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A study on tension behavior considering thermal effects in roll-to-roll E-printing [†]

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Abstract

The mathematical model for tension in a moving web by Shin [1] was extended by considering thermal strain due to temperature fluctuations in the drying of a roll-to-roll system. The extended model describes variations in tension and includes terms that represent the change of the Young's Modulus, the thermal coefficient, and the thermal strain. In this paper, a new control scheme based on the extended model is proposed for mitigation of tension disturbances due to thermal strain in the drying process. Tension feedback control logic generally is not be applied due to the fact that register errors can be induced by speed alterations that help to compensate for tension disturbances. But in our approach, the thermal strain in the web is compensated for by means of velocity adjustments without adding extra register errors in the steady state. A computer simulation followed by an experimental validation was carried out to confirm the performance of the proposed method. The results show that the proposed model is useful for describing tension behavior and suggest that tension control logic improves control precision for the drying module of a roll-to-roll e-printing system.

Keywords: Roll-to-roll; E-printing system; Drying section; Tension control; Thermal coefficient; Thermal strain

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1. Introduction

Typical configuration of a roll-to-roll system consists of unwinding, infeeding, printing, drying, cooling, outfeeding, and rewinding modules (Fig. 1). Roll-to-roll manufacturing involves the continuous transport and processing of prints of consistent width. The drying process, which follows printing, cures a printed pattern onto a substrate. In typical applications of electronic printing systems, the drying temperature can range from 50 °C to 300 °C, according to the curing condition of the ink. Temperatures as high as these can induce thermal strain on a flexible substrate, altering the substrate's Young's Modulus [2]. Tension disturbance induced by thermal strain is a major cause of wrinkles, register errors, and buckling [3, 4]. In general, feedback logic utilizing a load-cell or dancer is employed to control. However, a tension feedback control scheme cannot be applied in the printing phase of a dryer, because speed control of the printing roll is carried out to compensate for the register error between printed patterns on the substrate [3-5], and additional register error could be induced by adjusting the speed of a roll to compensate for tension disturbances. Therefore, a more comprehensive understanding of tension behavior is essential in designing an effective controller to attenuate tension fluctuations due to temperature changes.

Our method is based on a mathematical tension model involving the thermal effects in the drying module of a printing process. The method entails a feed-forward tension control scheme to eliminate tension disturbance due to thermal strain. A computer simulation and experimental studies were carried out to evaluate the performance of the proposed approach, showed improved performance.

2. Limitation of conventional tension model

The law of conservation of mass for the control volume shown in Fig. 2 can be written in the form of Eq. (1).

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

From Eq. (1), a nonlinear tension model that includes the tension transfer phenomenon was developed for the non-slip condition between the web and roller, such that [1-2]:

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

Eq. (2) describes tension behavior for a one-span web trans-

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Fig. 1. Typical roll-to-roll gravure printing system.

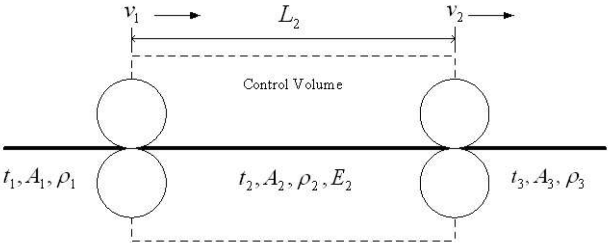


Fig. 2. One-span web transport system.

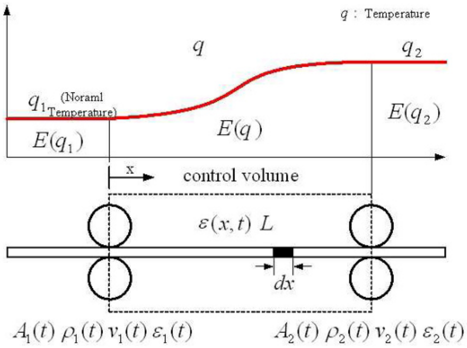


Fig. 3. A web span with temperature change.

port system when the temperature of the web is normal. However, it cannot properly describe the tension behavior of the web at higher temperatures because the Young's Modulus and the thermal strain of the strip are not uniform within the web span, as shown in Fig. 3.

A mathematical model describing the tension must therefore include the following terms:

(1) The thermal strain due to temperature change
(2) The variation in Young's Modulus due to temperature change
(3) The variation in the thermal coefficient due to temperature change

3. Tension model considering temperature change

In developing the proposed model, the following assumptions were made [2, 6, 7]:

(1) the temperature distribution within the web span is a function of distance (not a function of time) in the steady state, as shown in Fig. 3
(2) the variation in ambient temperatures can be ignored due to the small velocity changes from a steady state operating value
(3) the total strain of the moving web is a linear combination of elastic strain and thermal strain
(4) the web cross-section does not vary along the web

Using these assumptions, an equivalent strain within a web span, as shown in Fig. 3, is defined as

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

where $\varepsilon(x,t)$ is the strain of infinitesimal element dx, as shown in Fig. 3. Equation (3) accordingly can be rewritten as

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

where $\varepsilon_{eq}^{e}(t)$ is the equivalent elastic strain and $\varepsilon_{eq}^{th}(x)$ is the equivalent thermal strain. Further, $\varepsilon_{eq}^{e}(t)$ and $\varepsilon_{eq}^{th}(x)$ in Eq. (4) can be written as

$$\begin{aligned}\varepsilon_{eq}^{e}(t) &= \frac{1}{L}\int_0^L \varepsilon^{e}(x,t)dx = \frac{t(t)}{AL}\int_0^L \frac{1}{E(x)}dx \\ \varepsilon_{eq}^{th}(x) &= \frac{1}{L}\int_0^L \alpha(x)\left(\theta(x) - \theta_1\right)dx\end{aligned} \tag{5}$$

where α is the thermal coefficient of the substrate, θ_1 being the inlet temperature of a span. We formulated an equivalent Young's modulus as

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

Next, we calculated ε_{eq}^{th} by substituting the thermal coefficient within an infinitesimal element dx as

$$\varepsilon_{eq}(t) = \varepsilon_{eq}^{e}(t) + \varepsilon_{eq}^{th} = \frac{t(t)}{AE_{eq}} + \frac{1}{L}\int_0^L \alpha(x)\left(\theta(x) - \theta_1\right)dx \tag{7}$$

From Eqs. (2) and (3), we obtained Eq. (8) which represents the dynamic relationship between the web strain within the control volume and the velocity at the ends of the web span:

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

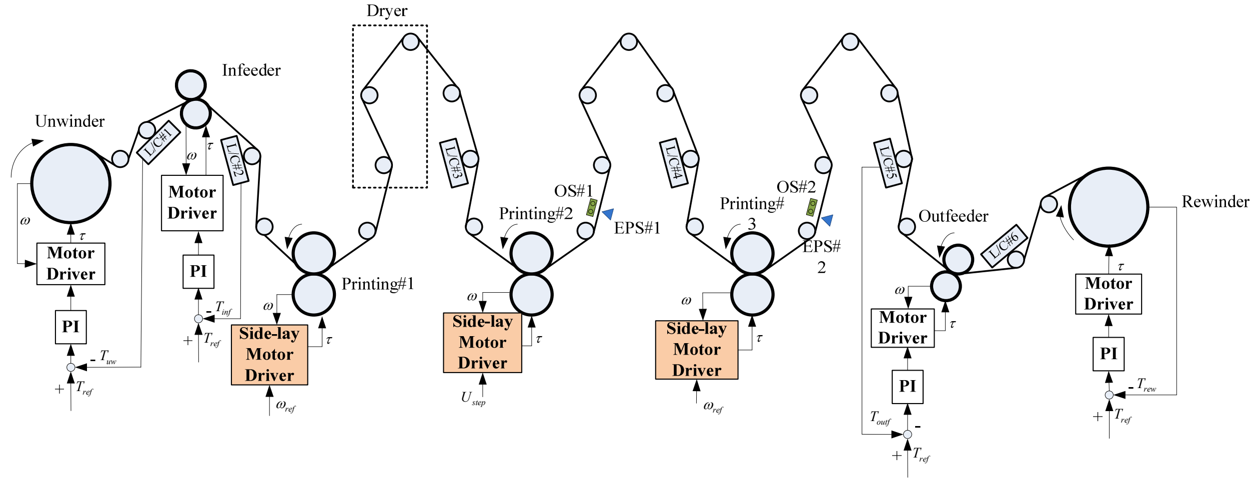


Fig. 4. Schematic of roll-to-roll printing system.

Combining Eqs. (7) and (8) yields

$$L\frac{d}{dt}\left(t_2(t)\right) = AE_{2eq}\varepsilon_1(t)v_1(t) - t_2(t)v_2(t) + AE_{2eq}\left(v_2(t)-v_1(t)\right) - AE_{2eq}\varepsilon_{eq}^{th}v_2(t) \tag{9}$$

The tension $t(t)$ is identical to $t_2(t)$ (the tension at the outlet of the control volume in Fig. 3, and $\varepsilon_1(t)$ is the strain at the inlet of the control volume. Thus, Eq. (9) can be written as

$$L\frac{d}{dt}\left(t_2(t)\right) = \frac{E_{2eq}}{E_{\theta 1}}t_1(t)v_1(t) - t_2(t)v_2(t) + AE_{2eq}\left(v_2(t)-v_1(t)\right) - AE_{2eq}\varepsilon_{2eq}^{th}v_2(t) \tag{10}$$

Eq. (10) can be linearized using the perturbation method as follows:

$$\frac{d}{dt}T_2(t) = \frac{v_{10}E_{2eq}}{LE_{\theta 1}}T_1(t) - \frac{v_{20}}{L}T_2(t) + \frac{AE_{2eq}}{L}\left(V_2(t)-V_1(t)\right) - \frac{AE_{2eq}\varepsilon_{2eq}^{th}}{L}v_{20} \tag{11}$$

Eq. (11) is a mathematical tension model of a moving web that considers temperature changes in a single span. The model can be extended for multiple spans as follows:

$$\frac{d}{dt}T_N(t) = \frac{v_{N,0}E_{N,eq}}{L_N E_{N-1,\theta}}T_{N-1}(t) - \frac{v_{N,0}}{L_N}T_N(t) + \frac{AE_{N,eq}}{L_N}\left(V_N(t)-V_{N-1}(t)\right) - \frac{AE_{N,eq}\varepsilon_{N,eq}^{th}}{L_N}v_{N,0} \tag{12}$$

4. Model-based feed-forward tension control scheme for a drying section

In general, tension in a printing process that includes a dryer (Fig. 4) is controlled by adjusting the velocities of the printing rollers at either end of the printing span without tension feedback (i.e., "open-loop draw control"). It is difficult to install tension meters such as a load cell because the temperature is high in the dryer of a printing section, and space for the equipment is usually insufficient. Furthermore, a tension feedback scheme is impossible because in steady state, speed control to compensate for register errors should be carried. That is to say, an additional register error could be induced if tension feedback control in consideration of thermal strain is carried out. Therefore, an open-loop draw control normally is employed. However, the conventional draw tension control scheme based on the conventional tension model [1] is not suitable for attenuating tension disturbances due specially to the thermal variations involved.

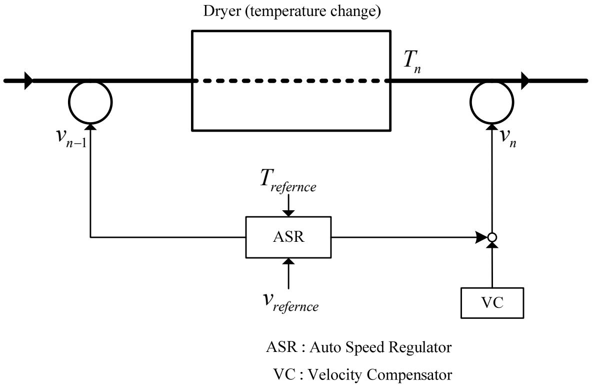


Fig. 5. Configuration of the proposed control scheme in a drying section.

In the present study, the feed-forward tension control scheme illustrated in Fig. 5 was developed. Fig. 6 shows the operation of a velocity compensator, which estimates the resultant tension variation due to thermal effects, and compensates for the tension disturbance by adjusting the speed of a printing roller in advance. The velocity compensator computes equivalent thermal strain and the equivalent Young's Modulus from the mechanical characteristics of the substrate (Fig. 7). Finally, the compensator adds the velocity difference to the reference of the auto speed regulator (ASR) to eliminate ten-

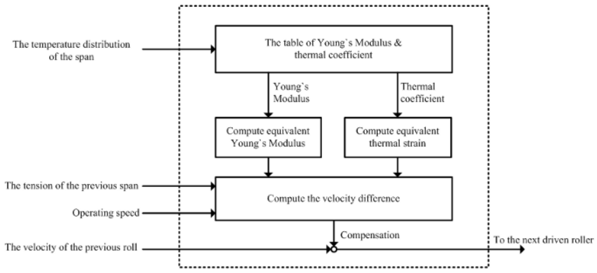


Fig. 6. Structure of the velocity compensator.

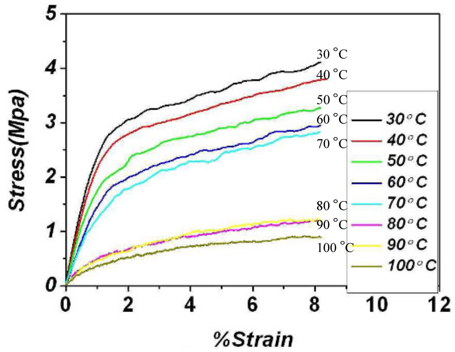


Fig. 7. Measured stress-strain curve of a substrate according to temperature.

sion disturbances due to temperature changes in the drying process. Speed compensation β_N from Eq. (13) could be derived from Eq. (12), because downstream tension converges into an upstream tension in the steady state ($\lim_{t\to\infty} T_N(t) = T_{N-1}(t)$). β_N in Eq. (13) was calculated using Eqs. (5) and (6) for a given temperature in the dryer. Therefore, by compensating for the velocity β_N, the tensions of each span converge into the upstream tension in the steady state, even with a temperature change in the drying process.

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

5. Experimental verification

A numerical simulation and experimental studies were carried out to evaluate the performance of the proposed model and feed-forward tension control method. It was assumed that the properties of rolls and motors were identical within the system. The configuration of the control scheme for the drying section is shown in Figs. 5 and 6. The tension converged on the operating tension (100 N) when the temperature in the dryer was 30°C. That is, the tension (dotted line in Fig. 8) can be well regulated using a conventional open-draw control scheme at room temperature. However, the tension (solid line in Fig. 8) was decreased due to the increased temperature in the drying module. Note that additional thermal strain was induced when the operating temperature increased (see Fig. 7). As discussed in the previous section, a tension feedback scheme generally cannot be used to control the tension of a moving web in the drying process, because unwanted register errors can be generated by compensating for tension disturbances.

Table 1. Simulation conditions.

Variables	Values
Operating tension [N]	100
Operating speed [m/min]	50
Substrate	OPP
Width of substrate [m]	1.1
Thickness of substrate [m]	0.000012
Temperature of the dryer [°C]	75
Length of the dryer [m]	5
Young's Modulus in room temperature [N/m^2]	1182

Fig. 9(a) shows the tension behavior of a moving web in the drying module. In the early stages of the drying process, the tension is decreased from the operating tension to 54 N when the temperature is 75°C. In order to compensate for the tension disturbance, the adjusted speed can be estimated by means of the developed model with reference to the temperature of the dryer, as shown in Fig. 9(b), after which the speed compensation can be applied at 1500 sec. From the mechanical characteristics such as the stress-strain curve of a flexible substrate with respect to temperature (Fig. 7), the equivalent thermal strain of 0.002015 is calculated for a given temperature condition and speed variation using Eq. (5). Finally, the velocity compensation value (30.06 RPM) for countering thermal defects is estimated using Eq. (13). The induced tension disturbances due to thermal strain and varied Young's Modulus are compensated for after applying the proposed feed-forward control scheme, as shown in Fig. 9(a). In general, the drying temperature is fixed in consideration of the curing condition of a ink used. Therefore, the tension disturbance due to thermal effects can be prevented, because the input value is the temperature of the dryer in the proposed mathematical model. The parameters used in the simulation are tabulated in Table 1.

Fig. 10 represents the signal flow of the proposed feed-forward logic. The main controller (SLC 501, Allen Bradley) calculated the speed compensation required to eliminate tension disturbances, and sent the command signals to the motor driver (INDRA-DRIVE, BOSCH) via device-net. The tension variation of the moving web was measured at the outlet in the dryer by a load cell (LM-PC, MITSUBISHI). The parameters

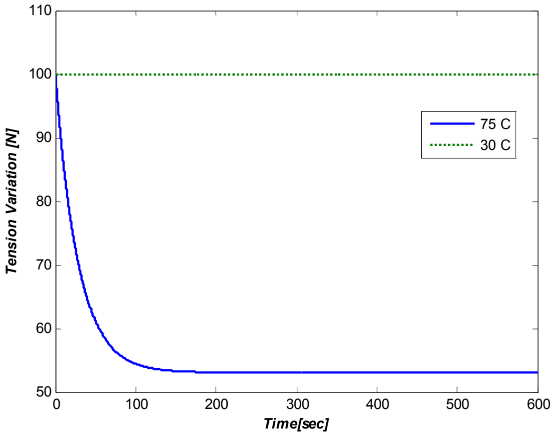
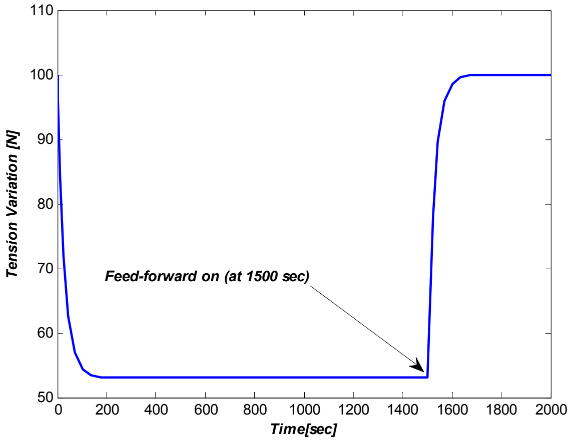
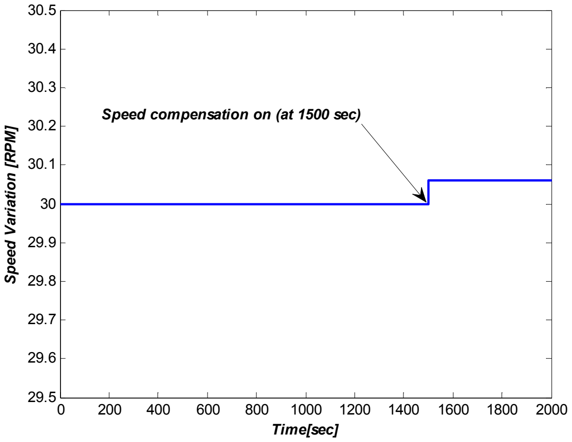


Fig. 8. Tension variation in printing process.



(a) Tension variation in drying process



(b) Speed compensation for countering tension disturbance

Fig. 9. Tension and velocity variation in drying process with proposed control scheme under temperature change.

for the experiments are identical to those listed in Table 1.

Figure. 11 shows the experimental results. The tension was decreased from the operating tension of 100N to 51N under high temperatures (75°C). Using Eq. (13), the speed compensation value was calculated on the basis of the estimated thermal strain and varied Young's Modulus for given inlet and outlet temperatures of the dryer. The speed value was sent to the motor drive at 3310 sec, as shown in Fig. 12(a). As a result, the tension in the drying module converged on the reference tension (100 N), as shown in Fig. 12(b). The analytical (see Fig. 8) and experimental (see Fig.11) results showed the same trend, though the measured tension value were slightly lower than predicted. This phenomenon appears again in Fig. 12. The prediction (see Fig. 9) followed the same trend as the measured data, except that the measured curve fell below the predicted tension of a moving web. One possible reason for the discrepancy is that the temperature distribution in the dryer was not uniform, even though the temperature of the air was

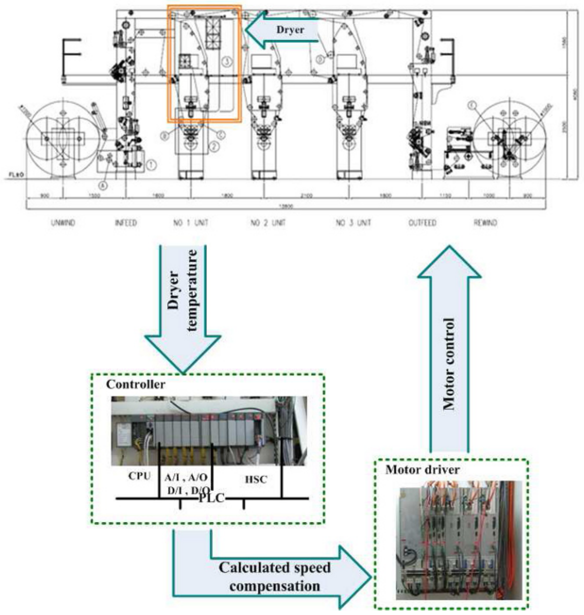


Fig. 10. Schematic of feed-forward logic.

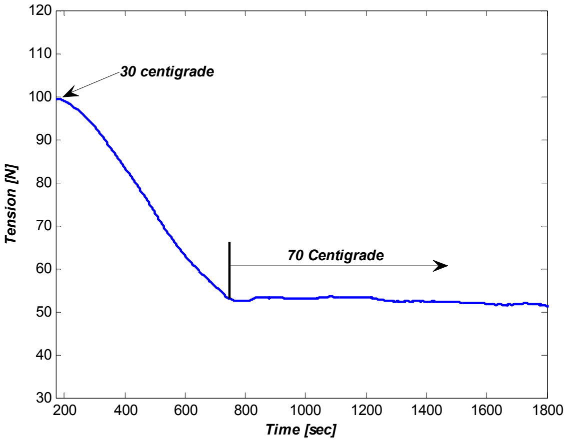
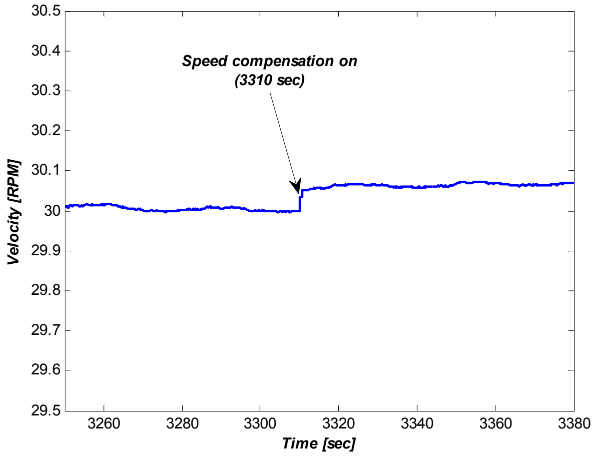
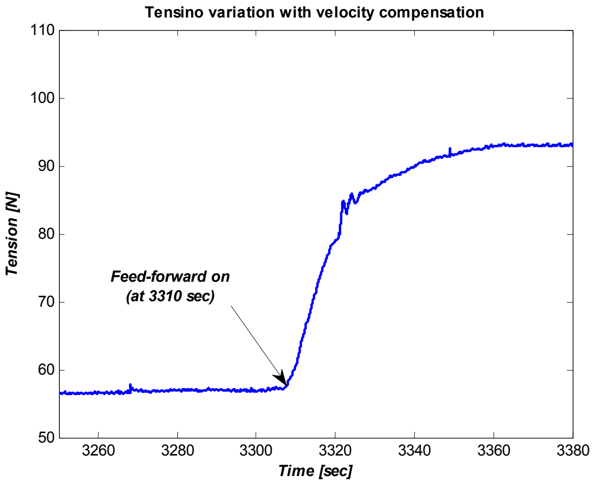


Fig. 11. Tension variation due to thermal effect in drying process before FF compensation.



(a) Speed compensation for rejecting the tension disturbance



(b) Tension variation in a drying section after FF compensation

Fig. 12. Experimental results of tension and velocity variation in drying section with proposed control scheme under temperature change.

controlled by a heater. The average temperature was around 75°C, but in the area of the dryer, the temperature varied from 73°C to 82°. This temperature error could be due to the fact that, for a large dryer volume and a hot-air heat source, temperature variations within the dryer are wider. The width and length of the dryers used were 0.5 and 5 m, respectively.

6. Conclusion

A mathematical model of tension behavior considering temperature change was developed to predict the tension of a moving web in a roll-to-roll printing system, and the performance of the model was experimentally verified. Generally, no tension feedback scheme is applied to printing processes because, in compensating for tension disturbances, additional misalignment (register error) between printed layers can be incurred. Thus, a speed-feed-forward logic for minimizing thermal defects, by means of the developed model, is here proposed. The experimental results show that the dynamic model is very useful in describing tension behavior in a printing module with a dryer. The proposed feed-forward logic, additionally, is very effective in attenuating tension disturbances due to thermal strain.

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Nomenclature

A : Cross-sectional area of web.
E : Young’s modulus.
L : Length of span.
T : Change in web tension from a steady-state operating value.
t : Tension of web.
V : Change in 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.

Subscripts

eq : Equivalent
N : Index
op : Steady-state operating value

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