Modeling and Control for a Coating Machine*

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Velocity and tension controls are important factors for the film in the coating machine. In this paper, an experimental coating machine is established to make control analyses. The mathematical model of the coating machine is firstly derived. Then, the sliding mode control (SMC) is used to control the tension and the velocity of the film. Finally, some experimental results are proposed to show the performance of the SMC scheme in the experimental coating machine.

Key Words: Coating Machine, Tension Control, Sliding Mode Control

1. Introduction

A so-called web means the material that its length is quite larger than its width and its width is quite larger than its thickness, such as paper, film, and metal foil. Because of the length reason, the material transmission is necessary in the manufacturing or in the finishing processes of these materials. In the manufacturing or the finishing processes, the tension and the velocity of these materials will affect directly the production quality. Reynolds⁽¹⁾ discussed the behavior of the web on the roller. It is proved that the transmitting velocity of the web is decreased by the web elongate deformation. Campbell⁽²⁾, King⁽³⁾, and Brandenburg⁽⁴⁾ established the mathematical model for this kind of system under different considerations. Campbell only considered the web tension between two rollers but neglected the web tension of entering the roller. In the work of King, the web tension of entering the roller is added to consider. Brandenburg more considered the factor of the cross-sectional area variation resulted from deformation. Young and Reid⁽⁵⁾ presented the analysis for both the longitudinal and the lateral dynamical behaviors of the web. In the early time, the draw control⁽⁶⁾ and the set-point-coordination control were used frequently in the manufac-

turing. The draw control is to control the velocities of two terminal rollers directly. The web tension is responded from the difference between two roller velocities. Such as this control method, the web tension is not fed back. Hence, the tension is quite sensitive to the difference between two roller velocities. For the set-point-coordination control, once the first roller starts, the next roller also receives the same signal to act at the same time. This control method has higher efficiency in the starting or in the stopping. Because the behind tension will be forced to change as the front tension changes, this control method is not appropriate for the multi-zones system with different tension in every zone. In the present, the roller velocity has been adjusted through the tension feedback in every zone. Young and Reid⁽⁵⁾ and Sakamoto⁽⁷⁾ used PID and PI control to control the web tension, respectively.

In this work, an experimental coating machine is established to provide the control research. Firstly, the mathematical model of the coating machine will be derived. In view of the modeling error between the system mathematical model and the real system or disturbances which usually occur in the practical control, the sliding mode control strategy is used to control the tension and velocity of film. Finally, some experimental results are proposed to show the performance of the sliding mode control scheme in the coating machine.

2. Modeling of Coating Machine

In the tape manufacturing⁽⁸⁾, the configuration of coating machine is shown in Fig.1. A coating machine must include an unwinding section, a coating

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Fig. 1 The configuration of coating machine

Fig. 2 Layout of experimental coating machine

Fig. 3 The relation between Rollers and film in a zone

section, a drying section, and a rewinding section.

In this work, an experimental coating machine is established for conducting research into the tension and velocity controls of film. The simplified layout of experimental coating machine is shown in Fig. 2.

Before the mathematical model of the experimental coating machine is derived, some assumptions are made for simplifying derivation as follows:

- (1) The tension variation is neglected where the roller contacts the film but is considered between two rollers;
- (2) The film thickness is quite small corresponding to the roller radius;
- (3) No slipping phenomena exists between film and the nip rollers;
- (4) In the whole process, the density, the modulus of elasticity, and the cross-sectional area of film are constant;
- (5) The strain of film is small.

Referring to the work⁽⁵⁾, the relation between the transmitting velocity and the tension of film will be given. Consider the C zone surrounded by the dotted line in Fig. 3, the transmitting velocity and the tension of film have the following relation according to the mass conservative law.

Fig. 4 A truncated piece of film

$$\frac{d}{dt} \left[\int_{x_1}^{x_2} t_{\rho C}(x, t) A_C(x, t) dx \right] = t_{\rho B}(t) A_B(t) v_1(t) - t_{\rho C}(t) A_C(t) v_2(t) \quad (1)$$

where v is the roller line velocity, t_{ρ} and A represent the density and cross-sectional area of film, respectively. From Fig. 4, we have the following results after the film is elongated.

$$\begin{aligned} dx &= (1 + \varepsilon_x) dx_u \\ t_w &= (1 + \varepsilon_y) t_{wu} \\ t_h &= (1 + \varepsilon_z) t_{hu} \end{aligned} \quad (2)$$

where t_h and t_w represent the thickness and the width of film, respectively, ε_n represents the strain of film in the n direction, and subscript u represents the film situation before the film is elongated. According to Assumption (5), it yields

$$dx_u = (1 - \varepsilon_x) dx \quad (3)$$

Substituting Eq. (3) into Eq. (1) and according to Assumption (4), it is obtained that

$$\frac{d}{dt} [(1 - \varepsilon_C) L_C] = (1 - \varepsilon_B) v_1 - (1 - \varepsilon_C) v_2 \quad (4)$$

where, shown in Fig. 3, L_C is the film length between two nip rollers, ε_B is the film strain between two nip rollers and ε_C is the film strain between the unwinder and the first nip rollers in the film transmitting direction. Therefore, the film velocity and the film strain have the following relation.

$$\begin{aligned} L_C \frac{d}{dt} \varepsilon_C(t) &= v_2(t) - v_1(t) - v_2(t) \varepsilon_C(t) + v_1(t) \varepsilon_B(t) \end{aligned} \quad (5)$$

From Assumption (4), it follows that from Hook's law

$$T_B = AE \varepsilon_B, \quad T_C = AE \varepsilon_C \quad (6)$$

where T and E represent the film tension and the elastic modulus of film, respectively. Then, Eq. (5) can be represented as

$$\begin{aligned} \frac{d}{dt} [T_C(t)] &= \frac{AE}{L_C} [v_2(t) - v_1(t)] \\ &\quad - \frac{1}{L_C} [v_2(t) T_C(t) - v_1(t) T_B(t)] \end{aligned} \quad (7)$$

As shown in Fig. 5, under that the transmitting efficiency of the belt is 100 percentage, it can be obtained that from energy conservative law

$$\begin{aligned} \Gamma_a(t) \omega_a(t) &= \Gamma_b(t) \omega_b(t) \\ \Gamma_b(t) &= \Gamma_a(t) \frac{R_b}{R_a} \end{aligned} \quad (8)$$

Fig. 5 Nip rollers, film, and motor

where ω represents the angular velocity of roller, Γ and R represent the torque and the radius of roller, respectively. The motor is a torque-typed motor in our work. Therefore, the motor torque is proportional to the input current $i(t)$.

$$\Gamma_a(t) = k_l \cdot i(t) \quad (9)$$

where k_l is motor torque constant and $i(t)$ is motor armature current. For simplify modeling, the motor input voltage $u(t)$ is proportional to the motor armature current $i(t)$ in our work, i.e. $u(t) = k \cdot i(t)$ with a positive constant k . Therefore, it yields that

$$\Gamma_b(t) = k_l \cdot k \frac{R_b}{R_a} u(t) \quad (10)$$

The representation of relationship between film tension and roller torque can be expressed by

$$\Gamma_b(t) + (T_b(t) - T_a(t))R_b = \dot{h}(t) + b\omega_b(t) \quad (11)$$

$$h(t) = J\omega_b(t)$$

where J is total inertia of motor, belt, and roller, and b is the rotation friction coefficient. Setting $k_{la} = k_l \cdot k \frac{R_b}{R_a}$ and arranging Eq. (8), it can be obtained that

$$\frac{d}{dt} \nu(t) = \frac{R_b}{J} (k_{la}(t)u(t)) + \frac{R_b^2}{J} (T_b(t) - T_a(t)) - \frac{b}{J} \nu(t) \quad (12)$$

In the experimental coating machine shown in Fig. 2, the film tension and the film velocity are controlled by three motors. The roller driven by motor z is a rewinding roller. Hence, the radius $R_z(t)$ and the inertia of this roller $J_z(R_z(t))$ will vary with time and are represented by the following equations, respectively.

$$\frac{d}{dt} R_z(t) = \frac{t_h}{2\pi} \omega(t) = \frac{t_h}{2\pi} \frac{\nu(t)}{R_z(t)} \quad (13)$$

$$J_z(R_z(t)) = J_m + \frac{t_{\rho} t_w \pi}{2} (R_z^4(t) - R_{z0}^4) \quad (14)$$

where J_m and R_0 is the inertia and the radius of internal metal roller, respectively. Referring to Eq. (7), it yields that

$$\frac{d}{dt} T_1(t) = -\frac{1}{L_1} \nu_y(t) T_1(t) + \frac{AE}{L_1} (\nu_y(t) - \nu_x(t)) \quad (15)$$

$$\frac{d}{dt} T_2(t) = \frac{1}{L_2} (\nu_y(t) T_1(t) - \nu_z(t) T_2(t)) + \frac{AE}{L_2} (\nu_z(t) - \nu_y(t)) \quad (16)$$

where L_1 and L_2 represent the film lengths between two nip rollers and between the second nip rollers and the rewinder, respectively. Referring to Eq. (12), it is given that

$$\frac{d}{dt} \nu_x(t) = \frac{R_x^2}{J_x} T_1(t) + \frac{k_{lx} R_x}{J_x} u_x(t) - \frac{b_x}{J_x} \nu_x(t) \quad (17)$$

$$\frac{d}{dt} \nu_y(t) = \frac{R_y^2}{J_y} T_2(t) - \frac{R_y^2}{J_y} T_1(t) + \frac{k_{ly} R_y}{J_y} u_y(t) - \frac{b_y}{J_y} \nu_y(t) \quad (18)$$

$$\frac{d}{dt} \nu_z(t) = \left[\frac{1}{J_m + \frac{t_{\rho} t_w \pi}{2} (R_z^4(t) - R_{z0}^4)} \right] \times (-T_2(t) R_z^2(t) + k_{lz} R_z u_z(t) - b_z \nu_z(t)) \quad (19)$$

Therefore, the system dynamics of the coating machine are described by state equations, which are represented in Eqs. (13), (15)–(19).

3. Control for Prototype Coating Machine

From Eqs. (13), (15)–(19) in the previous section, it is known that the mathematical model of the experimental coating machine has nonlinear terms. Hence, the system of coating machine is a nonlinear system. The mathematical model established in our work is only an approximate model for the experimental coating machine. Hence, it will exist some more or less modeling errors. In the experiment, there are not only modeling errors but also disturbances to affect the control performance. For the above causes, an appropriate control law, which is suitable for a nonlinear system and possesses robust property to modeling errors and disturbances, should be used in our experiment. In robust control design, sliding mode control is popularly adopted because the sliding mode control system possesses several attractive benefits in the sliding mode, such as good transient, fast response, and insensitivity to the variations of plant parameters and external disturbances^{(9)–(11)}. Therefore, the sliding mode control law will be applied in our experiment.

3.1 Sliding mode control

In the work, the control objective is to derive sliding mode control laws of u_x , u_y , and u_z , such that transmitting velocity ν_x , film tensions T_1 , T_2 can track specific values. From Eqs. (14)–(19), a dynamic equation can further be represented in the following form.

$$\begin{aligned}
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} &= \begin{bmatrix} \dot{\nu}_x \\ \dot{T}_1 \\ \dot{T}_2 \\ \dot{T}_2 \\ \dot{T}_2 \end{bmatrix} = \begin{bmatrix} -a_3x_1 + a_1x_2 \\ -g_2x_1 - g_1\nu_yx_2 \\ (g_1g_2\nu_y + g_2a_3)x_1 + (-g_2b_1 + g_1b_3\nu_y + g_1^2\nu_y^2 - g_2a_1)x_2 + g_2b_1x_4 - g_1b_1x_2x_4 + g_1b_1x_2^2 \\ h_1\nu_yx_2 - h_1\nu_zx_4 \\ -h_1g_2\nu_yx_1 + (-h_1b_3\nu_y + h_2b_1 - h_1g_1\nu_y^2 - h_1^2\nu_y\nu_z + h_1b_2u_y)x_2 - h_1b_1x_2^2 + h_1\frac{1}{J_z}R_z^2x_4^2 + h_1b_1x_2x_4 \\ + \left(-h_2b_1 + h_1\frac{1}{J_z}c_2\nu_z - h_2\frac{1}{J_z}R_z^2 + h_1^2\nu_z^2\right)x_4 \end{bmatrix} \\
&+ \begin{bmatrix} a_2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & g_2b_2 - g_1b_2x_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -h_1\frac{1}{J_z}c_1R_zx_4 + h_2\frac{1}{J_z}c_1R_z \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \\
&+ \begin{bmatrix} 0 \\ g_2\nu_y \\ -g_2a_2u_x - g_2b_3\nu_y - g_1g_2\nu_y^2 \\ -h_2\nu_y + h_2\nu_z \\ -h_2b_2u_y + h_1g_2\nu_y^2 - h_2\frac{1}{J_z}c_2\nu_z - h_1h_2\nu_z^2 + h_1h_2\nu_y\nu_z + h_2b_3\nu_y \end{bmatrix} \\
&= F(X, t) + G(X, t)U + M(t)
\end{aligned}$$

where x_1, x_2 , and x_4 are system outputs u_x, u_y , and u_z are control inputs, $X^T = [x_1 \ x_2 \ x_3 \ x_4 \ x_5]$, $U^T = [u_x \ u_y \ u_z]$, $a_1 = \frac{R_x}{J_x}$, $a_2 = \frac{k_{ix}R_z}{J_x}$, $a_3 = \frac{b_x}{J_x}$, $b_1 = \frac{R_y}{J_y}$, $b_2 = \frac{k_{iy}R_y}{J_y}$, $b_3 = \frac{b_y}{J_y}$, $g_1 = \frac{1}{L_1}$, $g_2 = \frac{AE}{L_1}$, $c_1 = K_z$, $c_2 = b_z$, $h_1 = \frac{1}{L_2}$, and $h_2 = \frac{AE}{L_2}$. To design a variable structure control system, a set of switching surfaces, which restrict the original system on the intersection of the switching surfaces to result in the desired behavior, are firstly defined as

$$S = C_1\tilde{X} + C_2 \int \tilde{X} dt = 0$$

where $S^T = [s_1 \ s_2 \ s_3]$ are a set of switching surfaces, $C_1 \in R^{3 \times 5}$ and $C_2 \in R^{3 \times 5}$ are appropriately designed constant matrices, and the error vector $\tilde{X}$ is defined as

$$\tilde{X} = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \\ \tilde{x}_4 \\ \tilde{x}_5 \end{bmatrix} = \begin{bmatrix} \nu_x - \nu_{xd} \\ T_1 - T_{1d} \\ \dot{T}_1 - \dot{T}_{1d} \\ T_2 - T_{2d} \\ \dot{T}_2 - \dot{T}_{2d} \end{bmatrix}$$

where ν_{xd} is the tracking goal of velocity ν_x , T_{1d} and T_{2d} are the tracking goals of film tensions T_1 and T_2 , respectively. The second stage is to determine an appropriate sliding mode control that is able to force the trajectory of the system approaching to and staying on the sliding surface. Therefore, the well-known sliding condition must hold, i.e. $S^T \dot{S} < 0$. As the following form is set,

$$\dot{S} = -K \operatorname{sgn}(S)$$

where $K = \begin{bmatrix} K_1 & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & K_3 \end{bmatrix}$, $K_1 > 0$, $K_2 > 0$, $K_3 > 0$, and

$\operatorname{sgn}(S) = \begin{bmatrix} \operatorname{sgn}(s_1) \\ \operatorname{sgn}(s_2) \\ \operatorname{sgn}(s_3) \end{bmatrix}$, it is very clear to find that the

sliding condition can be obtained from the following result.

$$\begin{aligned}
S^T \dot{S} &= -S^T K \operatorname{sgn}(S) \\
&= -(K_1|s_1| + K_2|s_2| + K_3|s_3|) < 0
\end{aligned}$$

Since ν_x , T_{1d} and T_{2d} are set to be fixed values, the sliding mode control law can be derived as

$$\begin{aligned}
\dot{S} &= C_1\dot{X} + C_2\ddot{X} = C_1[F(X, t) + M(t)] \\
&+ C_1G(X, t)U + C_2\ddot{X} = -K \operatorname{sgn}(S) \\
U &= [C_1G(X, t)]^{-1} \{-C_1[F(X, t) + M(t)] \\
&- C_2\ddot{X} - K \operatorname{sgn}(S)\} \quad (20)
\end{aligned}$$

In the work, constant matrices C_1 and C_2 are chosen as

$$C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 2\lambda_2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2\lambda_3 & 1 \end{bmatrix} \quad C_2 = \begin{bmatrix} \lambda_1 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_3^2 & 0 \end{bmatrix}$$

where λ_1, λ_2 , and λ_3 are strictly positive constants. Therefore, control inputs can be obtained from Eq. (20) as in the following forms

$$u_x = -\frac{1}{a_2} [K_1 \operatorname{sgn}(s_1) + a_1 T_1 - a_3 \nu_x + \lambda_1 (\nu_x - \nu_{xd})] \quad (21)$$

$$\begin{aligned}
u_y &= \frac{-1}{(g_2b_2 - g_1b_2T_1)} [K_2 \operatorname{sgn}(s_2) \\
&+ \lambda_2^2 (T_1 - T_{1d}) + 2\lambda_2 (-g_1\nu_yT_1 + g_2\nu_y - g_2\nu_x) \\
&- g_2(a_1T_1 + a_2u_x - a_3\nu_x) + g_2(b_1T_2 - b_1T_1 - b_3\nu_y) \\
&- g_1\nu_y(-g_1T_1\nu_y + g_2\nu_y - g_2\nu_x) \\
&- g_1T_1(b_1T_2 - b_1T_1 - b_3\nu_y)] \quad (22)
\end{aligned}$$

Fig. 6 Layout of experimental facilities

Fig. 7 Experimental coating machine

$$\begin{aligned}
 u_z = & \frac{-(J_z)}{c_1 R_z (-h_1 T_2 + h_2)} \left\{ K_3 \operatorname{sgn}(s_3) + \lambda_3^2 (T_2 - T_{2d}) \right. \\
 & + 2\lambda_3 [h_1 (T_1 \nu_y - T_2 \nu_z) + h_2 (\nu_z - \nu_y)] \\
 & + h_2 \left[\frac{1}{J_z} (-T_2 R_z^2 - c_2 \nu_z) \right. \\
 & \left. \left. - (b_1 T_2 - b_1 T_1 + b_2 u_y - b_3 \nu_y) \right] \right. \\
 & + h_1 \left\{ \nu_y (-g_1 \nu_y T_1 + g_2 \nu_y - g_2 \nu_x) \right. \\
 & + T_1 (b_1 T_2 - b_1 T_1 + b_2 u_y - b_3 \nu_y) \\
 & \left. - \nu_z [h_1 (T_1 \nu_y - T_2 \nu_z) + h_2 (\nu_z - \nu_y)] \right. \\
 & \left. \left. - T_2 \left[\frac{1}{J_z} (-T_2 R_z^2 - c_2 \nu_z) \right] \right\} \right\} \quad (23)
 \end{aligned}$$

3.2 Installment of experimental facilities

The layout of experimental facilities and the practical experimental coating machine are shown in Fig. 6 and 7, respectively. In this experiment, main experimental facilities are chosen as follows:

DC servomotor (IECHNOLOGIES INC-2234-ME 3298): $N_{\max}=6\,000$ rpm, $J_m=3.960\,5 \times 10^{-6}$ kg·m²;

Servo-motor driver (Yen-Shin Co-YSDC-1350P10): $I_R=2$ A, $I_{\max}=5$ A, $P=100$ W, $V_{\text{out}}=\pm 10$ V;

A/D converter (Advantech Co-PLC-812): $V_{\text{out}}=\pm 10$ V and resolution is 12 bits;

D/A converter (Advantech Co-PLC-812): $V_{\text{out}}=0\sim 5$ V and resolution is 12 bits.

System parameters are shown in Table 1. In the experiment, switching control gains K_i and λ_i are set as shown in Table 2. Experiment results are given in Figs. 8 and 9. Desired reference values are set as $\nu_{xd}=0.25$ m/s, $T_{1d}=T_{2d}=3.5$ N in Fig. 8. In Fig. 9, the desired transmitting velocity is changed to be $\nu_{xd}=$

Table 1 List of system parameters

E	Film elastic modulus	$1.2125 \times 10^7 \text{ N/m}^2$
A	Film cross-section area	$1.216 \times 10^{-3} \text{ m}^2$
L_1	Film length in the 1 st zone	0.535 m
L_2	Film length in the 2 nd zone	0.450 m
t_ρ	Film density	1203.466 kg/m^3
t_w	Film width	0.08 m
t_h	Film thickness	$1.52 \times 10^{-4} \text{ m}$
R_x	Radius of roller x	0.02 m
R_y	Radius of roller y	0.02 m
R_{z0}	Radius of roller z	0.01 m
J_x	Inertia of roller set x	$8 \times 10^{-4} \text{ kg} \cdot \text{m}^2$
J_y	Inertia of roller set y	$8 \times 10^{-4} \text{ kg} \cdot \text{m}^2$
J_m	Inertia of roller set z	$8 \times 10^{-4} \text{ kg} \cdot \text{m}^2$
b_x	Rotational friction coefficient of roller set x	$7 \times 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s}$
b_y	Rotational friction coefficient of roller set y	$7 \times 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s}$
b_z	Rotational friction coefficient of roller set z	$7 \times 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s}$
k_{fx}	Torque constant of motor x	$0.318 \text{ N} \cdot \text{m/V}$
k_{fy}	Torque constant of motor y	$0.318 \text{ N} \cdot \text{m/V}$
k_{fz}	Torque constant of motor z	$0.318 \text{ N} \cdot \text{m/V}$

Table 2 List of control parameters

v_x (m/s)	0.25	0.5
Controller parameter		
Controller parameter in v_x control	$K_1 = 60$ $\lambda_1 = 0.8$	$K_1 = 65$ $\lambda_1 = 0.8$
Controller parameter in T_1 control	$K_2 = 400$ $\lambda_2 = 5$	$K_2 = 700$ $\lambda_2 = 10$
Controller parameter in T_2 control	$K_3 = 800$ $\lambda_3 = 100$	$K_3 = 1200$ $\lambda_3 = 100$

0.5 m/s and desired film tensions are the same as those in Fig. 8. From experiment results, it is shown that the performance of sliding mode control applied to control film-transmitting velocity and tension is satisfactory.

4. Conclusions

In the experiment, the stability of the system subjected to modeling errors and disturbances can be enhanced by adjusting the switching control gain K . Nevertheless, it is noted that the better effect can not be obtained by boosting the switching control gain only but also has relation to the system sampling time. If the sampling time is not short enough, the higher K value will cause that the system state come and go through the sliding surface. Such this phenomenon will result in oscillation in tension and velocity controls. Therefore, when the switching control gain K is chosen, the restriction of the system hardware should be considered such that the better control can

Fig. 8 Velocity response of v_x , tension responses T_1 , T_2 and control inputs u_x , u_y , u_z at the transmitting velocity 0.25 m/s

Fig. 9 Velocity response of v_x , tension responses T_1 , T_2 and control inputs u_x , u_y , u_z at the transmitting velocity 0.5 m/s

be achieved.

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