^*(L^*s+V^*)}{AEL^*s}\end{aligned}\right\}\tag{10}$$

With this, Eq. 8, Eq. 9 and Eq. 10 constitute the feedforward controller of four-layer register system. Meanwhile, they and PID controller constitute the whole register controller, namely, feedforward PID controller.

4 The simulation

In order to verify the performance of the proposed feedforward PID register controller, simulation of register error with PID controller and feedforward PID controller are performed respectively.

4.1 Performance comparison under tension disturbance

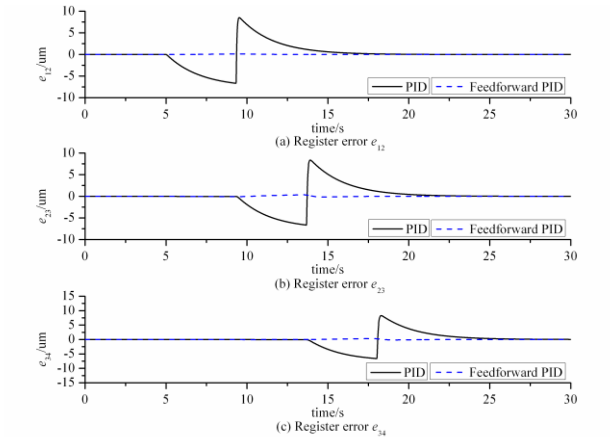
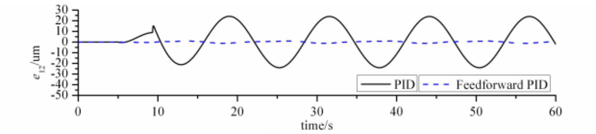


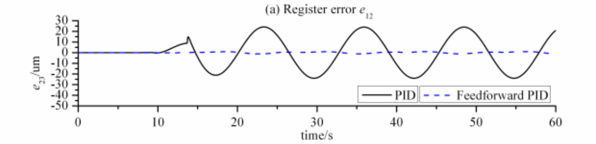
Figure 3. Simulation curve of register error with tension disturbance

The performance of PID controller and feedforward PID controller in simulation are shown in Figure 3 when the upstream tension T_0 has a step change from 100N to 120N after 5s stable operation of the system. Compared with the register error in PID control, the peak of register error controlled by feedforward PID controller is considerably decreased and there is no obvious time delay. It indicates that feedforward control can generate a control value in advance to compensate the register error caused by tension disturbance, which makes the performance of feedforward PID controller much better than that of traditional PID controller.

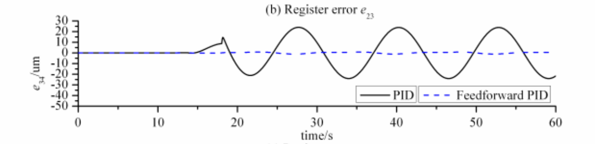
4.2 Performance comparison under speed disturbance



(a) Register error e_{12}



(b) Register error e_{23}



(c) Register error e_{34}

Figure 4. Simulation curve of register error with speed disturbance

In order to reflect the performance of different controllers in speed disturbance, simulation are performed with a man-made sinusoidal disturbance whose amplitude is 0.1r/min and frequency is 0.5rad/s after 5s stable operation of the system. As shown in Figure 4, the register error with the traditional PID control has a sinusoidal variation and the maximal register error is obviously larger than that with the proposed feedforward PID control. The results indicated that the proposed feedback controller can effectively reduce register error caused by the speed fluctuation.

5 Conclusion

The register error model and the control strategy of the sectional drive gravure printed electronic equipments are successfully studied in this paper. Based on the double layer register system model, a coupling mathematical model for the four-layer register error is derived, and linear model of register system is attained with one order Taylor formula. According to the established model, a feedforward PID controller is designed to alleviate the disturbance caused by the upstream tension and speed. In numerical simulation, the proposed feedforward PID controller was compared with traditional PID controller. The results showed that with the disturbances caused by the tension and speed, the performance of the proposed feedforward PID controller is much better than that of the traditional PID controller. The proposed feedforward controller can effectively alleviate the register errors caused by the disturbances from tension and speed.

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