NON-LINEAR TENSION CONTROL IN A WINDING PROCESS BY USING THE CONTACT ROLL

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ABSTRACT

In a web winding process, the contact roll plays many important roles including air-entrainment control and WIT(Winound In Tension) regulation. The behavior of the contact roll significantly affects the winding tension characteristics specifically at the time of contact and separation when the tangential velocities of contact roll and the winding roll are not synchronized. A new mathematical model which includes the behavior of the web tension, the winding roll, carrage and the contact roll is derived for the control of the winding tension. By using the model derived, a non-linear PID(NPID) controller is designed to control the winding tension at the time of contact and separation between the contact roll and the winding roll. Computer simulation study showed that the performance of the winding system with the NPID controller was significantly improved compared with that of a system with PID controller.

NOMENCLATURE

A	Cross-sectional area of web
b	Viscous friction coefficient
B	Damping coefficient of the web or the cylinder
D	Diameter of rolls
E	Modulus of elasticity
e	Error of the tension variation
F	Friction force
f_n	Contact force variation
J_n	Polar moment of inertia of roll or roller
K	Spring constant
k	Actuator gain

L_n	Length of web span
m_n	Mass of the carrage, contact roll
R_n	Radius of roll or roller
t_{n0}	Steady-state value of web tension
t_n	Web tension = $t_{n0} + T_n$
T_n	Change in web tension from a steady-state operating value
T_{nref}	Reference tension
u_{n0}	Steady-state value of input to a drive motor
u_n	Input to motor = $u_{n0} + U_n$
U_n	Change in input to a drive motor from a steady-state operating value
v_{n0}	Steady-state operating value of web velocity
v_n	Web velocity = $v_{n0} + V_n$
V_n	Change in web velocity from a steady-state operating value
α, β	Constants for controller gains
μ	Friction coefficient between the contact roll and the winding roll
τ	Change in the driving torque in the winding roll

Subscripts:

0	Steady-state operating condition
n	1,2,3,4 . . .
p	Cylinder
w	Winding roll

INTRODUCTION

A typical control problem in a multi-span web transport system is maintaining the required longitudinal tension level in each processing and winding section, and at the same time stabilizing the overall web transport system.

Specifically, the winding mechanism includes several complicated processes like the nipping of the contact/nip roll, the cutting of the web, the turreting for automatic roll change, etc.. The contact roll is usually used for the air-entrainment control and WIT(wound in tension) regulation. But, the contact roll may also generate huge tension variation in the web during winding, which can be often observed in the actual web processing plant, in case the tangential velocity of the contact roll is not synchronized with that of the winding roll. And the synchronization of the tangential velocity between the contact roll and the winding roll is usually very difficult to achieve.

There is quite an extensive literature concerning web tension control[1, 3, 4, 5, 6], but are not many on the study of the tension variation due to the mechanics of a rolling nip. Pfeiffer investigated the mechanics of a rolling nip on paper webs[7] and the effect of nip forces on wound-in tension[8]. But, it was hard to find literatures on the study of the mechanism of the contact roll in the tension-control point of view. On the other hand, Xu[9] reported his research result on the contact force control in the area of flexible robot application, which is partially applicable to the study of the contact mechanism of the rolling nip in the winding.

In this paper, a new mathematical model which includes the behavior of the web tension, the winding roll, carrage and the contact roll is derived for the control of the winding tension. A non-linear PID(NPID) controller is designed to control the winding tension by using the contact roll at the time of contact and separation between the contact roll and the winding roll. Computer simulation study showed that the performance of the winding system with the NPID controller was significantly improved compared with that of a system with the PID controller.

MATHEMATICAL MODEL

Consider a winding system which includes a winding roll, a contact roll, and the carrage as shown in Fig. 1. In the Fig. 1, the web enters to #1 driven roll, goes through the idle rolls in the carrage, and is wound in the winding roll. The contact roll is supported by a cylinder on the carrage. As the winding roll begins to wind the web, the carrage moves toward the winding roll until the contact roll on the carrage comes in contact with the winding roll to provide the contact force necessary to regulate the wound-in tension and the air entrainment during the winding process. When the contact roll comes across the winding roll, the contact roll may apply additional torque to the winding roll if the tangential velocities between the contact roll and the winding roll are not synchronized. This additional torque may change the tangential velocity of the winding roll and the winding tension.

A free body diagram for the winding roll is shown in Fig. 2. In the Fig. 2, f_n is the force applied to the winding roll due to the contact and T_5 is the winding tension. The Shin's mathematical model[1] for the tension and the velocity of the web can be extended to the equations (1) and (2) from the torque balance for the free body diagram shown in the Fig. 2.

$$\frac{dT_5(t)}{dt} = -\frac{V_{w0}}{L_5}T_5(t) + \frac{V_{40}}{L_5}T_4(t) + \frac{AE}{L_5}(V_w(t) - V_4(t)) \quad (1)$$

$$J_w\dot{V}_w(t) = -b_wV_w(t) + R_w^2(T_w(t) - T_5(t)) + R_w(\tau_w + FR_w) \quad (2)$$

The linearized mathematical model for the tension and velocity of the web between the rollers #1 and #4 in the Fig. 1 can be written as equations from (3) to (9)[1]. It was assumed that there was no slip between the web and rollers.

$$J_1\dot{V}_1(t) = -b_1V_1(t) + R_1^2(T_2(t) - T_1(t)) + R_1\tau_1 \quad (3)$$

$$\frac{dT_2(t)}{dt} = -\frac{V_{20}}{L_2}T_2(t) + \frac{V_{10}}{L_2}T_1(t) + \frac{AE}{L_2}(V_2(t) - V_1(t)) \quad (4)$$

$$J_2\dot{V}_2(t) = -b_2V_2(t) + R_2^2(T_3(t) - T_2(t)) \quad (5)$$

$$\frac{dT_3(t)}{dt} = -\frac{V_{30}}{L_3}T_3(t) + \frac{V_{20}}{L_3}T_2(t) + \frac{AE}{L_3}(V_3(t) - V_2(t)) \quad (6)$$

$$J_3\dot{V}_3(t) = -b_3V_3(t) + R_3^2\,(T_4(t) - T_3(t)) \tag{7}$$

$$\frac{dT_4(t)}{dt} = -\frac{V_{40}}{L_4}T_4(t) + \frac{V_{30}}{L_4}T_3(t) + \frac{AE}{L_4}(V_4(t) - V_3(t)) \tag{8}$$

$$J_4\dot{V}_4(t) = -b_4V_4(t) + R_4^2\,(T_5(t) - T_4(t)) \tag{9}$$

In order to analize the mechanism of the contact and separation of the contact roll, the contact roll, the carrage, and the winding roll is modeled as shown in Fig. 3. Total mass of the carrage is m_1, and the m_2 is the mass of the contact roller. The cylinder supporting the contact roller is modeled as spring and damper elements. The web wound in the winding roll is also modeled as spring and damper elements as shown in the Fig. 3. u_1 is the force applied to the carrage. f_p is the force applied to the contact roll, and the f_n is the contact force between the contact roll and the winding roll. By applying the Newton's second law for the model in the Fig. 3, equations from (10) to (13) can be derived to describe the behavior of the contact roll when it comes across and separates from the winding roll.

$$m_1\,\ddot{x}_1 + B_p\,(\dot{x}_1 - \dot{x}_2) + k_p\,(x_1 - x_2) = u_1 \tag{10}$$

$$m_2\,\ddot{x}_2 + B_w\,\dot{x}_2 + k_w\,x_2 = B_p\,(\dot{x}_1 - \dot{x}_2) + k_p\,(x_1 - x_2) \tag{11}$$

$$f_p = B_p\,(\dot{x}_1 - \dot{x}_2) + k_p\,(x_1 - x_2) \tag{12}$$

$$f_n = B_w\,\dot{x}_2 + k_w\,x_2 \tag{13}$$

The control problem of the winding tension can be studied by using the mathematical model represented by the equations from (1) to (13).

DESIGN OF CONTROLLER

The block diagram for the control of the winding tension is shown in the Fig. 4. A low pass filter is included to reject the disturbance in the experiment. A NPID(non-linear PID) controller is proposed in this paper as shown in the Fig. 4. The structure of the NPID controller is the same as the PID controller except the proportional and the derivative gains as shown in the equations from (14) to (15).

$$u(t)_{1\,NPID} = k\,(K_n\,e + B_n\,\dot{e}) + k\,K_i\int_0^t e\,dt \tag{14}$$

where,

$$e(t) = T_{5\,ref} - T_5 \tag{15}$$

$$B_n = \frac{B_1}{1 + \beta\,\exp^{\alpha\,\mathrm{sign}(\frac{dT_5}{dt})\,e}} + B_0 \tag{16}$$

$$K_n = \frac{K_1}{1 + \beta \exp^{\alpha\, \mathrm{sign}(\frac{dT_5}{dt})\, e}} + K_0 \qquad (17)$$

In the NPID controller proposed, the variation of the state is monitored, and the proportional and the derivative gains are adjused according to the trend of the tension variation as well as the magnitude of the tension error by using the equations (16) and (17). In equation (16), B_1, B_0 α, β are constants. B_0 is the minimum of the B_n and B_1+B_0 is the maximum of the B_n. α and β are weighting factors to decide the changing rate of the derivative gains according to the trend of the tension variation and the magnitude of the tension error. The proportional gain represented by equation (17) can be explained similarly.

Since the NPID controller can adjust its gains(proportional and derivative gains) in real time according to the size of the tension error and the trend of the tension variation, the NPID controller is able to reject the effect of various time-varying and non-linear elements in the winding process.

COMPUTER SIMULATION

The mathematical model represented by equations from (1) to (13) and the NPID controller described by equations from (14) to (17) were used to study the tension control in the winding section. Control gains designed are given in Table 1 and simulation parameters in Table 2. The winding roll was modeled as spring and damping elements as shown in the Fig. 3. Various conditions (e.g., change in the radius of roll) in the winding process were simulated by changing the spring (K_w) and the damping(B_w) constant in the Fig. 3.

At the beginning of the winding (or when the contact roll comes across the winding roll), the winding roll is assumed very hard(big spring constant, small damping constant) since the amount of the web wound into the core is relatively very little. Fig. 5 and 6 showes the velocity and the tension transient in the winding section when the contact roll comes in contact with the new winding roll on which a few wraps of web were wound (big K_w and small B_w). Behavior of the both the winding tension and the velocities of the web in the winding section with the NPID controller proved to be better than those of the system with PID controller as shown in the Fig. 5 and 6.

As the radius of the winding roll increases, the hardness of the winding roll is reduced compared with the beginning condition of the winding roll. This situation is simulated by using a small value of spring constant. Fig. 7 (a),(b) showes tension variation in the winding section with increased radius of winding roll(reduced value of K_w). When K_w is reduced(with increased radius of winding roll), the performance of the system with NPID controller is much better than that of system with PID controller as shown in the Fig. 7 (a),(b).

When the contact roll separates from the winding roll at the end of winding, the tension and the velocity variation in the winding section is shown in Fig. 8, 9, and 10. The perofrmance of the winding system with the NPID controller at the end of the winding(separation) was better than that of system with the PID controller just as the case of the beginning of the winding(contact).

CONCLUSIONS

A new mathematical model which includes the behavior of the web tension, the winding roll, carrage and the contact roll is derived for the control of the winding tension. By using the model derived, a non-linear PID(NPID) controller is designed to control the winding tension at the time of contact and separation between the contact roll and the winding roll. Computer simulation study showed that the performance of the winding system with the NPID controller was significantly improved compared with that of a system with PID controller for various time-varying and nonlinear conditions. Real-time experimental study is being carried on to validate the mathematical model derived and the NPID controller by using the Vxworks real-time scheduler and the force target board under UNIX environment.

REFERENCES

1. Shin, K.H., "Distributed Control of Tension in Multi-Span Web Transport Systems", Ph.D. Thesis, Oklahoma State Univ., May, 1991.
2. Xu, Y., Ma, D., and Hollerbach, J. M., "Nonlinear proportional and derivative control for high disturbance rejection and high gain force control", Proc. IEEE Int. Conf. Robotics and Automation, Atlanta, pp. 752-759, 1993
3. Grenfell, K.P., "Tension Control on Paper-Making and Converting Machinery", Proc. IEEE Ninth Annual Conference on Electrical Engineering in the Pulp and Paper Industry, June 20-21, 1963, Boston, Mass.
4. Wolfermann, W. and Schroder, D., "Application of Decoupling and State Space Control in Processing Machines with Continuous Moving Webs", Proc. International Federation of Automatic Control, 1987, Munhen.
5. Reid, K.N., Shin, K.H., Lin, K.C., "Variable-gain Control of Longitudinal Tension in a Web Transport System", AMD., Web Handling, ASME, Vol. 149, 1992.
6. Reid, K.N., Lin, K.C., "Control of Longitudinal Tension in Multi-Span Web Transport System during Start Up", Proc. on 3rd. Int. Conf. on Web Handling, pp.77-95 June 18-21, 1995, Web Handling Research Center, Oklahoma State Univ., Stillwater, Oklahoma.
7. J. David Pfeiffer, "Mechanics of a Rolling Nip on Paper Webs", TAPPI, Vol. 51, NO. 8, 1968.
8. J. David Pfeiffer, "Nip Force and their effect on wound-in tension", TAPPI, Vol. 60, NO. 2, 1977.
9. Xu, Y., Ma, D., and Hollerbach, J. M., "Force and Contact Trensient Control Using Nonlinear PD Control", Proc. IEEE Int. Conf. Robotics and Automation, Atlanta, pp. 924-930, 1994.

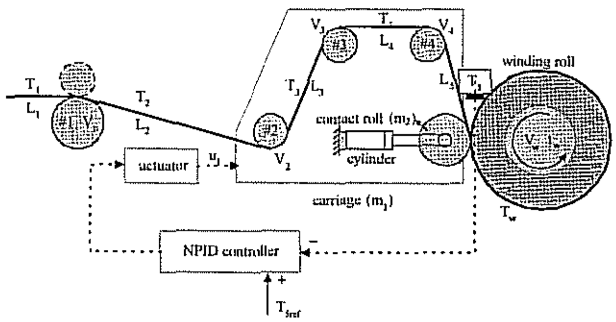


Fig. 1 Winding system configuration including a winding roll, a contact roll, and a carriage

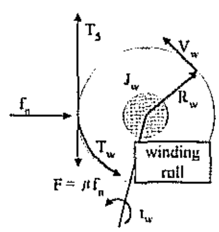


Fig. 2 Free body diagram for the winding roll

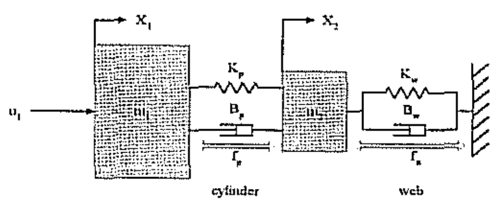


Fig. 3 Simplified model of a contact roll, a winding roll, and a carriage

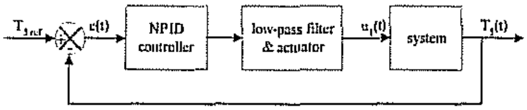


Fig. 4 Block diagram for the closed-loop tension control system

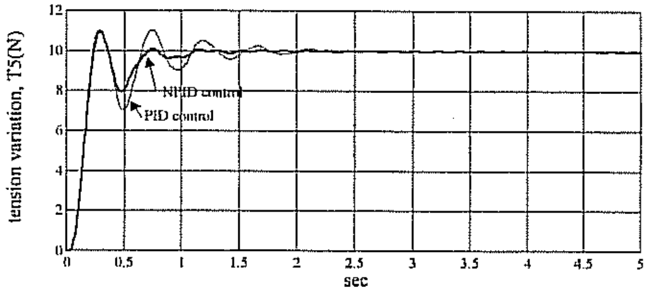


Fig. 5 Winding tension variation (K_w=1.5×10^5 N/m, B_w=700 N/ms^{-1})

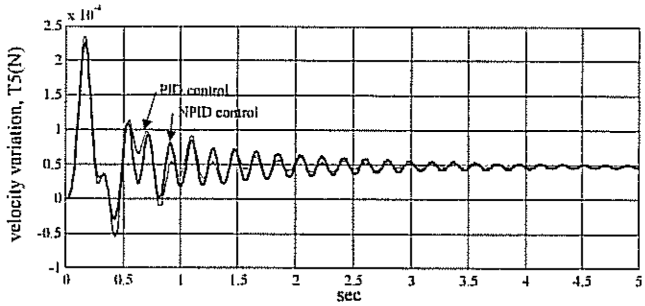
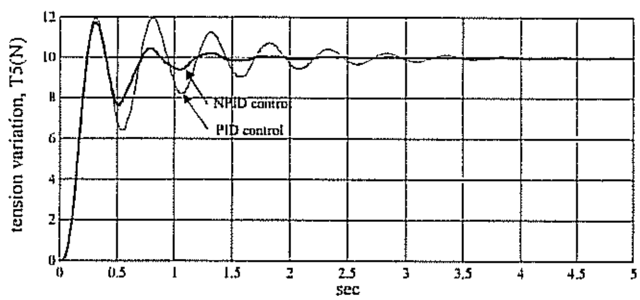
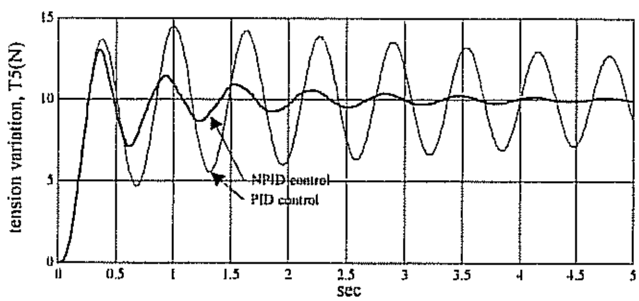


Fig. 6 Winding velocity variation (K_w=1.5×10^5 N/m, B_w=700 N/ms^{-1})

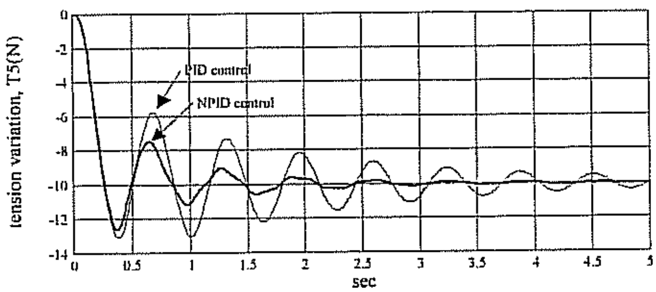


(a) K_w=1.0×10^5 N/m

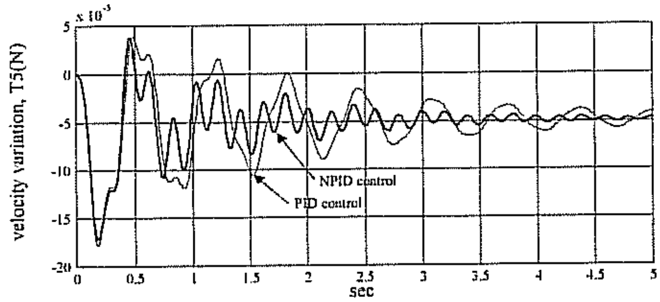


(b) K_w=0.5×10^5 N/m

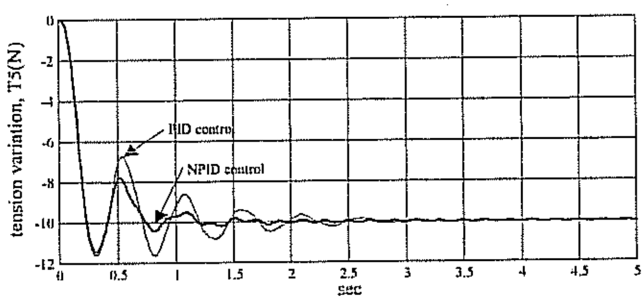
Fig. 7 Winding tension variation (B_w=700 N/ms^{-1})



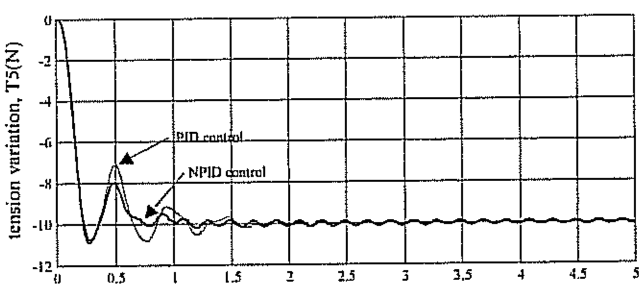
(K_w=0.5×10^5 N/m, B_w=1300 N/ms^{-1}, ΔJ_w=2 kg · m^2)
Fig. 8 Winding tension variation



(K_w=0.5×10^5 N/m, B_w=1300 N/ms^{-1}, ΔJ_w=2 kg · m^2)
Fig. 9 Winding velocity variation



(a) K_w=1.0×10^5 N/m



(b) K_w=1.5×10^5 N/m
Fig. 10 Winding tension variation (B_w=1300 N/ms^{-1}, ΔJ_w=2 kg · m^2)

Table 1 Control gains

PID	NPID	
$K = 1.1$	$K_l = 2.5$	$K_u = 1$
$B = 0.1$	$B_l = 3$	$B_u = 0.1$
	$\alpha = 1$	$\beta = 100$
$K_i = 10$	$K_i = 10$	
$k = 2$	$k = 2$	

Table 2 Simulation parameters

D_1	0.3 m	A	5.5×10^{-4} m^2
D_2, D_3, D_4	0.2 m	E	2.5×10^9 N/m^2
L_1	0.45 m	V_0	6.67 m/s
L_2	1.15 m	b_w	0.1
L_3	0.39 m	μ	0.3
L_4	0.4 m	m_1	500 kg
L_5	0.4 m	m_2	100 kg
J_1	7.7106 kg · m^2	K_p	100000 N/m
J_2, J_3, J_4	1.8933 kg · m^2	B_p	2000 N/ms^{-1}

Question - Was the stability problem checked with this non linear controller?

Answer - Yes, the Lyapunov method can be used to prove the stability problem.

Question - Have you seen them used in other applications?

Answer - Yes, similar application's were observed in the area of robot control, specifically in the control of contact force.

Thank you.