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Tension Estimation by Using Register Error in Roll to Roll e-Printing Systems

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Abstract: The focus of this study is on development of mathematical model and experimental verification of a tension estimation 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 causes the occurrence of a register error. But 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 loadcells in the conventional R2R systems. But installing loadcell on the R2R systems causes extra economic burden. In addition, the space for the loadcells on the R2R systems is limited due to many components including dryers and cooling units. 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. Numerical simulations and experimental results showed that the proposed model was effective to estimate the tension in a printing section.

1. INTRODUCTION

Recently, 'the printed electronics' production (e.g. e-circuit, RFID or MLCC etc.) using the R2R (Roll to Roll) systems become hot issues. The R2R system means inline continuous fabricating processes using a number of motors and driven rolls, and idle rollers. As shown in Fig. 1, the R2R system is composed of many sections including the un/re-winding section, the printing section, and the in/out A feeding section. In printing section, the tension must be precisely observed because several works have to be performed such as the printing, the drying, and the cooling operations. The tension is generally measured by the loadcell but installing the loadcell on the R2R systems causes extra economic burden. In addition, the space in the web flow is limited due to many components as the printing section, the dryer and cooling units. The estimation method provides the effective solutions such as the economical advantage, the flexible system design and the reliability, etc.

As an early work, a mathematical model for longitudinal dynamics of a substrate was derived by G. Brandenburg. 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 (G. Brandenburg, 1976). Typically tension estimation has become a widely used method to control the R2R dynamic systems. The estimation research has been carried out in the area of integral feedback, robust control, and another control work in the R2R systems (W. Wolfermann, 1997; J. Ruiz C. et. al, 1997; H., M. R. Leonard, 1999; Song et. al, 2000; T. Patri et. al, 2001; K. C. Lin, 2003).

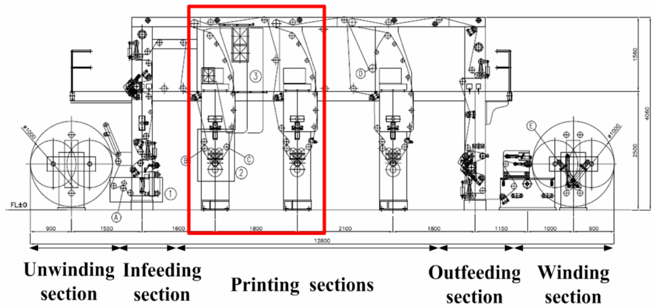


Fig. 1. A configuration of the R2R printing system

In this paper, a new mathematical model for the tension estimation is proposed. 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 effective to predict the tension in printing sections.

2. A NEW MATHEMATICAL MODEL FOR THE TENSION ESTIMATION

The simplified printing section is described in Fig. 2. Each printing section consists of a gravure roll, a rubber impression roll, a gear box, and a register control motor. In this R2R system, the register control is carried out with the phase offset in the downstream printing section. G. Brandenburg derived the linearized mathematical model of register error behavior in printing section as follows.

$$Y_{12}(s)=\left(v_{ref}/s\right)\left(-\in_2(s)+\in_1(s)e^{-\left(L/v_{ref}\right)S}\right) \tag{1}$$

where Y_{12} is the variation of register error between adjacent up/down-stream printing rolls, $\in$ means the small deviation of elastic strain from its steady-state value. s means the laplace variable. L denotes the span length. v_{ref} is a steady state operating value of the transported velocity.

Equation (2) 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, $R_1\omega_1$ and $R_2\omega_2$, at which there is no slippage between the substrate and the driven rollers (G. Brandenburg, 1976; Shin, 2000). The mathematical tension model was experimentally validated by Shin et al., using the web transport systems.

$$T_2 s=\frac{v_{ref}}{L}\left(-T_2+T_1\right)+\frac{AE}{L}\left(R_2\omega_2-R_1\omega_1\right) \tag{2}$$

where E, A, R is the elasticity modulus of transported substrate, the cross-sectional substrate area, and the radius of printing rollers respectively.

By assuming that AC/DC motors drive the rollers and there is no change in the moment of inertia of printing rollers, a relationship between the tension and the rotational velocity of the printing roller can be obtained from the equivalent torque equation as follows (K. Ogata, 1998)

$$J_{eq,1}\omega_1 s+b_1\omega_1-R_1\left(T_2-T_1\right)=\tau_1 \tag{3}$$

where, $J_{eq,1}$ denotes the equivalent rotation inertia of the 1st printing roller and b means the rotary constant bearing friction. τ is the value of change in driving torque of motor and r is a radius of printing roller. By combining the equations (1) ~ (3), the mathematical model for the tension estimation is derived as follows.

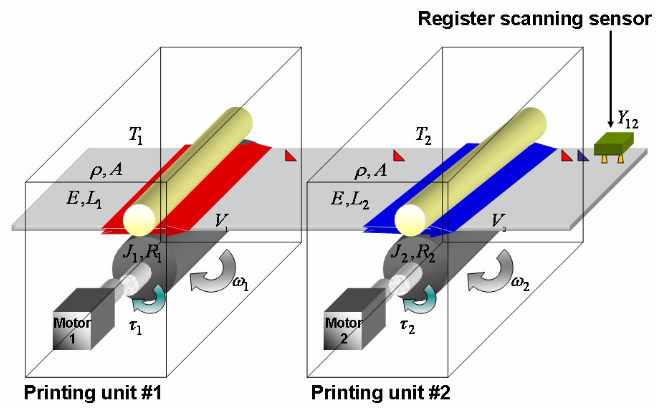


Fig. 2. A schematic view of the printing section

$$\begin{aligned}T_2(t)=&\left(\frac{v_{ref}}{R_1 L}\right)\left\{\int_0^t\left(\tau_1(x)-b\omega_1(x)\right)dx-J_{eq}\omega_1(t)\right\}\\&-\left(\frac{v_{ref}}{L}\right)\left(\int_0^t T_1(x)dx\right)\\&+\left\{T_1(t-\frac{L}{v_{ref}})+\left(\frac{v_{ref}}{L}\right)\left(\int_0^t T_1(x-\frac{L}{v_{ref}})dx\right)\right\}\\&-\left(\frac{AEY_N}{L}\right)\left\{\left(\frac{L}{v_{ref}}\right)\frac{d}{dt}\left(\frac{Y_{12}(t)}{Y_N}\right)+\frac{Y_{12}(t)}{Y_N}\right\}\end{aligned} \tag{4}$$

where Y_N is the nominal register error which is constant value and x is the integral variable.

The printing tension (T_2) in the equation (4) 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 substrate velocity (ω).

3. NUMERICAL SIMULATIONS OF PROPOSED ESTIMATION MODEL

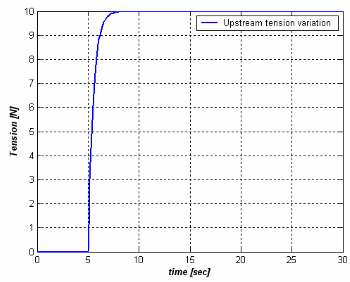
In the table 1, the parameter values in this study were summarized. The following simulation cases were chosen to emphasize the tension dynamic relationships by the equation (2) in a span.

Table 1. Parameter values used in the numerical simulations and the experimental verifications

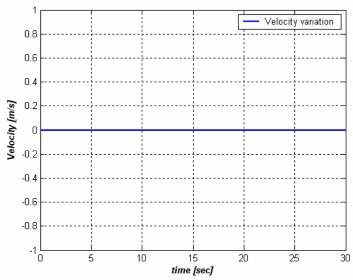
Symbol	value	Expression
J_{eq}	0.033 ($kgf \cdot m^2$)	Equivalent rotation inertia of printing roll
b	0. 003	Bearing friction
V_{ref}	30 (mpm)	Operating velocity
Y_N	0.1(mm)	Normal value of register error
E	1180(Mpa)	Young's modulus of substrate (P.E.T)
L	9500(mm)	Span length
R	0.21(m)	Radii of printing rolls
GR	3	Gear ratio

Simulation case 1: Tension estimation with upstream tension variation, without velocity variation. (i.e. $T_1 \neq 0$, $\left|R_2\omega_2-R_1\omega_1\right|=0$).

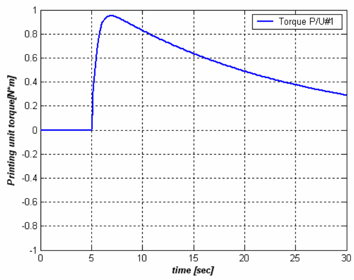
Fig. 3 (a) ~ (d) showed the input data set for estimating the tension. The upstream tension was changed from 0 to 10 N in Fig. 3(a). In Fig. 3(b), the change in the velocities at the ends of the span was not varied. The torque of the 1st printing motor and the register error were affected by the upstream tension variation as shown in Fig. 3(c), (d).



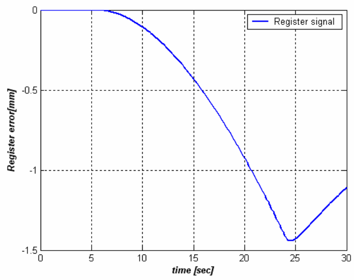
(a) Upstream tension variation $T_1(N)$



(b) Change of velocities in a span $|R_2\omega_2 - R_1\omega_1|$



(c) Load torque variation $\tau(N \cdot m)$



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

Fig. 3. Simulation case 1: input data set for a new model

The estimated tension (T_2) was calculated by the equation (4) using the input data set as shown in Fig. 4. The solid line is the estimated tension by the equation (4) and the dotted line means the calculated tension by the equation (2). The peak around 24 sec was generated because of the derivative term of register error in equation (4).

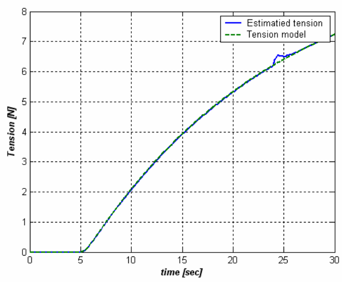
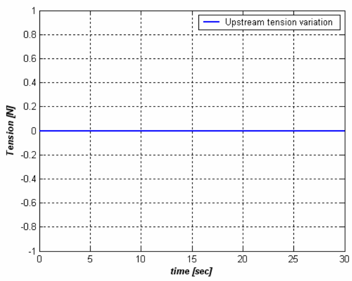


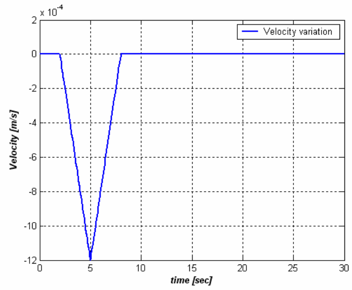
Fig. 4. Simulation case 1: the estimated tension $T_2(N)$

Simulation case 2: Tension estimation with velocity variation, without upstream tension variation. (i.e. $T_1 = 0$, $|R_2\omega_2 - R_1\omega_1| \neq 0$)

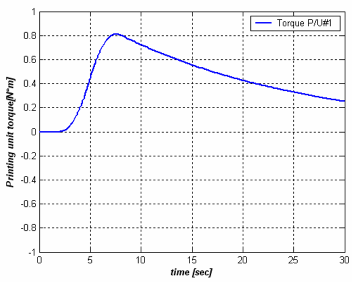
Through the simulation case 2, the upstream tension was not varied as shown in Fig. 5(a) and the velocity variation was changed in Fig. 5(b). The torque of the 1st printing motor and the register error were affected by the velocity variation as shown in Fig. 5(c), (d).



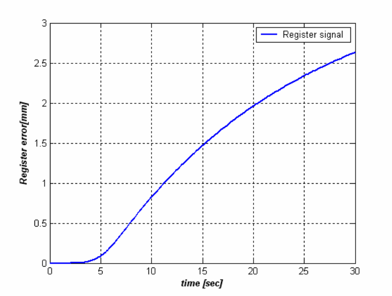
(a) Upstream tension variation $T_1(N)$



(b) Change of velocities in a span $|R_2\omega_2 - R_1\omega_1|$



(c) Load torque variation $\tau(N \cdot m)$



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

Fig. 5. Simulation case 2: input data set for a new model

In Fig. 6, time-delay 0.1sed and tension-offset 1 N were appeared because the derivative filter was used to eliminate the discontinuity effects such as peak value as shown in Fig. 4. The new model was worked well to predict the printing tension and showed the characteristic of its performance which was deeply influenced by the variance of register error.

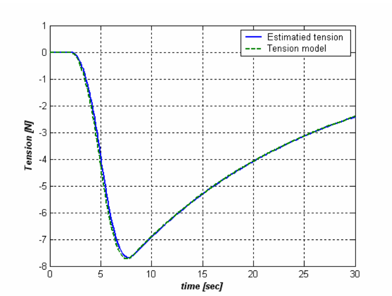
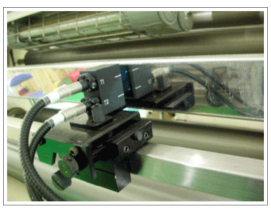


Fig. 6. Simulation case 2: the estimated tension $T_2(N)$

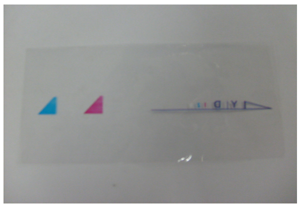
4. EXPERIMENTAL VERIFICATIONS OF PROPOSED ESTIMATION MODEL

The model verifications were performed on a R2R converting system as shown in Fig. 7(a). The tensions, in the upstream section and the printing section, were measured by the loadcells mounted on the shaft of an idle roller. The register error was measured by using the lighting sensor as shown in Fig. 7(b). In this R2R converting system, the register mark was printed one time per one revolution in each printing section. So the register mark as shown in Fig. 7(c) causes that the register error graph could be shown as a discrete signal. A data measurement system was installed to collect data set such as the tensions, the torques, the velocities, and the register errors as shown in Fig. 7(d).

(a) Roll to Roll system



(b) Register-error scanning sensor



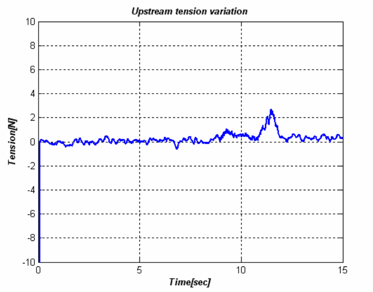
(c) Register marks

(d) Acquisition board (NI)

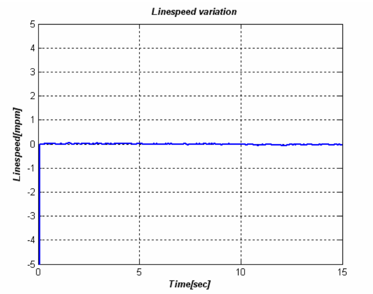
Fig. 7. Experiment equipments for the tension estimation

Experimental case 1: Tension estimation in steady-state condition. (i.e. $T_1 = 0$, $|R_2\omega_2 - R_1\omega_1| = 0$ **).**

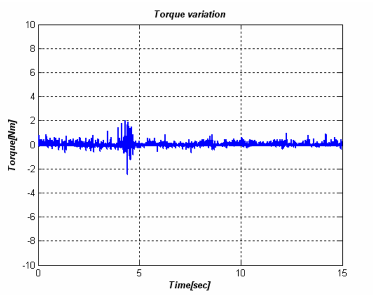
The input data set of the experimental case 1 was shown in Fig. 8. There is the tension disturbance ± 2% in upstream span. In Fig. 9, the estimation error was only less than 0.5% in steady-state in which the dotted line was the measured tension using loadcell and the solid line was the estimated tension, respectively.



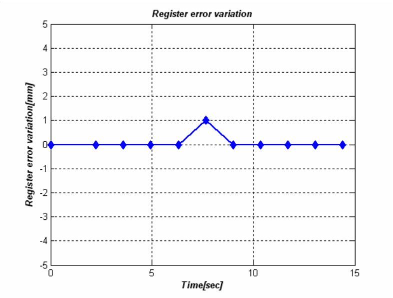
(a) Upstream tension variation ($T_{op} = 120N$)



(b) The change of velocities in a span ($V_{op} = 30mpm$)



(c) Load torque variation $\tau(N \cdot m)$



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

Fig. 8. Experimental case 1: input data set for a new model

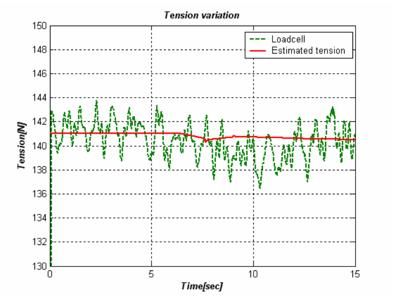
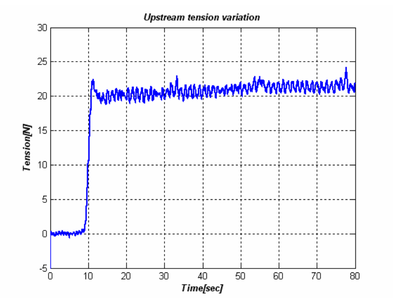


Fig. 9. Experimental case 1: the estimated tension $T_2(N)$

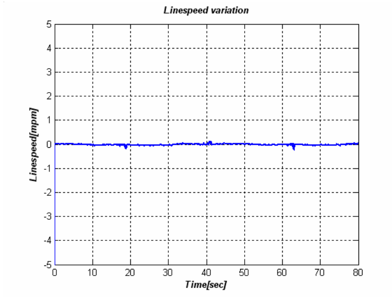
Experimental case 2: Tension estimation in the upstream tension variation. (i.e. $T_1 \neq 0$ **,** $|R_2\omega_2 - R_1\omega_1| = 0$ **).**

Fig. 10 showed that the upstream tension was changed. The variation of the torque and the register error were affected by the tension variation as shown in Fig. 5 (c), (d). Fig. 11 showed that the estimation error was less than 1.5% (2N) in the steady-state. But the unexpected error was generated in the transient-state because the inaccuracy measurement and its calculation were caused register error.

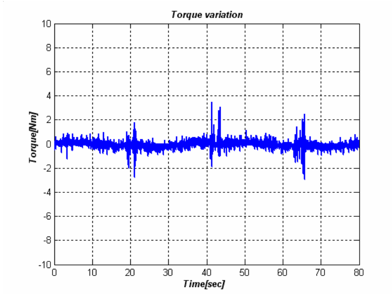
The experiment results were showed that the estimating performance of proposed model was accurate in steady-state and if the register error is continuously calculated, the estimation ability can be more improved.



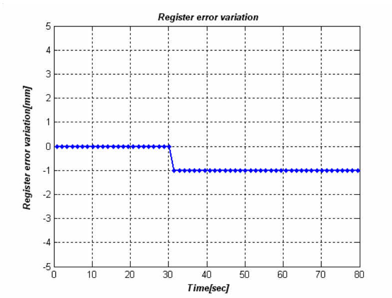
(a) Upstream tension variation ($T_{op} = 120N$)



(b) The change of velocities in a span ($V_{op} = 30mpm$)



(c) Load torque variation $\tau(N \cdot m)$



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

Fig. 10. Experimental case 2: input data set for a new model

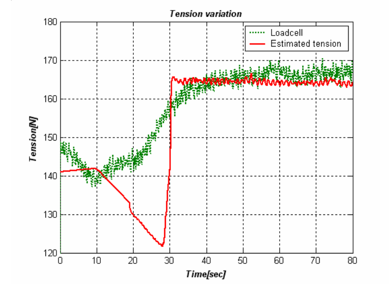


Fig. 11. Experimental case 2: the estimated tension $T_2(N)$

5. CONCLUSIONS

A new model was proposed to estimate the tension in printing section of the R2R machines. The proposed estimation model was verified by the experimental studies. The conclusions are as follows:

1) A new model effectively estimates of the tension behavior with less than the 1.5% error in steady-state condition.

2) In transient-state condition, if the register error is continuously measured, the model performance can be improved.

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