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Cross direction register modeling and control in a multi-layer gravure printing †

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Abstract

For the adaptation of the roll-to-roll printing method to printed electronics, it is mandatory to increase the resolution of the register control. Therefore, it is desired to derive a mathematical model for the register and to develop a controller to reduce register error. The mathematical model of cross direction register was derived considering both a lateral motion of a moving web and a transverse position of a printing roll. The proposed mathematical model could be used to improve the performance of the cross direction (CD) register controller in a large area, roll-to-roll printing machine. The mathematical model was validated by numerical simulations and experimental verifications in various operating conditions using a multi-layer direct gravure printing machine. The results showed that the proposed model was effective in predicting the CD register in multi-layer printing.

Keywords: 2-D Register; Mathematical modeling; Roll-to-roll; Gravure printing; Printed electronics

1. Introduction

Rising demand for the fabrication of flexible electronics using roll-to-roll technology greatly challenges researchers to demonstrate printing trials with low cost and high productivity. Most demonstrations are conducted using discrete printing method such as sheet printing, ink-jet printing, and spin coating due to the high accessibility and ease of experimentation with less amount of required material [1-6]. Other researchers have carried out laboratory-scale continuous printing with gravure, flexography, offset, and so on [7-12], but it is not sufficient to cover for the adaptation of large area, continuous roll-to-roll printing for printed electronics. If there are several printing rolls between the unwinder and rewinder for multi-layer patterning, not only does each printing roll has a phase variation but the web also goes along the path with a lateral movement and strain variation. Thus, the strain and lateral position of the substrate should be controlled to minimize the register errors in successive roll-to-roll printing.

The register error of a moving web is defined in two printing rollers as a relative difference of the distance between the previous printed pattern in the upstream printing roller and the printed pattern in the downstream printing roller. The register error is defined as two-dimensional errors, machine direction (MD), and cross direction (CD) errors, as shown in Fig. 1.

The register error is as critical as the surface topography in ensuring that the functionality of the printed circuit is without fault. It determines the printing quality of the final product. In addition, printing quality is more important in printed electronics because short or leakage could occur due to the register error of multi-layered patterns in printed electric devices such as organic photovoltaic and flexible display. Therefore, the register error of a moving web should be precisely controlled for the fabrication of printed electronics.

Brandenburg derived a linear mathematical model of the MD register of a moving web in a first-order differential equation using an equilibrium equation of mass transported by the printing rolls. A non-interacting control method between tension and cut-off register error was also proposed [13-14]. Yoshida proposed a nonlinear MD register controller to compensate for a downstream register error caused by an upstream tension fluctuation in gravure printing. Komatsu developed a delay-dependent nonlinear control approach by adjusting a new coordinate and delay-dependent feedback law [15-16].

All of these results were carried out with a typical assumption that the lateral position of a moving web is not changed in the machine direction; thus, there is no CD register error in the multi-layered printed patterns. The lateral position of a moving web varies along the web path within a certain range, and it causes the CD register errors in the printed patterns. For this reason, it is necessary to derive a mathematical model for the CD register for a more accurate register control, but there has been no research yet that deals with the dynamics of the CD

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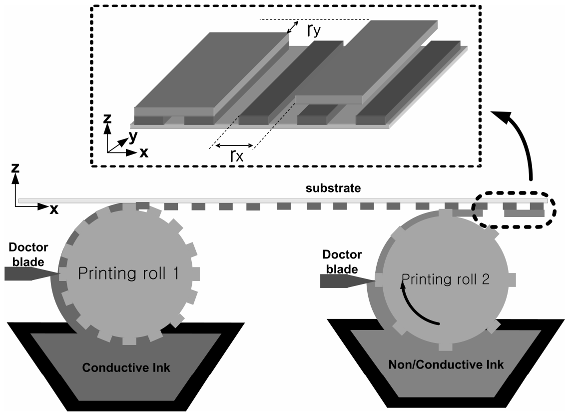


Fig. 1. Two-dimensional register errors.

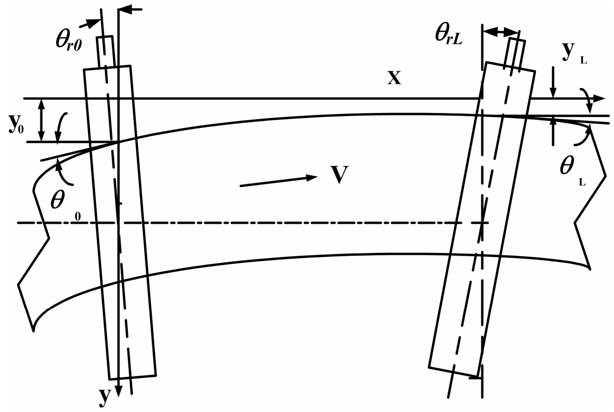


Fig. 2. Boundary conditions.

register.

In this paper, the mathematical model of the CD register was derived using both the lateral dynamics of a moving web and the relative difference of the lateral positions between the printing roll and the web, which goes through the printing section.

The CD register error was controlled by the translational motion of a printing roll; the translation generated transient CD register errors in the downstream printing sections. The mathematical model was validated by numerical simulations and was verified by experimental studies for several operating conditions.

The results showed that the proposed model was effective in predicting the CD register in multi-layer printing.

2. Mathematical modeling

2.1 Second-order lateral motion of a moving web

In this section, the modeling of the lateral motion of a moving web, which was suggested by Shelton, is summarized. The modeling of the CD register was derived using the lateral motion of a moving web including the translations of the printing roll [17, 18]. Shelton derived the first- and second-order models of the lateral motion of a web. The lateral motion can be described more accurately by the second-order model than the first-order. Thus, the second-order model was summarized and used for the derivation of the CD register.

The differential equation of the web elastic curve can be derived from the beam theory if the tension acts on the web. The beam equation, which is a fourth-order differential equation, is shown in Eq. (1). Eq. (2) is a general solution of Eq. (1). The boundary conditions shown in Fig. 2 can be used to determine the coefficients of Eq. (2). The boundary conditions are shown in Eq. (3).

$$\frac{\partial^4 y}{\partial x^4} - K^2 \frac{\partial^2 y}{\partial x^2} = 0, \quad K^2 = \frac{T}{EI} \tag{1}$$

where EI is the bending stiffness.

$$y = C_1 \sinh(Kx) + C_2 \cosh(Kx) + C_3 x + C_4 \tag{2}$$

$$y(0) = y_0,\ \theta(0) = \theta_0,\ y(L) = y_L,\ \theta(L) = \theta_L \tag{3}$$

Using Eq. (2), the curvature of the downstream roll can be obtained as Eq. (4).

$$\left.\frac{\partial^2 y}{\partial x^2}\right|_{x=L} = \frac{f_1(KL)}{L^2}(y_0 - y_L) + \frac{f_2(KL)}{L}\theta_L + \frac{f_3(KL)}{L}\theta_0 \tag{4}$$

where
$$f_1(KL) = \frac{(KL)^2(\cosh(KL)-1)}{KL\sinh(KL) - 2\cosh(KL) + 2},$$
$$f_2(KL) = \frac{KL\left(KL\cosh(KL) - \sinh(KL)\right)}{KL\sinh(KL) - 2\cosh(KL) + 2},$$
$$f_3(KL) = \frac{KL\left(\sinh(KL) - KL\right)}{KL\sinh(KL) - 2\cosh(KL) + 2}$$

The lateral velocity of a web is shown in Eq. (5), and the lateral acceleration is given by Eq. (6).

$$\frac{dy_L}{dt} = V(\theta_r - \frac{\partial y_L}{\partial x}) + \frac{dw_L}{dt} \tag{5}$$

$$\frac{d^2 y_L}{dt^2} = V^2 \left.\frac{\partial^2 y}{\partial x^2}\right|_L + \frac{d^2 w_L}{dt^2} \tag{6}$$

where $\partial y_L / \partial x$ is the slope of the web at the downstream roll.

Substituting Eq. (4) and (5) into Eq. (6), the second-order differential equation can be derived as Eq. (7).

$$\frac{d^2 y_L}{dt^2} = a_1 \frac{dy_L}{dt} + a_2 y_L + a_3 \frac{dy_0}{dt} + a_4 y_0 + a_5 u_L + a_6 u_0 + b_1 \frac{d^2 w_L}{dt^2} + b_2 \frac{dw_L}{dt} + b_3 \frac{dw_0}{dt} \tag{7}$$

$$\theta = \frac{\partial y}{\partial x},\ \theta_r = \frac{u}{c},\ \tau = \frac{L}{V}, a_1 = -\frac{f_2(KL)}{\tau}, a_2 = -\frac{f_1(KL)}{\tau^2},$$

where $a_3 = -\frac{f_3(KL)}{\tau}, a_4 = \frac{f_1(KL)}{\tau^2}, a_5 = \frac{V^2}{Lc} f_2(KL),$

$$a_6 = \frac{V^2}{Lc} f_3(KL), b_1 = 1, b_2 = \frac{f_2(KL)}{\tau}, b_3 = \frac{f_3(KL)}{\tau}$$

In the printing section, the CD register error should be controlled only by the translational motions of the printing roller so that the lateral motion of Eq. (7) yields Eq. (8). The transfer function, that is, the response of y_L to the input of y_0, w_u, and w_0, can be derived as Eq. (9).

$$\frac{d^2 y_L}{dt^2} = a_1 \frac{dy_L}{dt} + a_2 y_L + a_3 \frac{dy_0}{dt} + a_4 y_0 + b_1 \frac{d^2 w_L}{dt^2} + b_2 \frac{dw_L}{dt} + b_3 \frac{dw_0}{dt} \tag{8}$$

$$Y_L(s) = A(s) Y_0(s) + B(s) W_L(s) + C(s) W_0(s) \tag{9}$$

where $A(s) = \frac{a_3 s + a_4}{s^2 - a_1 s - a_2}, B(s) = \frac{b_1 s^2 + b_2 s}{s^2 - a_1 s - a_2},$ $C(s) = \frac{b_3 s}{s^2 - a_1 s - a_2}$

2.2 Cross direction register modeling

The schematic view of the three-layer printing system, which has three printing rolls, is shown in Fig. 3. When the second printing roll prints a pattern on the web, the CD register is produced by the relative difference of the lateral position of both successive printing roll and the moving web. The CD register may occur due to the relative distance of the printing roll even with a straight moving web. Furthermore, there are no translations of the printing roll present, and the CD register is induced by a variation of the lateral positioning of a moving web. Accordingly, it is significant to control the lateral position of both the web and the printing roll and to compare the lateral position of the upstream traveling pattern with the current printing of the pattern for the CD registration.

The CD register is composed of two patterns, which imply the history of printing as a period of time constant (L/V). This means that the upstream pattern (roll No. 1 in Fig. 3.) made ahead of the "time constant" and the current being-printed pattern in the downstream (roll No. 2 in Fig. 3.) complete the definition of CD register in Eq. (10).

$$r_{y,n}(t) = [y_n(t) - w_n(t)] - [y_{n-1}(t-\tau) - w_{n-1}(t-\tau)] \tag{10}$$

where $r_{y,i}(t)$ is the i-th CD register, $y_i(t)$ is the lateral position of the i–th web, and $w_i(t)$ is the lateral position of the i-th roll.

The lateral position of a moving web is calculated by Eq. (9), while the lateral position of a printing roll is the input value of the translational motion. Eq. (10) can be Laplace-transformed as Eq. (11).

$$R_{y,n}(s) = [Y_n(s) - W_n(s)] - [Y_{n-1}(s) - W_{n-1}(s)] e^{-\tau s} \tag{11}$$

Under the assumption that all spans, which are structured between printing rolls, have the same length, Eq. (9) of the lateral positioning of the web can be expanded as Eq. (12).

$$\begin{aligned} Y_{n-1}(s) &= A(s) Y_{n-2}(s) + B(s) W_{n-1}(s) + C(s) W_{n-2}(s) \\ Y_n(s) &= A(s) Y_{n-1}(s) + B(s) W_n(s) + C(s) W_{n-1}(s) \end{aligned} \tag{12}$$

Substituting Eq. (12) into (11) and rearranging the resulting equation gives Eq. (13).

$$\begin{aligned} R_{y,n}(s) &= A(s)\left[Y_{n-1}(s) - Y_{n-2}(s) e^{-\tau s}\right] \\ &+ B(s)\left[W_n(s) - W_{n-1}(s) e^{-\tau s}\right] \\ &+ C(s)\left[W_{n-1}(s) - W_{n-2}(s) e^{-\tau s}\right] \\ &- \left[W_n(s) - W_{n-1}(s) e^{-\tau s}\right] \end{aligned} \tag{13}$$

In addition, the roll-to-roll printing machine consists of many idle rolls in the middle of the printing sections, as shown in Fig. 4, which are for the prevention of the wrinkling of a moving web or the constitution of the structures of the desired path for dryers, prevention of slippage, and so on. As a result, Eq. (10) of CD register should be expanded to include idle rolls as in Eq. (14). Substituting Eq. (12) of the lateral positioning of the web into Eq. (14) and Laplace-transforming it gives Eq. (15).

$$r_{y,n}(t) = [y_n(t) - w_n(t)] - [y_{n-m}(t-\tau_m) - w_{n-m}(t-\tau_m)] \tag{14}$$

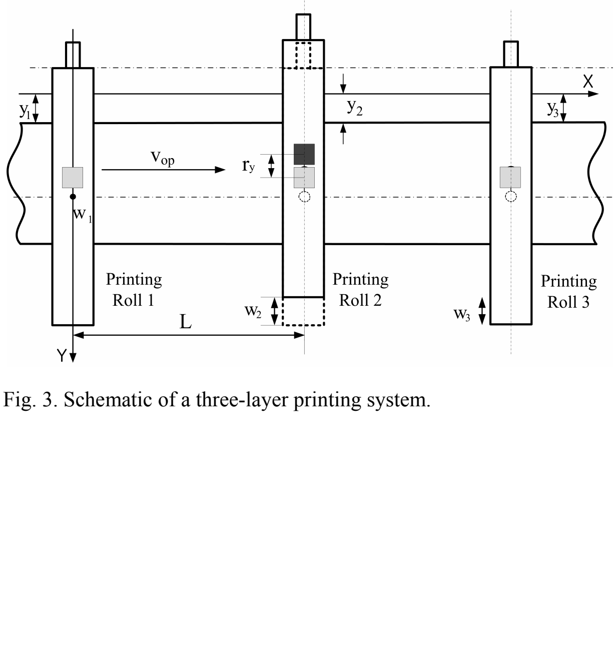


Fig. 3. Schematic of a three-layer printing system.

Table 1. Simulation conditions.

Operating tension (N)	100
Operating velocity (m/min)	30
Length of span between idle rolls (m)	1
Length of span between printing rolls (m)	8
Proportional gain of CD register controller	0.01
Derivative gain of CD register controller	0.15
Young's modulus of substrate (GPa)	3.6
Width of substrate (m)	1
Thickness of substrate (micron)	12

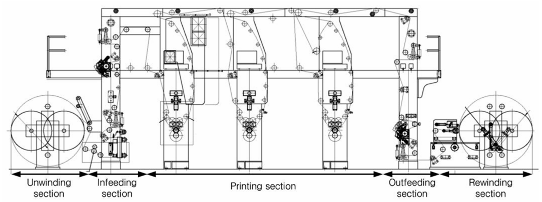


Fig. 4. Three-layer gravure printing machine.

$$R_{y,n}(s) = A(s)^{m-1}\left[A(s)B(s)+C(s)\right]W_{n-m}(s) + B(s)W_n(s) - W_n(s) + W_{n-m}(s)e^{-\tau_m s} - B(s)W_{n-m}(s)e^{-\tau_m s} \quad (15)$$

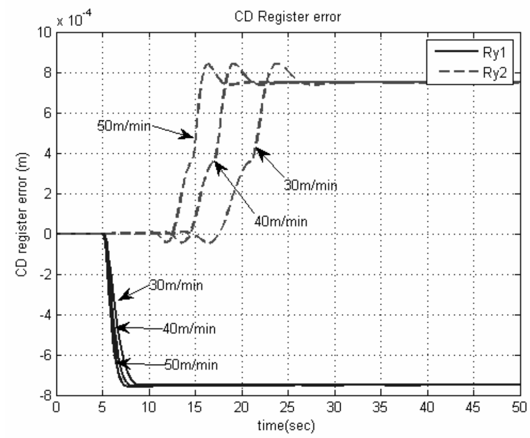
where m is the number of spans between a pair of printing rolls structured by idle rolls.

3. Numerical simulations

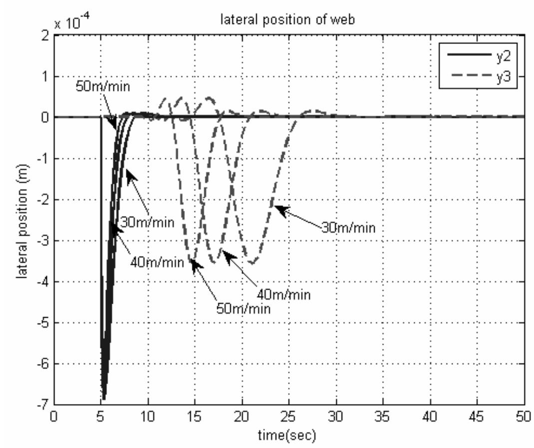
The numerical simulations to validate the proposed modeling of CD register were carried out in various velocity conditions. The simulation model is composed of three printing rolls and idle rolls, as shown in Fig. 4, using MATLAB SIMULINK. The simulation conditions are summarized in Table 1.

The translational motion of the second printing roll was generated as an input at 5 s and 0.75 mm. The step response of the CD register and lateral position is illustrated in Fig. 5(a) and (b), respectively. The input caused a transient lateral disturbance of the second printing roll at 5 s, and the disturbance was transferred to the downstream printing roll with a time delay(L/V) as shown in Fig. 5(b).

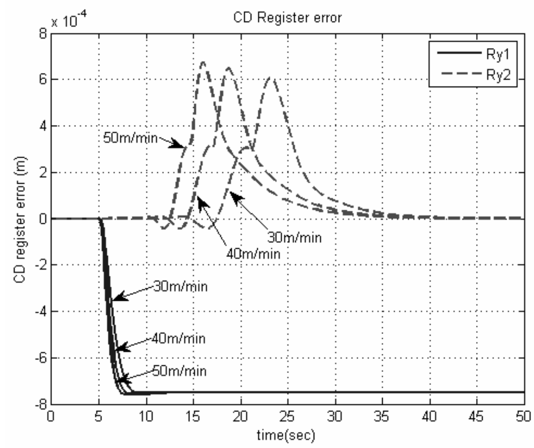
As the operating velocity was increased, the time delay was decreased as well. The dynamics of the lateral motion and translations of the printing roll are related to the characteristics of CD register errors. The translation had the same magnitude and took the opposite direction as the CD register, as shown in Fig. 5 (a). Fig. 5 (c) shows the performance of the proportional-derivative controller of the CD register. As the velocity increased, the overshot increased as well, but the settling time was decreased.



(a) CD registers error at the second and third printing rolls



(b) Lateral positions of the web at the second and third printing rolls



(c) CD registers error using the feedback control of R_{y2}.

Fig. 5. Numerical simulation results.

4. Experimental verification

Experimental studies were performed to verify the CD register model using a three-layer gravure printing machine. The experimental setup is shown in Fig. 6. Figs. 7-9 show the system configurations of the experiment. The system includes unwinding,

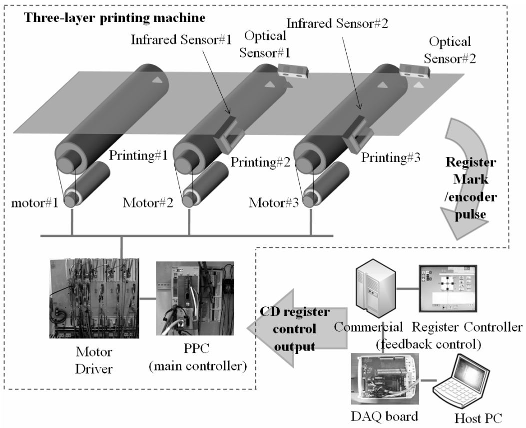


Fig. 6. Experimental setup.

Fig. 7. Three-layer gravure printing machine.

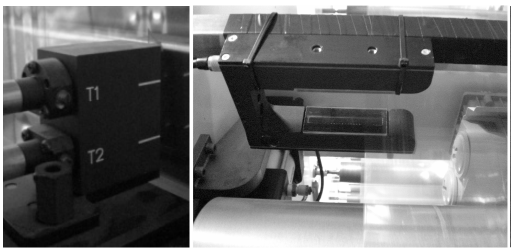


Fig. 8. Optical sensor for the printed mark (left) and infrared sensor for lateral position of web (right).

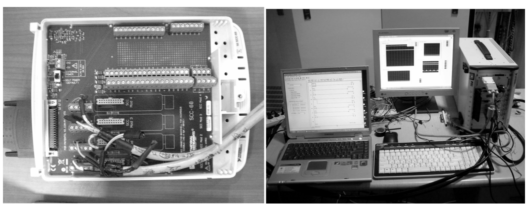
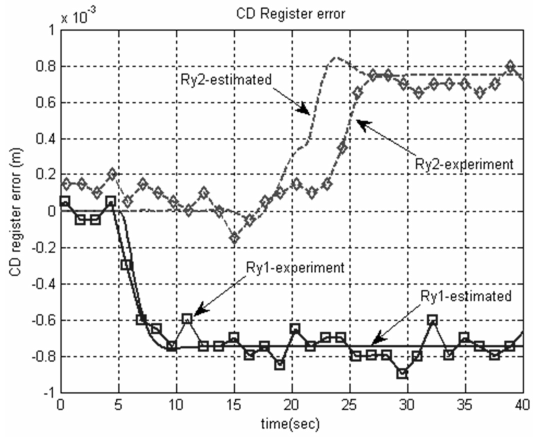
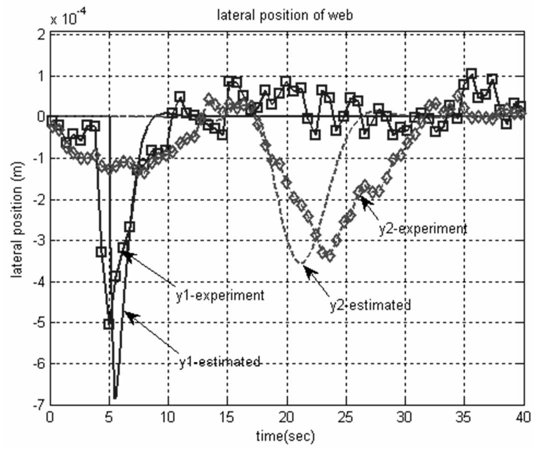


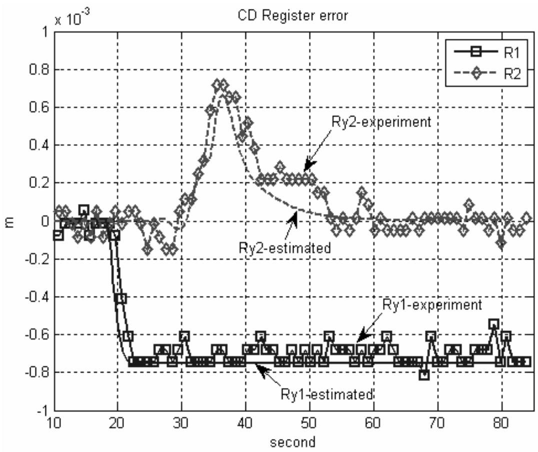
Fig. 9. DAQ systems for data collecting.



(a) Estimated and experiment CD register errors



(b) Estimated and experiment Lateral positions



(c) Estimated and experiment CD registers with PD control

Fig. 10. CD register errors and lateral position (100N, 30m/ min).

rewinding, infeeding, outfeeding, three printing rollers, commercial register controller (ArTec. Co), and main controller (Bosch Rexroth, PPC). In each span, tensions were measured by the load-cell (Dover, Model C2DFL) with an amplifier (Dover, TI17). The register marks were measured by an optical sensor and amplifier (ArTec Co.), as shown in Fig. 8. The lateral position of a moving web was measured by an Edge Position Sensor (EPS), infrared sensor (FIFE, SE-23) with amplifier, as also shown in Fig. 8. Data acquisition software, LabView 8.2 (National Instruments), was used for collecting and saving the signal of the loadcell, infrared sensor, and optical sensors with a DAQ board (National Instruments, SCC-68) and an A/D converter (National Instruments, PXI-6251), as shown in Fig. 9.

The step responses of the lateral position and CD register caused by the translation of the second printing roll are depicted in Fig. 10(a), (b), and (c). The translational motion of the second printing roll created a transient lateral disturbance, and it transferred to the downstream after a time delay (L/V), as shown in Fig. 10(b). The other side is the translation-induced steady-state CD register errors, which are of the same magnitude and in the reverse direction, as shown in Fig. 10 (a). The experimental results and simulations of the derived model were almost the same in the upstream CD register of R_{y1}, as shown in Fig. 10(a). On the other hand, the downstream CD register of R_{y2} had a 3 s delay and the same steady state value. The difference in the settling time of R_{y2} between the estimation and experiment results is due to the modeling error, mechanical loss, and cross-directional slip between the web and the nip roller in printing. The span lengths of the printing section structured by the idle rolls are assumed the same, but the actual length is different from the simulated one.

5. Conclusions

The mathematical model for the CD register was derived using the lateral position of a moving web, the translation of a printing roll, and the time delay (L/V). The register occurred because of the relative difference between the adjacent printed patterns on the web. Therefore, the lateral position of the web should be considered for controlling the CD register. The proposed modeling was validated by the numerical simulations and was verified by experimental studies. It showed that the CD register model was enough to describe the errors in multi-layer printing. Generally, printing rolls are translated for the control of CD register; therefore, the derived model is worthwhile to be developed as an effective CD register controller.

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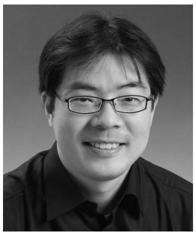

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