Springer

Journal of Mechanical Science and Technology 23 (2009) 212~220

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0927-2

A study on the tension estimator by using register error in a printing section of roll to roll e-printing systems †

Changwoo Lee[1], Jangwon Lee[2], Hyunkyoo Kang[3] and Keehyun Shin[3,*]

[1]*Flexible Display Roll to Roll Research Center, Konkuk University,Seoul, 143-701, Korea*
[2]*Advanced Technology R&D Center of SKC, Jeongja-1 dong, Jangan-gu, Suwon-Si, Gyeonggi-do, 440-301, Korea*
[3]*Department of Mechanical and Aerospace Engineering, Konkuk University,Seoul, 143-701, Korea*

(Manuscript Received June 4, 2008; Revised September 16, 2008; Accepted September 25, 2008)

Abstract

The focus of this study is on the development of a mathematical model for estimating tension of a printing section by using the register error in R2R (Roll to Roll) e-Printing systems. In a printing section of conventional R2R printing systems, the tension is generally measured not for controlling but for monitoring, because the tension control may cause the occurrence of a register error. But, for high precision control, the tension in the R2R e-Printing system must be controlled as well as measured for more precise control of the register error. The tension can be measured by the loadcell in the conventional R2R systems. However, installing a loadcell on the R2R systems causes extra economic burden. In addition, the space for adding a loadcell on R2R systems is limited due to many components including dryers, lateral guider, doctor blade, ink supply unit and cooling unit. Therefore, a tension estimator can be another possibility for predicting the tension in a printing section. In this study, a new tension estimation model is proposed. The proposed model is based on the register error model, the equivalent torque equation, and the tension model considering tension transfer. Numerical simulations and experimental results showed that the proposed model was effective in estimating the tension in a printing section.

Keywords: Estimator; e-Printing; Register error; Roll to roll system; Tension

1. Introduction

Recently, ‘the printed electronics’ productions (e.g., e-circuit, RFID, MLCC,OLED lighting etc.) using the R2R (Roll to Roll) systems have become more attractive. The R2R system means inline continuous fabricating processes using a number of motors and driven rolls, and idle rollers. The R2R system is composed of many sections including a rewinding, unwinding, printing, infeeding and outfeeding sections as shown in Fig. 1. Especially, several works have to be performed such as printing, drying, register control, lateral control and cooling operations in a printing section. In a conventional R2R system, a draw tension control is generally applied because high precision tension control is not needed. However, precision tension control for high quality product is requested in a printed electronics system. The tension is generally measured by the loadcell but installing the loadcell on the R2R systems may cause extra economic burden. In

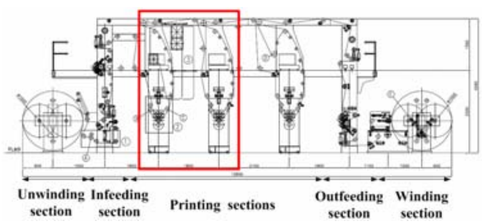


Fig. 1. Configuration of R2R systems.

† This paper was recommended for publication in revised form by Associate Editor Hong Hee Yoo

*Corresponding author. +82 2 450 3072, Fax.: +82 2 450 5886
E-mail address: khshin@konkuk.ac.kr

addition, the space for installing a loadcell is limited due to many components in a printing section. The estimation method provides effective solutions such as the economical advantage, flexible system design and reliability, etc.

Early work by Brandenburg [1] provided a general mathematical model for longitudinal dynamics of a substrate. That showed a correlation between the tension variation and the register error. The register error means, in the case of multi-printing, relative displacement between each printed pattern on the substrate by the series of printing sections. Shin [2] derived a mathematical tension model considering tension. The observed based tension feedback control was proposed by Lin [3]. Wolferman [4] established the method of sensorless tension control in continuous process systems. Previous studies on the estimation of tension were focused on optimal tension control regardless of register control.

Therefore, in this paper, a new mathematical model for the tension estimation considering register error is proposed. The register error is applied for high precision estimation because the register error is to be controlled under 10 μm in general. The proposed model-based tension estimator is constructed in main controller of a R2R system. The model is based on a register error model, an equivalent torque equation, and a tension model. The study was carried out to verify performance of the proposed model through numerical simulations and experiments. Results showed that the proposed model was very effective to predict the tension in a printing section.

2. A mathematical model for tension estimation

A schematic view of the simplified printing section is shown in Fig. 1. By assuming that there is no change in the moment of inertia, a relationship between the tension and the rotational velocity of the printing roller can be obtained from the equivalent torque equation as Eq. (1).

$$J_{eq,1}\frac{V_1}{R_1}s + b_1\frac{V_1}{R_1} - R_1\left(T_2 - T_1\right) = \tau_1 \tag{1}$$

where, $J_{eq,1}$ is the equivalent moment of inertia which is calculated by using the moment of inertia of printing roll and the shaft. But the moment of inertia of the gearbox is not considered. T_1 is the tension variation in each span. R , s mean the Laplace variable and the radius of printing roller, respectively.

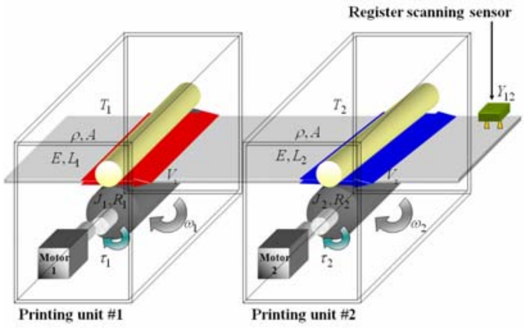


Fig. 2. Schematic of printing section.

Eq. (2) is the register error model which is derived by Brandenburg [1] under the no slip condition between printing roll and substrate and mass balance theory in a free web section.

$$\frac{Y_{12}}{Y_N} = \left\{ \frac{\dfrac{(V_1 - V_2)}{v_{ref}}}{\left(\dfrac{Y_N}{v_{ref}}\right)\left(\dfrac{L}{v_{ref}}\right)s^2 + \left(\dfrac{Y_N}{v_{ref}}\right)s} \right\} + \left(\frac{T_1}{AE}\right)\left\{ \left\{ \frac{1}{\left(\dfrac{Y_N}{v_{ref}}\right)\left(\dfrac{L}{v_{ref}}\right)s^2 + \left(\dfrac{Y_N}{v_{ref}}\right)s} \right\} + \frac{e^{-\left(\frac{L}{v_{ref}}\right)s}}{\left(\dfrac{Y_N}{v_{ref}}\right)s} \right\} \tag{2}$$

where Y_{12} is the variation of register error between adjacent up/down-stream printing rolls, L denotes the span length. v_{ref} is a steady state operating value of the transported velocity. E , A are the elasticity modulus of transported substrate, the cross-sectional substrate area respectively. It is clear that the register error is function of strains which are determined by the velocity of the printing roll.

Eq. (3) represents a linearized dynamic relationship between the changes in the tension within the current span, T_2 , and the changes in the tangential velocities at the ends of the span, V_1 and V_2 , at which there is no slippage between the substrate and the driven rollers [1, 2].

$$T_2 s = \frac{v_{ref}}{L}\left(-T_2 + T_1\right) + \frac{AE}{L}\left(V_2 - V_1\right) \tag{3}$$

In Eq. (1) ~ (3), each equation is derived by the Laplace transform which is easily calculated to the simultaneous equations. The tension model in Eq. (3) can be rewritten as Eq. (4).

Eq. (5) is derived in that equation (4) is applied to Eq. (1).

$$T_2 - T_1 = \left(\frac{AE}{L}\right)(V_2 - V_1) - \left(\frac{L}{v_{ref}}\right)(T_2 s) \tag{4}$$

$$T_2(s) = \left(\frac{v_{ref}}{R_1 L}\right)\left\{\frac{\tau_1 + \left(\frac{AER_1}{r_1 L}\right)(V_2 - V_1) - b_1\frac{V_1}{R_1} - J_{eq}\frac{V_1}{R_1}s}{s}\right\} \tag{5}$$

The register error model in Eq. (2) can be rewritten as Eq. (6).

$$(V_2 - V_1) = -\left(\frac{T_1 v_{ref}}{EA}\right) + \left(\frac{T_1 v_{ref}}{EA}\right)\left(\frac{Ls}{v_{ref}} + 1\right)e^{-\left(\frac{L}{v_{ref}}\right)s} - \frac{Y_{12}}{Y_N}s\left(\frac{Y_N L}{v_{ref}}s^2 + Y_N s\right) \tag{6}$$

Eq. (7) is derived in that Eq. (4) is applied to Eq. (1).

$$T_2(s) = \left(\frac{v_{ref}}{R_1 L}\right)\left(\frac{1}{s}\right)\left\{\begin{array}{l}\tau_1 - b\frac{V_1}{R_1^2} - J_{eq,1}\frac{V_1}{R_1^2}s \\ + \left(\frac{r_1 AE}{v_{ref}}\right)\left(\begin{array}{l} -\left(\frac{T_1 v_{ref}}{AE}\right) + \left(\frac{T_1 v_{ref}}{AE}\right)\left(\frac{L}{v_{ref}}s + 1\right)e^{-\left(\frac{L}{v_{ref}}\right)s} \\ -\frac{Y_{12}}{Y_N}\left(\frac{Y_N L}{v_{ref}}s^2 + Y_N s\right)\end{array}\right)\end{array}\right\} \tag{7}$$

where Y_N is the nominal register error which is a constant value and x is the integral variable. The printing tension (T_2), in the development of tension estimation model in Eq. (8), is estimated by the input factors such as the register error (Y_{12} / Y_N), the torque value of the printing motor (τ_1), the upstream tension (T_1), and the angular velocity (V_1 / R_1) of the printing roll. The development of the tension estimation model can be transformed to Eq. (8) by using the inverse Laplace transformation. In Eq. (8), it is found that the input data set (upstream tension, torque, speed variation, register error) is needed to obtain the tension value of the printing section.

$$\begin{aligned} T_2(t) = \left(\frac{v_{ref}}{R_1 L}\right)&\left\{\int_0^t\left(\tau_1(x) - b\frac{V_1}{R_1}(x)\right)dx - J_{eq}\frac{V_1}{R_1}(t)\right\} \\ &-\left(\frac{v_{ref}}{L}\right)\left(\int_0^t T_1(x)dx\right) \\ &+\left\{T_1(t - \frac{L}{v_{ref}}) + \left(\frac{v_{ref}}{L}\right)\left(\int_0^t T_1(x - \frac{L}{v_{ref}})dx\right)\right\} \\ &-\left(\frac{AEY_N}{L}\right)\left\{\left(\frac{L}{v_{ref}}\right)\frac{d}{dt}\left(\frac{Y_{12}(t)}{Y_N}\right) + \frac{Y_{12}(t)}{Y_N}\right\} \end{aligned} \tag{8}$$

3. Numerical simulations

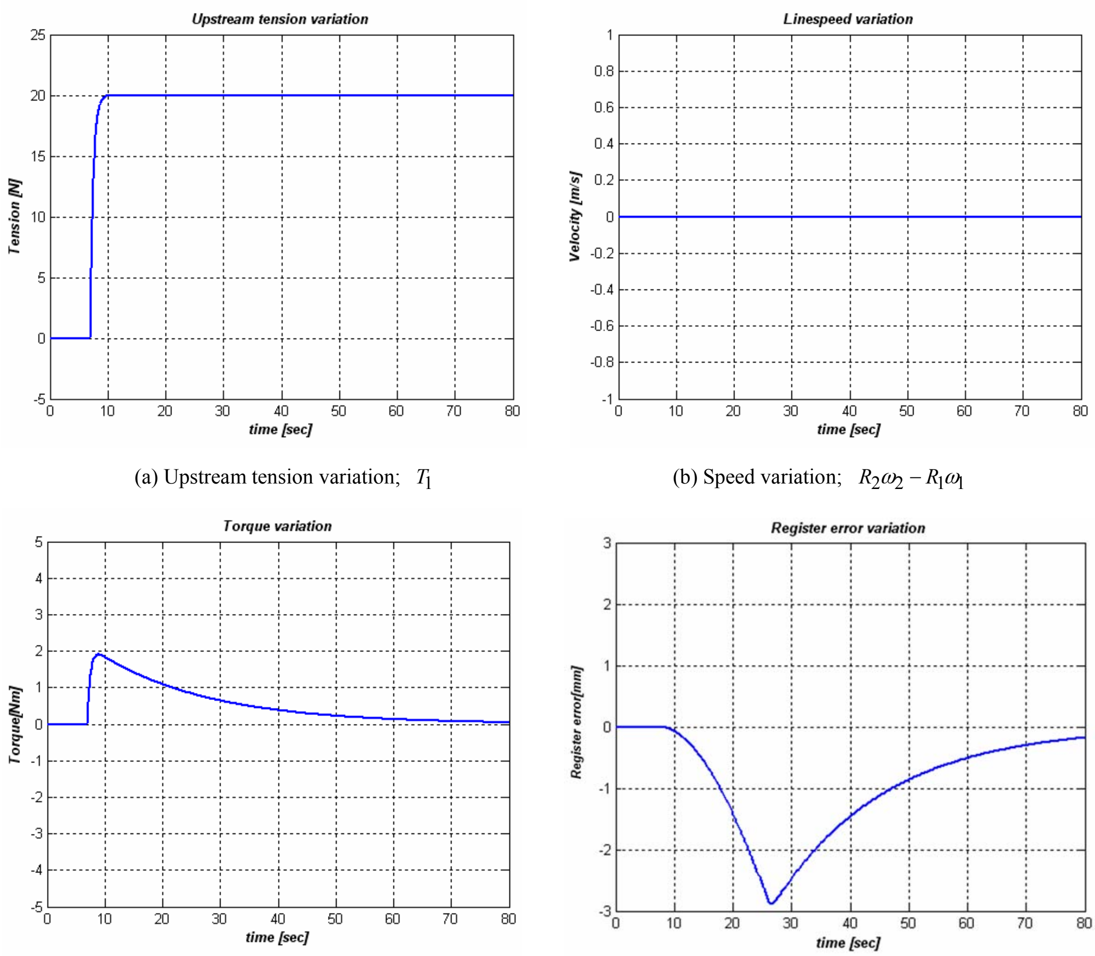
The numerical simulations for verifying the performance of the proposed tension estimation were carried out for two cases. : one, that upstream tension disturbance is used for input data, and the other is that speed variation of a driven roll is used. The parameters for numerical studies are summarized in Table 1.

3.1 Case1: Tension estimation with upstream tension variation, without speed change

Fig. 3(a) through Fig. 3(d) show the input data set (upstream tension, speed variation, torque, register error) for estimating a tension. The upstream tension was changed from 0 to 20 N as shown in Fig. 3(a). In Fig. 3(b), the change in the velocities at the ends of the span was not varied. The torque of the first printing motor and the register error were affected by the upstream tension variation as shown in Fig. 3(c), (d). The estimated tension (T_2) can be obtained by using the mathematical model (Eq. (8)) as shown in Fig. 4. The solid line is the estimated tension and the dotted line means the calculated reference by Eq. (3). The peak around 26 sec was generated because of the derivative term of register error in Eq. (8). To minimize the peak, a first order low-pass filter was used whose filter coefficient was chosen as 0.1 in the numerical simulations.

Table 1. Numerical simulation conditions.

Variables values	
Equivalent rotation inertia [kgf m^2]	0.033
Bearing friction	0. 003
Time constant of printing section [sec]	19
Normal value of register error [mm]	0.1
Young's modulus of P.E.T substrate [MPa]	1180
Radii of printing rolls [m]	0.21



(a) Upstream tension variation; T_1

(b) Speed variation; $R_2\omega_2 - R_1\omega_1$

(c) Load torque variation; τ

(d) Register error variation in printing section; Y_{12}

Fig. 3. Numerical simulation results.

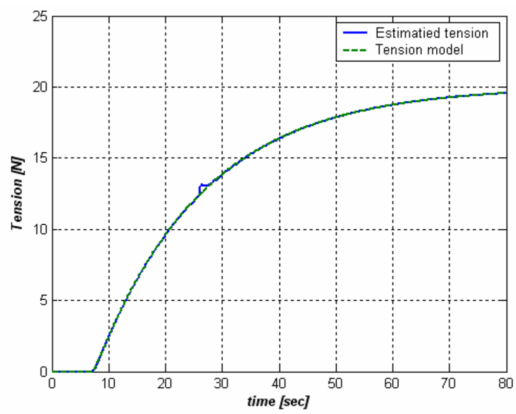
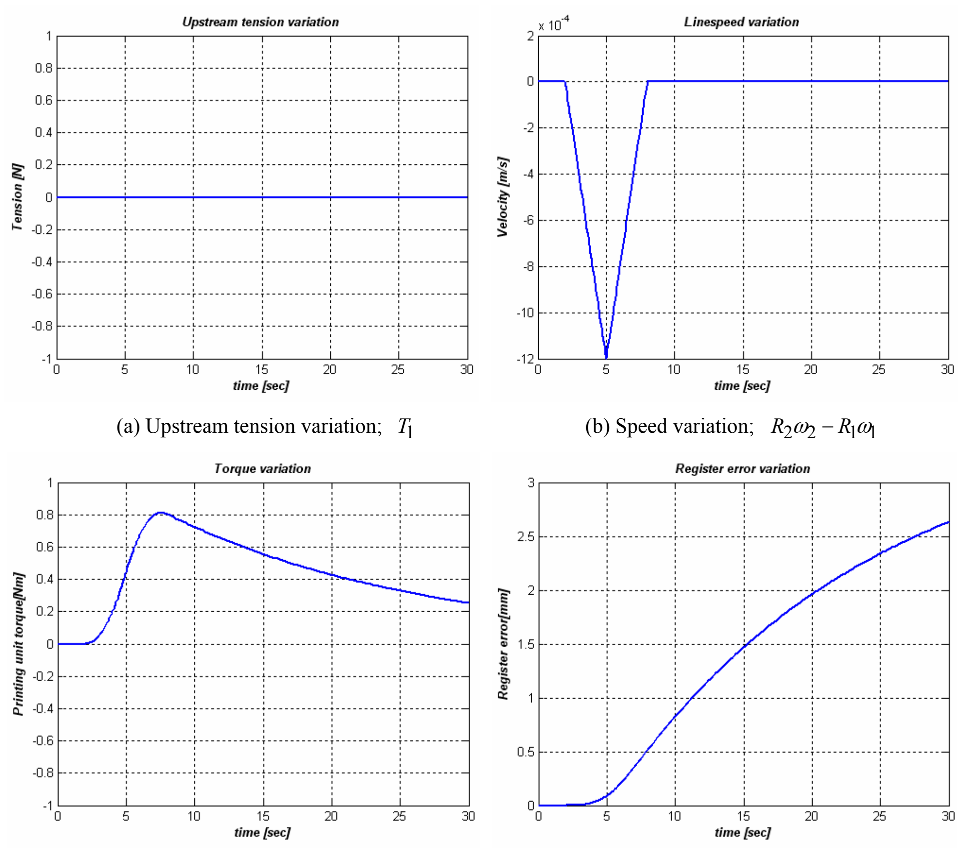


Fig. 4. The estimated tension (T_2).

3.2 Case2: Tension estimation with speed change, without upstream tension variation

The input data set (upstream tension, speed variation, torque, register error) is as shown in Fig. 5. The upstream tension was a constant as shown in Fig. 5(a), and the velocity was changed as shown in Fig. 5(b). The torque of the first printing motor and the register error were affected by the velocity variation as shown in Fig. 5(c) and Fig. 5(d).

The estimated tension (T_2) under velocity variation can be obtained by using the mathematical model (Eq. (8)) as shown in Fig. 6, There is a time delay (0.1sec) due to the low-pass filter for minimizing the peak of Fig. 4.



(a) Upstream tension variation; T_1

(b) Speed variation; $R_2\omega_2 - R_1\omega_1$

(c) Load torque variation; τ

(d)Register error variation in printing section; Y_{12}

Fig. 5. Numerical simulation results.

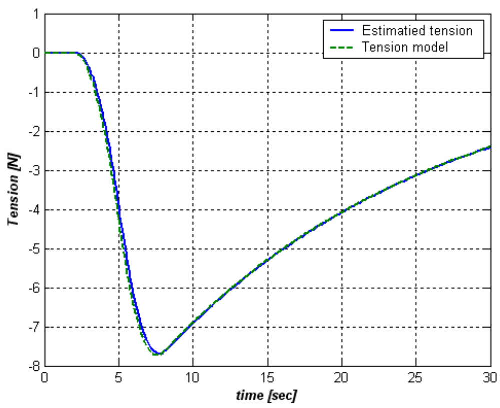


Fig. 6. Numerical simulation results.

Fig. 7. Commercial roll to roll system.

Through numerical studies, it is confirmed that the proposed tension estimator works well to predict the tension of a printing section even though there are some little peaks and a time delay.

4. Experimental verification

4.1 Experimental set up

The experimental studies were performed by using

Fig. 8. Loadcell and amplifier.

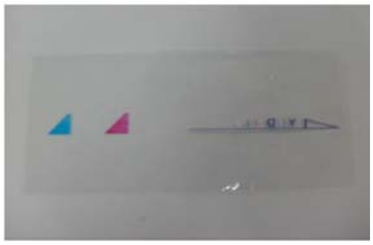


Fig. 9. Register mark.

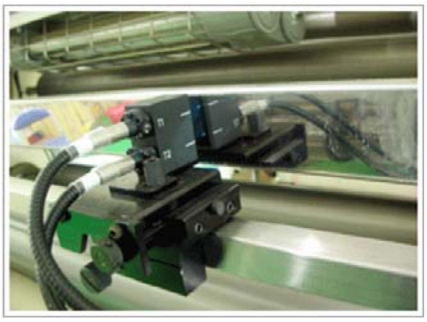


Fig. 10. Measuremt system for register mark.

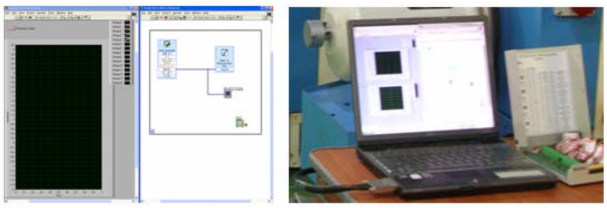
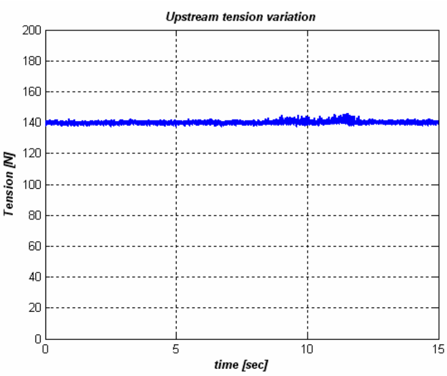
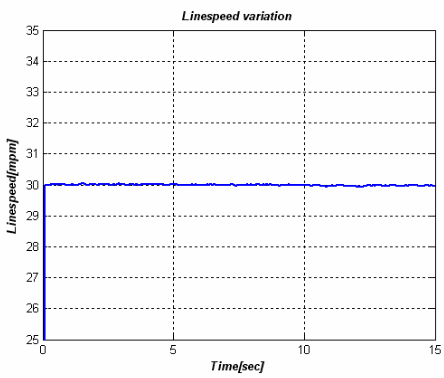


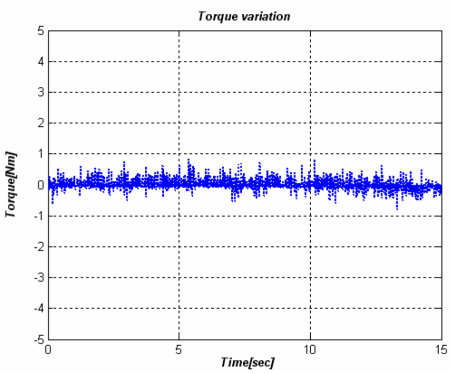
Fig. 11. Data acquisition systems.



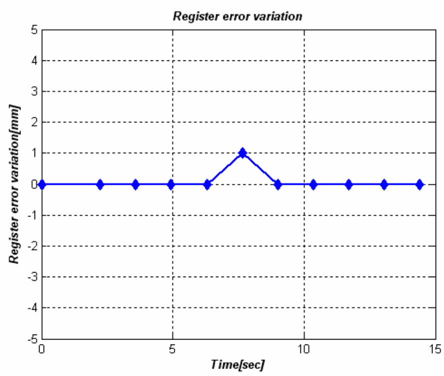
(a) Upstream tension variation; T_1



(b) Speed variation; $R_2\omega_2 - R_1\omega_1$



(c) Load torque variation; τ



(d) Register error variation in printing section; Y_{12}

Fig. 12. Input data for experimental verification.

The tensions, in the upstream section and the printing section, were measured by the loadcell (MITSUBISH, LX-TD-909) with amplifier (MITSBISH, LM-PC) as shown in Fig. 8. The register mark of Fig. 9 was measured by using the lighting sensor as shown in Fig. 10. Digital data acquisition software, LabVIEW 8.2, was used for collecting and storing the data and the output signal of the loadcell; register sensors were connected to the analog input channel of the data acquisition board (National Instrument, SCC-68), which was connected to the A/D converter (National Instrument, DAQ card-6062E) as shown in Fig. 11.

4.2 Experiments on tension estimation in steady-state

As discussed above, the input data (upstream tension, speed variation, torque, and register error) are needed to estimate the tension in a printing section as shown in Fig. 12. The upstream tension is controlled under 2% disturbance by a using dancer system as shown in Fig.12(a). The speed error is less than 0.2% as shown in Fig. 12(b). The register error can be obtained through linear interpolation of a discrete register mark as shown in Fig. 12(d).

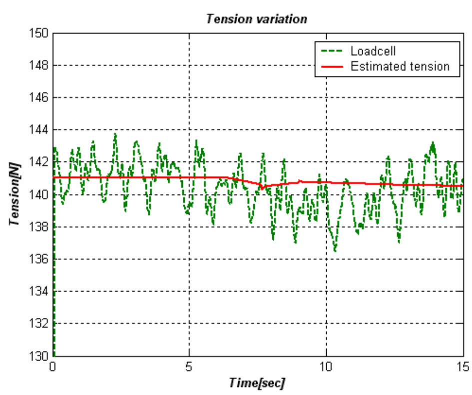
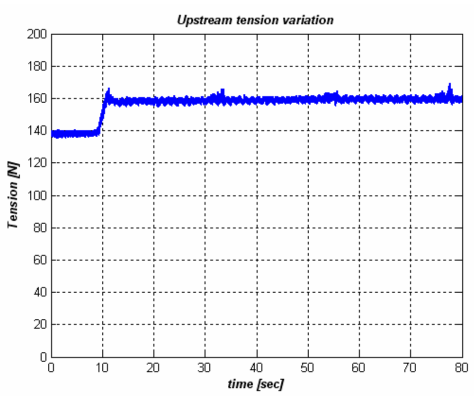
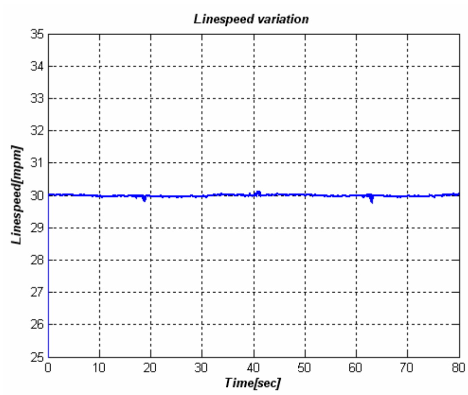


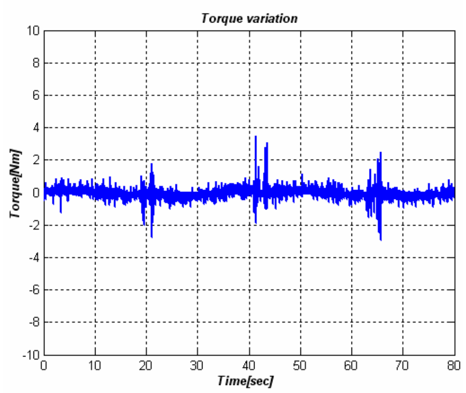
Fig. 13. Experimental result.



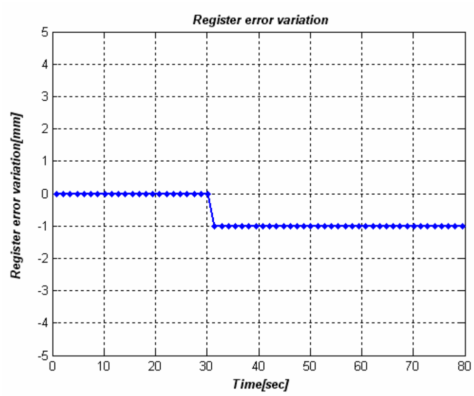
(a) Upstream tension variation; T_1



(b) Speed variation; $R_2\omega_2 - R_1\omega_1$



(c) Load torque variation; τ



(d) Register error variation in printing section; Y_{12}

Fig. 14. Input data for experimental verification.

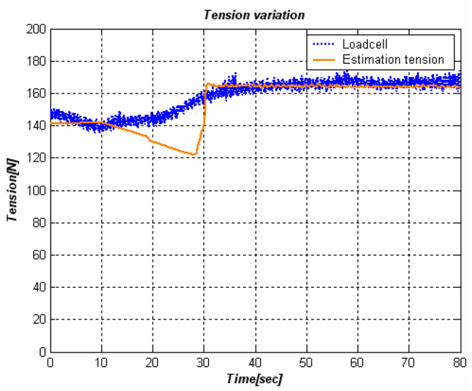


Fig. 15. Experimental result.

The tension in the printing section can be predicted by using the proposed tension estimator as shown in Fig. 13. In Fig. 13, the estimation error was less than 0.5% under the steady-state in which the dotted line was the measured tension using loadcell and the solid line was the estimated tension, respectively.

4.3 Experiments on tension estimation with upstream tension disturbance

The upstream tension was changed from 140 N to 160N as shown in Fig. 14(a). The torque of the printing roll and register error were affected by the upstream tension as shown in Fig. 14(c) and (d). It seemed to be degrading the estimation performance during the transient state (9~30sec) as shown in the Fig. 15. However, the estimation error was caused not by the inaccuracy of tension estimator but by the limitation of capability of register sensor for detecting register error.

A register scanning sensor with resolution (over 100 micrometer) was installed in the R2R system because it was not needed for the register error under 100 micrometers to be controlled in that R2R system. Therefore, the register sensor could not detect, even though a register error was induced in the transient state (9~30 sec) as shown in Fig. 14 (d). In other words, there were some differences between the estimated tension and measured tension in the transient state (9~30sec) because the induced register error under 100 micrometer was not measured.

5. Conclusion

A dynamic model and tension estimator have been developed for an R2R printed electronic system. The relationship between tension and register error was analyzed based on mathematical models. The estimator is proposed to detect the tension of the printing section and the derivative filter is used to suppress the overshoot of the measured register error. The proposed tension estimator in this study is effective for detecting the tension of a printing section. The performance of the estimator is demonstrated by numerical analysis and experimental study. The results show that a tension estimation method without the loadcell provides effective solutions such as economical advantage, flexible system design, and system reliability.

Acknowledgment

This research is supported by "Seoul R&BD Program (10848), Korea" and "the Korea Foundation for International Cooperation of Science & Technology (KICOS) through a grant provided by the Korean Ministry of Education, Science & Technology (MEST) in K20701040597-07A0404-05110".

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Chang-Woo Lee received a B.S. degree in Mechanical Engineering from Konkuk University in 2001. He received his M.S. and Ph.D. degrees from Konkuk university in 2003 and 2008, respectively. Dr. Lee is currently a researcher at the Flexible Display Roll to Roll Research Center at Konkuk University in Seoul, Korea. Dr. Lee's research interests are in the area of fault tolerant control, R2R e-Printing line design, and tension-register control. He is the holder of several patents related to R2R e-Printing system.

Jang-Won Lee received the B.S. and M.S.degrees in mechanical engineering from Konkuk University, Seoul, Korea. He studied continuous flexible process at the FDRC (Flexible Display R2R Research Center, Project Director: Kee-Hyun Shin), as a reseacher from the concentment to 2008. Since 2008, he has been a Research Engineer with the SKC Films R&D, Suwon, Gyeonggi-do, Korea. Now he is great on the plastic flim mechanics such as a scratch on the film surface, film extruding, winding/slitting mecha-nism and coating processes.

Hyunkyoo Kang received the B.S. and M.S degree in 2000 and 2003 res-pectively from Konkuk Uni-versity, Seoul, Korea, where he is currently working toward the Ph. D. degree in mechanical design. He took part in the development of an autoalign guiding system for high-speed winding in a cable winding system, a 3-D roll-shape diagnosis method in a steel rolling system, a design of register controller for high-speed converting machine and real-time control design of electronic printing machine. His research topics include register modeling and control for printed electronics and distributed real-time control.

Kee-Hyun Shin received the B.S. degree from Seoul National University, Seoul, Korea, and the M.S. and Ph.D. degrees in mechanical engineering from Oklahoma State University (OSU), Stillwater. Since 1992, he has been a Professor with the Department of Mechanical and Aerospace Engineering, Konkuk University, Seoul, Korea. For more than 18 years, he has covered several research topics in the area of web handling, including tension control, lateral dynamics, diagnosis of defect rolls/rollers, and fault-tolerant real-time control in the Flexible Display Roll-to-Roll Research Center, Konkuk University, of which he has also been a Director. He is the author of Tension Control (TAPPI Press, 2000) and is the holder of several patents related to R2R e-Printing system.