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論 文
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The Design of Web Tension Control System Using a Nonlinear Feedback

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Abstract – We consider a web transport system. The objective of this paper is to design the controller such that desired tension and processing on web transport system. We propose the new design method which is independent with operating condition. The proposed method used a nonlinear feedback to transform to linear system. We show a performance of controller via the simulation.

Key Words : web transport system, nonlinear feedback, tension control

1. Introduction

The precise control of web tension is very important to improve the quality of product such as a textile industry. There have been some works to control the tension and processing speed[1,2,3,4]. The control method for tension and process speed control has been used the gain scheduling method[1,2]. The gain scheduling method is one of the popular methods to handle the nonlinearity in the system[5]. Linearization around operating point has to be performed to utilize the well developed linear controller design method in the gain scheduling. However the gain scheduling method is only valid in the neighborhood of operating point. Therefore it is possible that the system using a gain scheduling method might not be satisfied the desired performance, when the operating point is changed. The work[1] fixed the processing speed with some operating condition to handle a nonlinearity in the web process dynamics. After fixing the processing speed, the system was changed to a linear system. The linear controller was designed to control the tension and process speed of a web transport system. This approach could cause a problem when the operation condition is changed. To avoid this problem, we propose a new control design method which uses the nonlinear feedback to transform to a linear system. We show that the web transport system considered in this paper can be transformed to a linear system by cancelling the nonlinearity using feedback after the change of coordinate. After transformation to a linear system using the change of coordinate, we design a controller to achieve the control objectives. The proposed method works on the every operation condition, since we do not fix the system parameters to remove the nonlinearity existed in the system dynamics.

2. System modeling and controller design

2.1 System modeling

The web transport system to be considered in this paper is shown in Fig 1. Motors are used to drive the unwind roller and rewind roller. Idle rollers guide the web to load cell. The load cell is used to measure the tension of web. The tension and velocity control can be done by controlling the velocity of the unwind roller and rewind roller. The tension of the web can be controlled by torque control of the unwind roller' motor: the unwind roller acts as if a brake against moving web. The speed of web can be controlled by the torque control of the rewind roller' motor. The dynamic equations for the web transport system in Fig. 1 can be described by the following equation[1,3].

$$\begin{aligned} J_u \frac{dw_u(t)}{dt} &= -B_u w_u + r_u T(t) - \tau_u \\ \frac{dT(t)}{dt} &= -\frac{r_r w_r}{L} T(t) + K[r_r w_r - r_u w_u] \quad (1) \\ J_r \frac{dw_r(t)}{dt} &= -B_r w_r + r_r T(t) + \tau_r \end{aligned}$$

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where $J_u \equiv$ moment of inertia of unwind roll including motor($kg/m/\sec^2$), $J_r \equiv$ moment of inertia of unwind roll including motor($kg/m/\sec^2$), $w_u \equiv$ angular velocity of the unwind roll(rad/sec), $w_r \equiv$ angular velocity of the wind roll(rad/s), $B_u \equiv$ coefficient of viscous friction of unwind roll(kg-m-s/rad), $B_r \equiv$ coefficient of viscous friction of wind roll(kg-m-s/rad), $r_u \equiv$ radius of the unwind roll(m), $r_r \equiv$ radius of the unwind roll(m), $T \equiv$ web tension(kg), $\tau_u \equiv$ torque generated by unwind motor(kg/m), $\tau_r \equiv$ torque generated by wind motor(kg/m), $L \equiv$ total length of web(m), $K \equiv$ spring constant of web(kg/m). Note that we neglected the Coulomb friction and dynamics of idle roller and load cell in the equation (1).

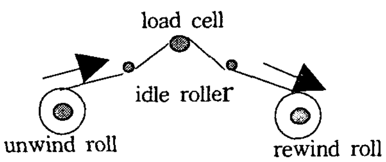

Fig. 1. The web transport system

2.2 Feedback linearization and controller design

The main object of this paper is to design the torques generated by unwind roll and rewind roll enabling a desired angular velocity of rewind roll and tension of moving web. The desired processing speed of web can be achieved by controling the angular velocity of the rewind roll. The term w_r of $-r_r w_r / L$ in the equation(1) was fixed at an operating point in the paper[1] because of nonlinearity. After w_r was assumed at the operating condition, the equation (1) is a linear system and one can design the desired controller by using a standard controller design technique for linear system. However the design method used in the paper[1] may cause a problem when operating point is changed. There are some progresses in the nonlinear system theory during the last decade[5,6]. A class of nonlinear system can be transformed to a linear system via a change of coordinate. The class of system is called a feedback linearizable system. To check the feedback linearizability, we rewrite the equation (1) as the following equation.

$$\begin{bmatrix} \dot{w}_u \\ \dot{T} \\ \dot{w}_r \end{bmatrix} = f(w_u, T, w_r) + g \cdot \begin{bmatrix} \tau_u \\ \tau_r \end{bmatrix} \qquad (2)$$

where

$$f(w_u, T, w_r) = \begin{bmatrix} k_1 w_u + k_2 T \\ k_4 w_u + k_5 T w_r + k_6 w_r \\ k_7 T + k_8 w_r \end{bmatrix}, \quad g = \begin{bmatrix} k_3 & 0 \\ 0 & 0 \\ 0 & k_9 \end{bmatrix}, \quad k_1 = -\frac{B_u}{J_u},$$

$k_2 = r_u/J_u$, $k_3 = -1/J_u$, $k_4 = -Kr_u$, $k_5 = -r_r/L$, $k_6 = Kr_r$, $k_7 = -r_r/Jr$, $k_8 = -B_r/J_r$, $k_9 = 1/J_r$. Our interesting outputs are T(t) and w_r. Since $L_{g1}L_f^0 T = 0$, $L_{g1}L_f^1 T = k_3 k_4 \neq 0$,, $L_{g2}L_f^0 T = 0$, $L_{g2}L_f^1 T = (k_5 T + k_6)k_9 \neq 0$, $L_{g1}L_f^0 w_r = 0$, and $L_{g2}^1 L_f^0 w_r = k_9 \neq 0$, where $L_f^1 T$ is the derivative of T along a vector field f, i.e., $L_f^1 T \equiv \left[\frac{\partial T}{\partial w_u} \ \frac{\partial T}{\partial T} \ \frac{\partial T}{\partial w_r} \right] \cdot f$, $L_f^0 T \equiv T$, and similarly $L_{gi}L_f^1 T$, $L_{gi}L_f^0 w_r$ are defined where g_i is the i th column vector of , the equation (2) has a vector relative degree of [2,1]. Thus implies that the equation (2) is feedback linearizable system. Define $z_1 = T$, $z_2 = k_4 w_u + k_5 T w_r + k_6 w_r$, $z_3 = w_r$. It can be shown that the equation (2) can be rewritten as

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} = \begin{bmatrix} z_2 \\ b_1(z) + a_{11}(z)\tau_u + a_{12}(z)\tau_r \\ b_2(z) + k_9 \tau_r \end{bmatrix} \qquad (3)$$

where $z = [z_1, z_2, z_3]^T$, $b_2(z) = k_7 z_1 + k_8 z_3$, $a_{11}(z) = k_3 k_4$, $a_{12}(z) = k_5 k_9 z_1 + k_6 k_9$, and

$b_1(z) = (k_5 k_8 - k_1 k_5) z_1 z_3 + k_5 z_2 z_3 + k_5 k_7 z_1^2 + (k_6 k_7 + k_2 k_4) z_1 + k_1 z_2 + (k_6 k_8 - k_1 k_6) z_3$

After choosing

$\tau_u = \frac{1}{a_{11}} [-b_1(z) - a_{12}(z)\tau_r + v_u]$ and $\tau_r = \frac{1}{k_9}[-b_2(z) + v_r]$

where v_u and v_r are to be defined later on, the equation (3) results in the following equation

$$\dot{z} = Az + Bv \qquad (4)$$

where $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$, $v = \begin{bmatrix} v_u \\ v_r \end{bmatrix}$. One can use the standard linear system design method[7] for the design of v_u and v_r. One can verify that $[A, B]$ is controllable pair. Therefore we can choose the control input v to achieve the desired tension and angular velocity of rewind roll. Since [A,B] is controllable pair, one can choose c_i with $v_u = c_1(z_1 - T_d) + c_2 z_2$, $v_r = c_3(z_3 - w_{rd})$ such that the closed loop poles are located in open left half plane. Note that T_d and w_{rd} denote the desired tension value and the desired angular velocity respectively.

3. Simulation Results

We consider the experimental system given in [1] as an example. The experimental system has the following data:

$J_u = J_r = 1.95 \times 10^{-5} kg - m - s^2$, L=0.3m, K=200 kg/m,

$B_u = B_r = 2.533 \times 10^{-5}$ kg-m, $r_u = 0.04$ m, $r_r = 0.015$ m.

We consider that the desired tension is $T_d = 0.5kg$ and the desired angular velocity is $w_{rd} = 87.5$ rad/sec initially and then the desired angular velocity is changed to 175 rad/sec. Two controllers are designed for the comparison. We design the controller according the proposed method.

The control gains are chosen as c_1=-20, c_2=− 9, c_3=-4 which is corresponded that the closed loop eigen values are [-4,-5,-4]. Fig. 2 and Fig. 3 show that we can achieve our control objective. The time profile of tension of the web is followed to 0.5 kg as in the Fig. 2. The time profile of angular velocity of rewind web is also well followed 87.5 rad/sec which is the desired one initially in Fig. 3. After changing the desired angular velocity to 175 rad/sec, the time profile of angular velocity of rewind web is well followed 175 rad/sec in Fig. 3.

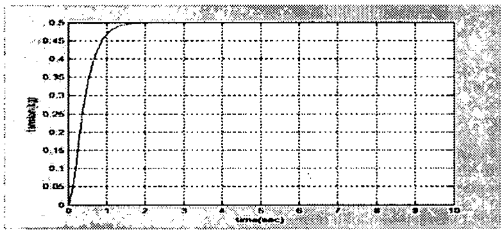

Fig. 2 The plot of tension of web with nonlinear feedback

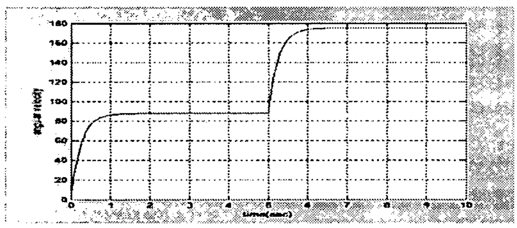

Fig. 3 The plot of angular velocity of rewind roll with nonlinear feedback

We simulated the another controller using linearization technique which is used in [1]. After fixing $w_r = 87.5$ rad/sec in equation (1), we design the controller such that the closed loop eigen value is equal to [-3, -4, -5]. Fig. 4 is the simulation results. One can observe that the tension is well followed the desired value during the first 5 second. However the tension is not followed the desired value after the first 5 second which is corresponded to the change of the desired angular velocity being 175 rad/sec, since the controller is designed for the system being linearized with $w_r = 87.5$ rad/sec.

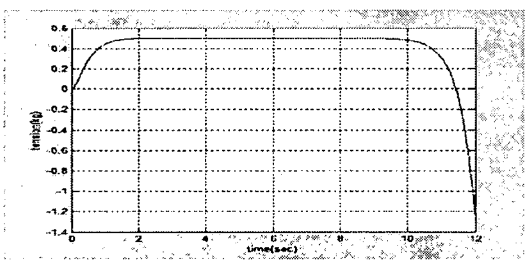

Fig. 4 The plot of tension of web with linearization at $w_r = 87.5$ rad/sec

4. Conclusion

We consider a web transport system. We propose the new control design method using nonlinear feedback. The proposed controller can work any operating condition, while the previous work[1] restricted to the certain operation condition. We demonstrate that the proposed control design method is working very well under the any operating point, while the previous design method is not working in the different operating point via a simulation.

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