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A Feed-forward Tension Control in Drying section of Roll to Roll e-Printing Systems

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Abstract: The mathematical model for tension behaviors of a moving web by Shin (Shin, 2000) is extended to the tension model considering the thermal strain due to temperature variation in a dryer of the roll to roll systems. The extended model includes the terms that take into account the effect of the change of the Young's Modulus, the thermal coefficient, and the thermal strain on the variation of tension. By using the extended tension model, a new tension control method is suggested in this paper. The key factors of suggested tension control method include that the thermal strain of web could be compensated by using the velocity adjustment. The computer simulation and experimental validation was carried out to confirm the performance of the proposed tension control method. The results show that the suggested tension control logic improves the performance of tension control in a dryer section of the roll to roll systems.

NOMENCLATURE

A : Cross-sectional area of web

E : Young's modulus

L : Length of span

T : Change in the web tension from a steady-state operating value

t : Tension of web

V : Change in the web velocity from a steady-state operating value

v : Velocity of roller

α : Thermal coefficient

β : Velocity difference

ε : Strain of web

ε^{th} : Thermal strain

ε^{e} : Elastic strain

θ : Temperature

ρ : Density of web

SUBSCRIPT

eq : Equivalent

N : Index

op : Steady-state operating value

θ : Temperature

1. INTRODUCTION

A typical configuration of the roll-to-roll systems usually consists of unwinding, infeeding, printing, drying, cooling, outfeeding and rewinding module as shown in Fig. 1. In printed electronics systems, a drying temperature can be from 50 to 300 degrees Celsius depending on the curing condition of ink. Therefore, thermal strain takes place in a web because of temperature variation in drying sections, and at the same time the Young's Modulus of material varies as well. A thermal strain generates tension disturbance in the span and such a tension disturbance can be a major cause for wrinkle and register error, buckling, etc. It is hard to measure a tension by using tension meter because there is additional cost, lack of installation space.

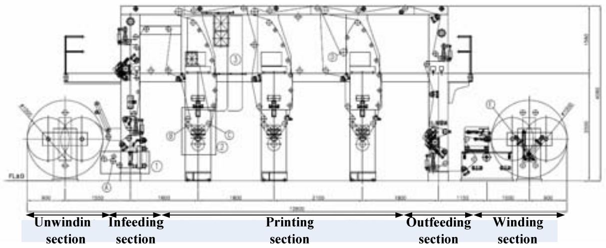

Fig. 1 A typical roll-to-roll gravure printing system

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Consequently, in order to improve productivity and quality of products, it is important to develop the tension control method considering the thermal effect in drying section of roll-to-roll systems. In this study, a mathematical model considering the thermal effect was developed. A new control logic that includes velocity compensator is suggested in order to compensate thermal effect due to temperature change in a dry section without additional instrument. The computer simulation study was carried out to confirm the performance of the suggested tension control method. Experimental results show that the suggested tension control logic improves the performance of tension control in a roll-to-roll system.

2. LIMITATION OF CONVENTIONAL TENSION MODEL

The law of conservation of mass for the control volume as shown in Fig. 2 can be written such as equation (1)(Shin, 200).

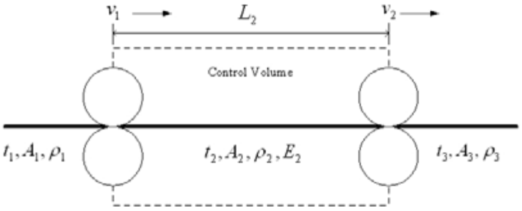


Fig. 2. One-span web transport system

$$\frac{d}{dt}\left(\int_0^L \rho(x,t)A(x,t)dx\right) = \rho_1(t)A_1(t)v_1(t) - \rho_2(t)A_2(t)v_2(t) \quad (1)$$

From equation (1), a nonlinear tension model by Shin (Shin, 2000; Shin and Hong, 1998) can be developed such as equation (2).

$$L_2\frac{d}{dt}\left(t_2(t)\right) = v_1(t)t_1(t) - v_2(t)t_2(t) + EA\left(v_2(t) - v_1(t)\right) \quad (2)$$

Equation (2) describes tension behavior for one-span web transport system when the temperature of the web is normal. But in the case of considering temperature change of substrate as shown in Fig. 3, equation (2) can not properly describe tension behavior for the web because the Young's Modulus and thermal strain of the strip is not uniform within the web span anymore.

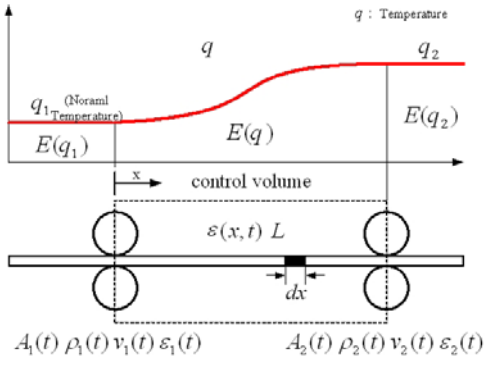


Fig. 3. A web span in temperature change

Therefore, the mathematical tension model must include the following terms to properly describe tension behavior considering temperature change of the web.

1) The thermal strain due to temperature change.

2) The Young's Modulus variation due to temperature change.

3) The thermal coefficient variation due to temperature change.

3. TENION MODEL CONSIDERING TEMPERATURE CHANGE

To develop the tension model considering thermal effect, the following assumptions were made.

1) The temperature distribution within the web span as shown in Fig. 3 is in steady-state, therefore it is not a function of time t (Jeong et al., 1990).

2) The variation of ambient temperature distribution can be ignored due to the small velocity change from a steady-state operating value.

3) The strain within a web is linear combination of elastic strain and thermal strain.

4) The web cross-section does not vary along the web.

An equivalent strain within a web span in Fig. 3 is defined such as equation (3).

$$\varepsilon_{eq}(t) = \frac{1}{L}\int_0^L \varepsilon(x,t)dx \quad (3)$$

Where $\varepsilon(x,t)$ is strain of infinitesimal element dx as shown in Fig. 4. Under assumptions 1) and 3), equation (3) can be rewritten as equation (4).

$$\begin{aligned}\varepsilon_{eq}(t) &= \frac{1}{L}\int_0^L \varepsilon(x,t)dx = \frac{1}{L}\int_0^L \left(\varepsilon^e(x,t) + \varepsilon^{th}(x)\right)dx \\ &= \frac{1}{L}\int_0^L \varepsilon^e(x,t)dx + \frac{1}{L}\int_0^L \varepsilon^{th}(x)dx \\ &= \varepsilon_{eq}^e(t) + \varepsilon_{eq}^{th}\end{aligned} \quad (4)$$

$\varepsilon_{eq}^e(t)$ in equation (4) can be written as equation (5).

$$\varepsilon_{eq}^e(t) = \frac{1}{L}\int_0^L \varepsilon^e(x,t)dx = \frac{t(t)}{AL}\int_0^L \frac{1}{E(x)}dx \quad (5)$$

Defining an equivalent Young's Modulus as equation (6), and calculating ε_{eq}^{th} by using substituting thermal coefficient α, then equation (4) can be written for ε_{eq} within an infinitesimal element dx as equation (7).

$$E_{eq} = \frac{L}{\int_0^L \frac{1}{E(x)}dx} \quad (6)$$

$$\varepsilon_{eq}(t)=\varepsilon^{e}_{eq}(t)+\varepsilon^{th}_{eq}=\frac{t(t)}{AE}+\frac{1}{L}\int_0^L \alpha(x)\big(\theta(x)-\theta_1\big)dx \tag{7}$$

From equations (1) and (3), we can get equation (8) that represents a dynamic relationship between the web strain within the control volume and the velocity at the ends of the web span.

$$L\frac{d}{dt}\big(\varepsilon_{2eq}(t)\big)=\varepsilon_1(t)v_1(t)-\varepsilon_{2eq}(t)v_2(t)+\big(v_2(t)-v_1(t)\big) \tag{8}$$

Combining equations (7) and (8) gives

$$\begin{aligned}L\frac{d}{dt}\big(t_2(t)\big)&=AE_{2eq}\varepsilon_1(t)v_1(t)\\&-t_2(t)v_2(t)+AE_{2eq}\big(v_2(t)-v_1(t)\big)-AE_{2eq}\varepsilon^{th}_{eq}v_2(t)\end{aligned} \tag{9}$$

The tension $t(t)$ is identical to $t_2(t)$ (the tension at out-let of the control volume at Fig. 3.) and $\varepsilon_1(t)$ is the strain at the in-let of control volume. Thus equation (9) can be written as equation (10).

$$\begin{aligned}L\frac{d}{dt}\big(t_2(t)\big)&=\frac{E_{2eq}}{E_{\theta1}}t_1(t)v_1(t)\\&-t_2(t)v_2(t)+AE_{2eq}\big(v_2(t)-v_1(t)\big)-AE_{2eq}\varepsilon^{th}_{2eq}v_2(t)\end{aligned} \tag{10}$$

Equation (10) can be linearized as equation (11) by using the perturbation method.

$$\begin{aligned}\frac{d}{dt}T_2(t)&=\frac{v_{10}E_{2eq}}{LE_{\theta1}}T_1(t)\\&-\frac{v_{20}}{L}T_2(t)+\frac{AE_{2eq}}{L}\big(V_2(t)-V_1(t)\big)-\frac{AE_{2eq}\varepsilon^{th}_{2eq}}{L}v_{20}\end{aligned} \tag{11}$$

Equation (11) is the mathematical model for tension behavior of a moving web considering the temperature change. Finally, multi-span model for tension control can be represented as follow equation (12).

$$\begin{aligned}\frac{d}{dt}T_N(t)&=\frac{v_{N0}E_{N,eq}}{L_NE_{N-1,\theta}}T_{N-1}(t)-\frac{v_{N0}}{L_N}T_N(t)\\&+\frac{AE_{N,eq}}{L_N}\big(V_N(t)-V_{N-1}(t)\big)-\frac{AE_{N,eq}\varepsilon^{th}_{N,eq}}{L_N}v_{N0}\end{aligned} \tag{12}$$

4. PROPOSED FEED-FORWARD CONTROL SCHEME IN A DRYING SECTION

A typical roll to roll system is consist of unwinding, infeeding, printing, drying, cooling, outfeeding and rewinding module as shown in Fig. 4. In a conventional roll to roll system, tension in a printing section including dryer is controlled by controlling the velocities of rollers at either end of the printing span. It is called "open-loop draw control." Because a temperature is too high in dryer of printing sections, it is difficult to install a tension meter such as load cell in printing section. Thus, a draw control is used in printing sections. In the drying sections, the following problems might occur:

1) The tension becomes different by the amount of the thermal strain due to temperature change of the material.

2) Although the elastic strain of each span is equal, the tension is not because the Young's Modulus varies according to temperature of the material.

For this reason, the conventional draw tension control scheme may not suitable for regulating the tension in a section with temperature change.

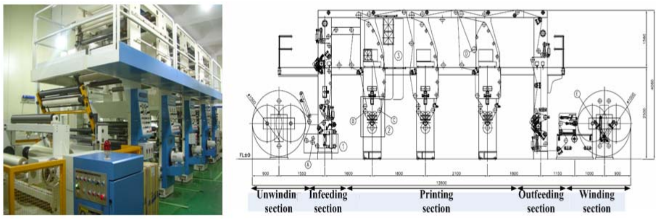


Fig. 4. A roll-to-roll system

Hence, a new feed-forward tension control scheme considering temperature change is proposed as shown in Fig. 5. A key idea in the suggested control scheme is the velocity compensator which estimates the resultant tension variation due to the thermal effect and compensates that variation by changing the velocity of rollers in advance. The structure of the velocity compensator is shown in Fig. 6. The velocity compensator computes equivalent thermal strain and equivalent Young's Modulus from a measured data such as shown in Fig. 7.

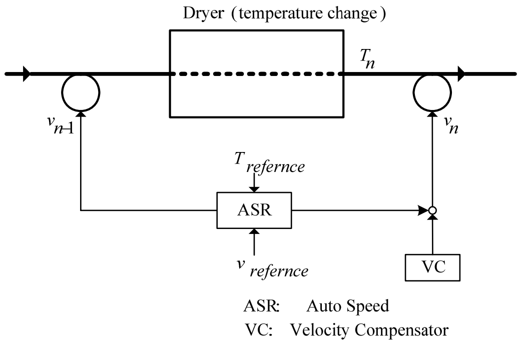


Fig. 5. The configuration of a dry section with proposed control scheme

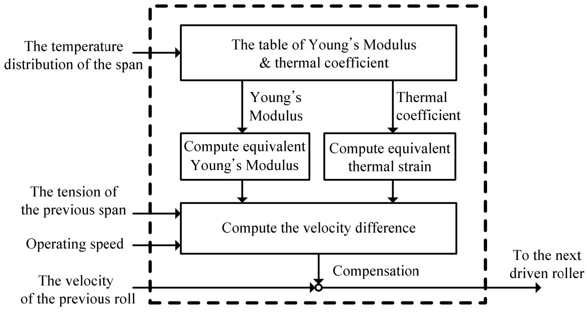


Fig. 6. The structure of the velocity compensator

Then it transforms those into velocity difference using the equation (11). Finally, the velocity compensator adds velocity difference to velocity reference of the ASR (Auto Speed) to eliminate the tension variation due to temperature change in a drying section. For example, assuming that the temperature distribution of each span, Young's Modulus, and thermal coefficient is linear for a specific temperature zone, then the velocity compensation term can be derived from equation (11) as following equation (13).

$$\beta_N = v_{op}\left\{\frac{T_{N-1}(t)}{A}\left(\frac{1}{E_{eq,N}}-\frac{1}{E_{\theta_{n-1}}}\right)+\varepsilon^{th}_{eq,N}\right\} \tag{13}$$

β_N in equation (13) is the value of velocity difference to be compensated between the roll at in-let and the one at out-let in drying section, and it can be used to eliminate the Young's Modulus and thermal coefficient variation due to temperature change. Therefore, even with temperature change in the section, the tensions of each span converge to the one of upstream in steady-state by compensating the velocity difference β_N .

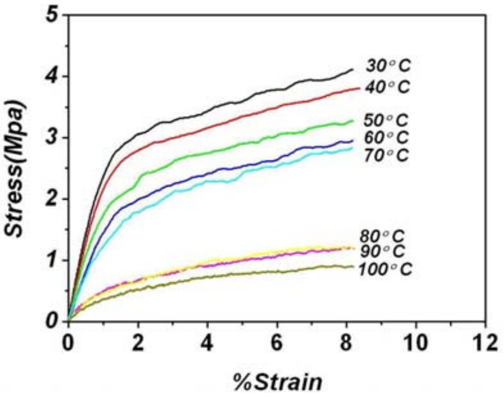


Fig. 7. Stress-strain curve of a substrate (measured data)

5. NUMERICAL SIMULATION RESULTS

A numerical and experimental study for the drying section and the final cooling section has been carried out in order to confirm the limitation of conventional control scheme and to verify the performance of the proposed control scheme.

It was assumed that the property of rolls and motors was identical within the system. The configuration of control scheme for heating section is same as that of Fig. 5. and Fig. 6.

When the temperature is assumed to be uniform in the drying section, the tension behaviors in the drying section are shown in Fig. 8. The Inlet and outlet temperature of dryer is 30 degree. The operating speed is 30 MPM and the substrate is OPP. The tension converges on the reference tension (90N). That is, the tension of drying section can be regulated well by using conventional control scheme with no change in temperature.

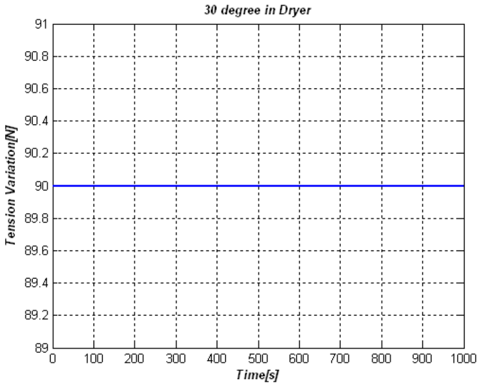


Fig.8. Tension variation in drying sections

But, assuming that there is temperature change in the material as shown in Fig. 3, the tension behaviors in the drying section with conventional control scheme are shown in Fig. 9. The Inlet and outlet temperature of dryer is 30 and 75 degree respectively. The operating speed is 50 MPM and the substrate is OPP.

Fig. 10 shows the result of applying the proposed control scheme to the control of tension in the drying section. The results show that the velocity compensator works well (at 100sec) even with thermal effect (thermal strain and varied Young's Modulus) on tension variation. Therefore in the case of applying the proposed control scheme to a drying section, the thermal effect due to temperature change can be eliminated.

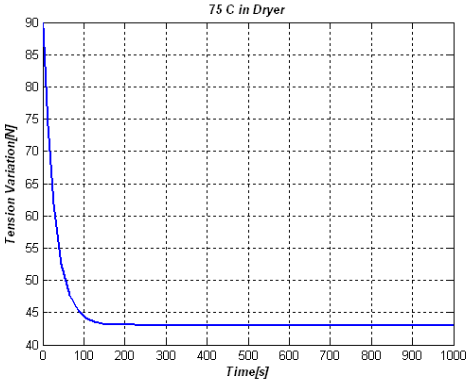
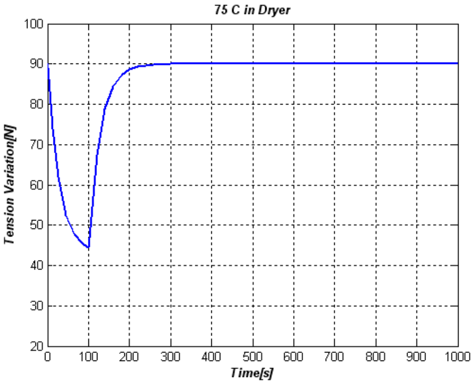
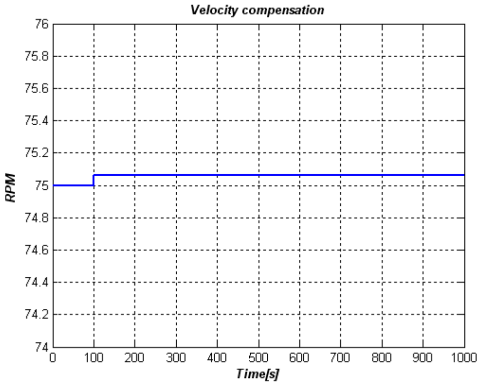


Fig. 9. Tension variation in drying sections



(a) Tension variation



(b) Velocity variation

Fig. 10. Tension and velocity variation in drying section with proposed control scheme under temperature change

6. EXPERIMENTAL RESULTS

Fig. 11 shows the implementation of the proposed feed-forward control logic in roll to roll e-Printing systems. In estimator(PLC), a velocity is calculated to eliminate tension disturbance due to temperature change. The velocity compensator sends a compensation value to motor driver via DeviceNet.

The Inlet and outlet temperature of dryer is 30 and 75 degree respectively. The operating speed is 30 MPM and the substrate is OPP. The operating tension is 100 N and the operating speed is 50 MPM. The substrate is OPP.

The tension behavior in the drying section with conventional control scheme is shown in Fig. 12. The tension goes down due to temperature change, though the reference tension is 100N.

Fig. 13 shows the result of applying the proposed control scheme to the control of tension in the drying section. The experimental results show that the velocity compensator works well (from 3310sec) even with thermal effect (thermal strain and varied Young's Modulus) on tension variation. The tension in drying section converges on the reference tension (100N) after velocity compensation. Therefore in the case of applying the proposed control scheme to a drying section, the thermal effect due to temperature change can be eliminated.

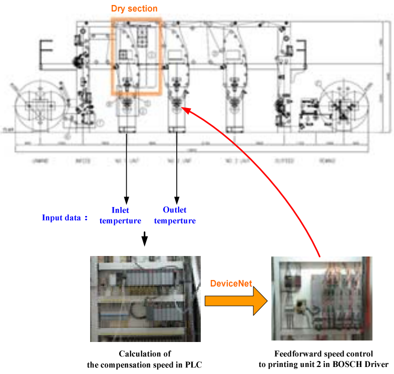


Fig. 11. The flowchart of proposed control scheme

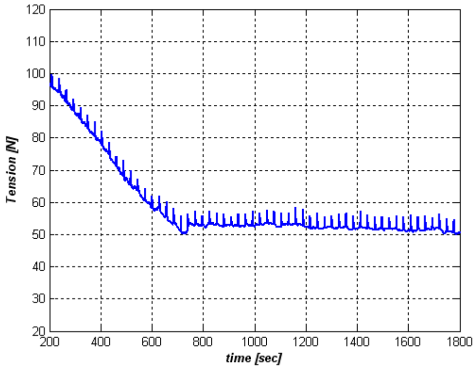


Fig. 12. Tension variation due to temperature change in drying section

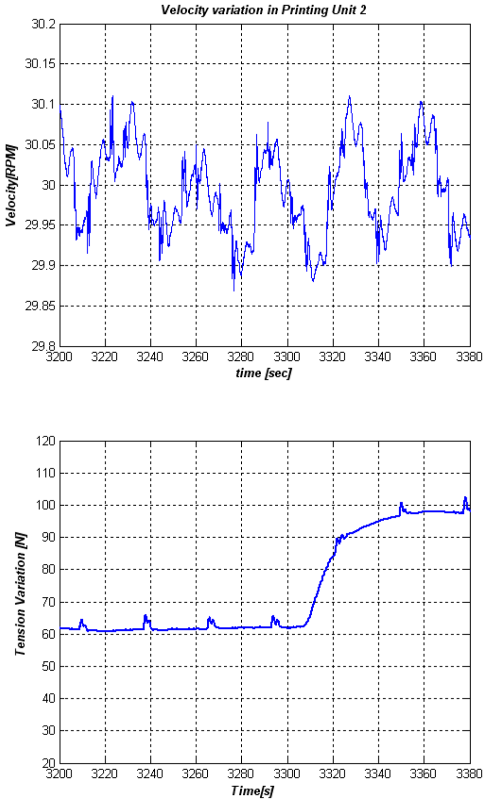


Fig. 13. Experimental results with proposed control scheme

7. CONCLUSIONS

In this paper, a mathematical model for tension behavior considering temperature change is developed in order to study tension behavior of the plants with heating or cooling materials just like in roll to roll e-Printing system. Using the mathematical model developed, we demonstrated that it is impossible to regulate the tension in a section by using the conventional draw control scheme. A new control scheme including velocity compensator for the roll to roll system is proposed in order to overcome the problems of the conventional control scheme.

In order to verify the performance of proposed control scheme, a numerical and experimental study was carried out for a drying section with temperature change. From the results, it is confirmed that the tension variation due to temperature change could be eliminated well by the proposed control scheme in the heating/cooling section of the roll to roll e-Printing systems.

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