

A dynamic span model and associated control strategy for roll-transport systems used for sheet materials (Part II)

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Abstract

In this study, we propose a mathematical model that simulates the tension occurring at stands between rolls in a roll-transport system, and then we propose a method to estimate tension. The model is a lumped parameter system described by an ordinary differential equation (ODE). The ODE is derived on the basis of the tension of the stages between drive rolls on the stands. To build a realistic system, we utilized an estimation theory, which is the Kalman filter theory in a control theory. As a result, the proposed system is highly feasible.

Keyword: lumped parameter system, ordinary differential equation, tension, kalman filter, sheet materials.

1 Introduction

We previously reported on the use of a mathematical state model to design a control system configuration for a drying oven. The model is described using a transfer function with a quadratic time delay[1, 2, 3]. The state of the drying oven in the control system is defined by a one-dimensional advection diffusion equation (ODE) in which the object model has a constant speed of v . However, developing a quantifiable state estimate is difficult with such a model. Therefore, we propose to use optimal filter theory based on functional analysis to estimate the state of such a model when subjected to state-dependent noise. For state-independent noise, we can use the Kalman filter for conventional state estimation.

In our previous Bulletin[1, 2, 3], we reported that when materials on a sheet in a drying oven moved, we applied a vapor pressure propagation model to the solvent contained in substrates in an effort to solve the state estimation problem. By applying this model, it is possible to design an optimal control system.

Our findings related to transportation of sheet substrates were recently applied under a manufacturing context, to a roll transport system for textile processing machinery[4]. The model has also been used recently for a sheet transport/thin film transport system and with various chemically processed substrates such as a nonmoving fabric transport system.

Roll transport systems are important mechanical elements of drive systems in transport drive systems for sheet substrates[9]. The underlying principal of these systems for transporting substrates is to apply a vertical load of a cylindrical roll and a frictional force between substrates and rolls, as illustrated in Fig. 1. It is then possible to change the angle of sheet substrate transport by connecting a motor and using that motor to forcibly rotate a drive roll in a given direction (see Fig. 2).

Generally, manufacturing equipment lines are long, and the drive rolls are utilized with multiple pieces of equipment. In many cases, a drive roll is used with well over twenty pieces of equipment. The equipment that supplies substrates to these systems, known as an unwinding device, is usually installed at the inlet side. Then, sheet-type base substrates are fed using a driving roll product wound into a roll. Then, the device, which is called a winder for winding the processed product, is in some cases installed at an outlet. Obviously, other devices are in some cases installed in certain locations.

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The first system control problem in roll transport systems is process control in various processing devices and the second is control of the tension generated in the transport middle base of the sheet substrate; the latter is a major issue. In this study, we considered a dynamic model to control tension in materials during transportation. Our study is based on metal rolling process theory[5, 6]. We then applied appropriate parameters in a tandem mill control system to resolve the material tension problem that occurs when dealing with substrate films[10, 11, 12, 13, 14]. Moreover, using the model, we were able to study another control problem; we applied a boundary control function to study optimal speed tracking[16, 17].

In this study, applying the tension model of rolling processes, we propose a mathematical model of the tension generated during each stage. The model is a lumped parameter system described by an ordinary differential equation (ODE). The ODE is derived on the basis of the tension of the stages between drive rolls on stands 1 and 2.

Moreover, we utilized the Kalman filter theory in a control theory to estimate the tension between drive rolls[18]. Finally, we developed a numerical simulation to verify our mathematical model and estimation method.

2 Lumped kinetic model on drive rolls between stage

The kinetic model of stage between stands shows in Fig.3. Here, $(i - 1)$, i and $(i + 1)$ represent a stand each. A drive roll is installed on these stands and are driven by an electric motor M_1 , M_2 and M_3 each. It is called as “ Stage 1 ” between $(i - 1)$ and (i) and is called as “ Stage 2 ” between (i) and $(i + 1)$. The it's distance of stages between stand are L_1 and L_2 respectively. A tension C_1 and C_2 occur on the stage 1 and stage 2 respectively. Moreover, A processing unit 1 is installed between $(i - 1)$ and (i) . Similarly, a processing unit 2 is installed between (i) and $(i + 1)$ [1, 2, 3].

Assumption 2.1 *Assumption Tension is caused by alterations of the substrate due to chemical or physical changes as the substrate passes through processing unit 1, a component of the transport equipment. For example, tension is caused by applying a coating to the substrate with a solvent or by drying the coating.*

Assumption 2.2 *Assumption Tension is caused by a slip or a change in the Young ' s modulus after passing through the drive roll, considering the above assumption 2.1.*

Assumption 2.3 *Assumption Tension is caused by differences in the speeds of the rolls, considering the above assumptions 2.2.*

Assumption 2.4 *Assumption The tension at each stage can be controlled during a separate stage.*

These assumptions 2.1-2.4 can be applied because this is similar to the differences between the forward and backward speeds of the substrates installed in each stand of the rolling process[4, 5, 6, 10].

When you apply the tension model of rolling process, the tension generated model of stage 1 is

$$L_1 \frac{dC_1(t)}{dt} = E_1(v_{b_i} - v_{f_{i-1}}) \quad (2.1)$$

where C_1 is a generated tension, the unit is $[kg \cdot f/mm^2]$.

Stage 2 is the same as stage 1. The model equation is

$$L_1 \frac{dC_1(t)}{dt} = E_2(v_{b_{i-1}} - v_{f_i}) \quad (2.2)$$

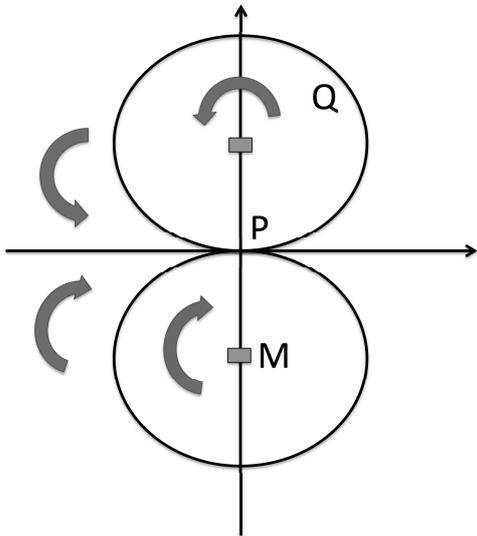


Fig. 1: Processing unit 1 of a drive roll

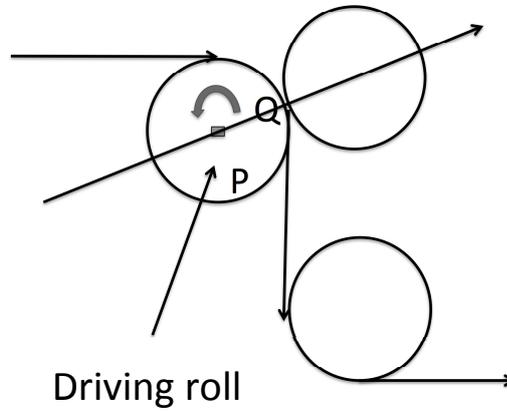


Fig. 2: Processing unit 2 of a drive roll

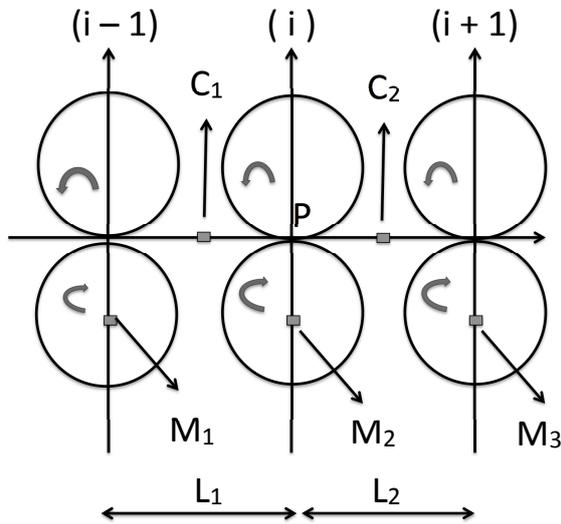


Fig. 3: Conceptual model diagram between the stand

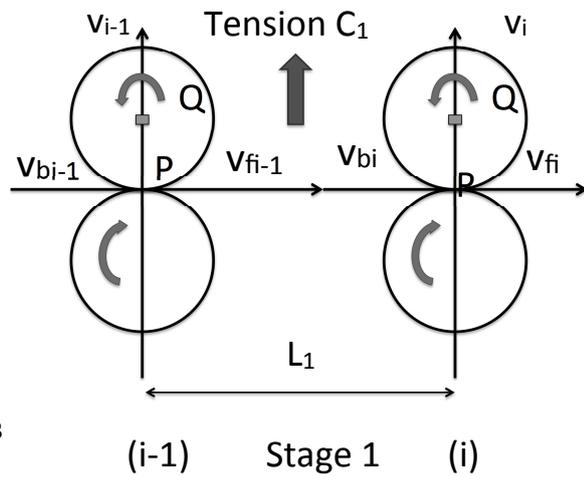


Fig. 4: Tension outbreak model for stage between rolls

Table. 1: Physical meaning of each symbol

E_1	Young's modulus of stage 1
$v_{b_{i-1}}$	Inlet side substrate speed of $(i-1)$ stand
$v_{f_{i-1}}$	Outlet side substrate speed of $(i-1)$ stand
v_{b_i}	Inlet side substrate speed of (i) stand
v_{f_i}	Outlet side substrate speed of (i) stand
v_{i-1}	Drive roll speed of $(i-1)$ stand
v_i	Drive roll speed of (i) stand

where C_2 is a generated tension, the unit is $[kg \cdot f / mm^2]$ [5, 6].

At this time, a degree of influence that $(i-1)$ stand gives to an outlet stand, puts $F_{i-1}(t)$.

$$F_{i-1}(t) = \frac{v_{f_{i-1}}}{U_{i-1}(t)} \quad (2.3)$$

where U_{i-1} is a circumferential speed of roll at the $(i-1)$ stand.

In the same manner, an impact received from the Inlet stand (i) is

$$B_i(t) = \frac{v_{b_i}}{U_i(t)} \quad (2.4)$$

where $U_i(t)$ is a circumferential speed of roll at the (i) stand.

Therefore, in the same manner, $F_i(t)$ and $B_{i+1}(t)$ are

$$F_i(t) = \frac{v_{f_i}}{U_i(t)} \quad (2.5)$$

$$B_{i+1}(t) = \frac{v_{b_{i+1}}}{U_{i+1}(t)} \quad (2.6)$$

where, using Eqs.(2.3) – (2.6), these items are able to be deformed as

$$v_{f_{i-1}}(t) = F_{i-1} \cdot U_i(t) \quad (2.7)$$

$$v_{b_i}(t) = B_i \cdot U_i(t) \quad (2.8)$$

$$v_{f_i}(t) = F_i \cdot U_i(t) \quad (2.9)$$

$$v_{b_{i+1}}(t) = B_{i+1} \cdot U_{i+1}(t) \quad (2.10)$$

Next, with respect to $F_i(t)$, we put the value of no tension at the time as F_i^0 . Then, by applying a rolling process model described as above at the time of tension,

$$F_i(t) = F_i^0(1 + K_b^1 \cdot C_1 + K_f^2 \cdot C_2) \quad (2.11)$$

where K_b^1 and K_f^2 are parameters called as a backward rate and a forward rate respectively[10, 12, 11].

Specifically, the forward rate and the backward rate at the (i) stand respectively are

Definition 2.1 *Definition*

$$K_f^i \equiv \frac{v_{f_i}}{v_i}, \quad K_b^i \equiv \frac{K_{b_i}}{v_i} \quad (2.12)$$

Eqn.(2.12) represents the material speed ratio from the forward and backward against the target drive roll speed[14].

In the same manner, $B_i(t)$ is

$$B_{i+1}(t) = B_{i+1}^0(1 + K_b^2 \cdot C_2 + K_f^3 \cdot C_3) \quad (2.13)$$

where $K_f^3 \cdot C_3$ the forward rate and a tension at backward stage ($i + 1$), which we are not assumed in this model.

Definition 2.2 Definition F_i^0 and B_{i+1}^0

$$F_i^0 = \frac{v_{fi}^0}{U_i^0}, \quad B_{i+1}^0 = \frac{v_{b_{i+1}}^0}{U_{i+1}^0} \quad (2.14)$$

Then, if a no tension occurs,

$$v_{fi}^0 = v_{b_{i+1}}^0 \quad (2.15)$$

From Eqn.(2.14), an equilibrium condition is

$$F_i^0 \cdot U_i^0 = B_{i+1}^0 \cdot U_{i+1}^0 \quad (2.16)$$

Eqn.(2.16) is called as a no tension equilibrium conditions[13].

With respect to a circumferential speed of drive roll at stand (i),

$$U_i(t) = U_i^0 \left(1 + \frac{\Delta U_i}{U_i^0} \right) \quad (2.17)$$

where, $\Delta U_i/U_i^0$ is a speed variation rate of the drive roll itself.

Therefore, from the above described equations, Eqn.(2.1) is

$$\frac{dC_1(t)}{dt} = \frac{E_1}{L_1} (v_{b_i} - v_{f_{i-1}}) = \frac{E_1}{L_1} \left\{ B_i(t) \cdot U_i(t) - F_{i-1}(t) \cdot U_{i-1}(t) \right\} \quad (2.18)$$

$$= \frac{E_1}{L_1} \left\{ B_i(t) \cdot U_i^0 \left(1 + \frac{\Delta U_i}{U_i^0} \right) - F_{i-1}(t) \cdot U_{i-1}^0 \left(1 + \frac{\Delta U_{i-1}}{U_{i-1}^0} \right) \right\} \quad (2.19)$$

Then, Substitute Eqn.(2.19) to Eqs.(2.11) and (2.13).

$$\begin{aligned} \frac{dC_1(t)}{dt} = & \frac{E_1}{L_1} \left\{ B_i^0(t) \cdot U_i^0 (1 + K_b^1 \cdot C_1 + K_f^2 \cdot C_2) \left(1 + \frac{\Delta U_i}{U_i^0} \right) \right. \\ & \left. - F_{i-1}^0 \cdot U_{i-1} (1 + K_b^0 \cdot C_0 + K_f^1 \cdot C_1) \left(1 + \frac{\Delta U_{i-1}}{U_{i-1}^0} \right) \right\} \end{aligned} \quad (2.20)$$

where, in accordance with $F_i(t)$, $F_{i-1}(t)$ is

$$F_{i-1}(t) = F_{i-1}^0 (1 + K_b^0 \cdot C_0 + K_f^1 \cdot C_1) \quad (2.21)$$

where, the variable $K_b^0 \cdot C_0$ is not assumed in this model described above.

Using Eqn.(2.16), Eqn.(2.20) is deformed as

$$\begin{aligned}
\frac{dC_1(t)}{dt} &= \frac{E_1}{L_1} F_{i-1}^0(t) \cdot U_{i-1}^0 \left\{ (1 + K_b^1 \cdot C_1 + K_f^2 \cdot C_2) \left(1 + \frac{\Delta U_i}{U_i^0} \right) \right. \\
&\quad \left. - (1 + K_b^0 \cdot C_0 + K_f^1 \cdot C_1) \left(1 + \frac{\Delta U_{i-1}}{U_{i-1}^0} \right) \right\} \\
&= \frac{E_1}{L_1} F_{i-1}^0(t) \cdot U_{i-1}^0 \left\{ K_b^1 \cdot C_1 + K_f^2 \cdot C_2 - K_b^0 \cdot C_0 - K_f^1 \cdot C_1 + \left(\frac{\Delta U_i}{U_i^0} - \frac{\Delta U_{i-1}}{U_{i-1}^0} \right) \right. \\
&\quad \left. + (K_b^1 \cdot C_1 + K_f^2 \cdot C_2) \frac{\Delta U_i}{U_i^0} - (K_b^0 \cdot C_0 + K_f^1 \cdot C_1) \frac{\Delta U_{i-1}}{U_{i-1}^0} \right. \\
&\quad \left. \simeq \frac{E_1}{L_1} F_{i-1}^0(t) \cdot U_{i-1}^0 \left\{ -K_b^0 \cdot C_0 + (K_b^1 - K_f^1) \cdot C_1 + K_f^2 \cdot C_2 \right\} \right. \tag{2.22}
\end{aligned}$$

where, we ignore the each speed variation rate of the drive roll itself in Eqn(2.22). The main causes of the tension generated are assumed to be the effect of K_b and K_f . A speed variation rate of the drive roll itself is assumed to be an extremely small value. Therefore, in a similar manner, the tension generated model of stage 2 is

$$\frac{dC_2(t)}{dt} \simeq \frac{E_2}{L_2} F_i^0(t) \cdot U_i^0 \left\{ -K_b^1 \cdot C_1 + (K_b^2 - K_f^2) \cdot C_2 + K_f^3 \cdot C_3 \right\} \tag{2.23}$$

Then, with respect to Eqs.(2.22) and (2.23),

$$a_1 = \frac{E_1}{L_1} F_{i-1}^0(t) \cdot U_{i-1}^0, \quad a_2 = \frac{E_2}{L_2} F_i^0(t) \cdot U_i^0 \tag{2.24}$$

Eqs.(2.22) and (2.23) are respectively

$$\frac{dC_1(t)}{dt} \simeq a_1 (-K_b^0 \cdot C_0 + (K_b^1 - K_f^1) \cdot C_1 + K_f^2 \cdot C_2) \tag{2.25}$$

$$\frac{dC_2(t)}{dt} \simeq a_2 (-K_b^1 \cdot C_1 + (K_b^2 - K_f^2) \cdot C_2 + K_f^3 \cdot C_3) \tag{2.26}$$

Moreover, we ignore an effects of C_0 and C_3 .

$$\frac{dC_1(t)}{dt} \simeq a_1 \left\{ (K_b^1 - K_f^1) \cdot C_1 + K_f^2 \cdot C_2 \right\} \tag{2.27}$$

$$\frac{dC_2(t)}{dt} \simeq a_2 \left\{ -K_b^1 \cdot C_1 + (K_b^2 - K_f^2) \cdot C_2 \right\} \tag{2.28}$$

3 The relationship between the electric motor in the peripheral drive roll and a generated tension

With respect to describe about the relationship between the electric motor in the peripheral drive roll and a generated tension, we assume the following[8, 14, 19].

Assumption 3.1 *Assumption Load torque with tension C*

$$q_d = WhRC \tag{3.1}$$

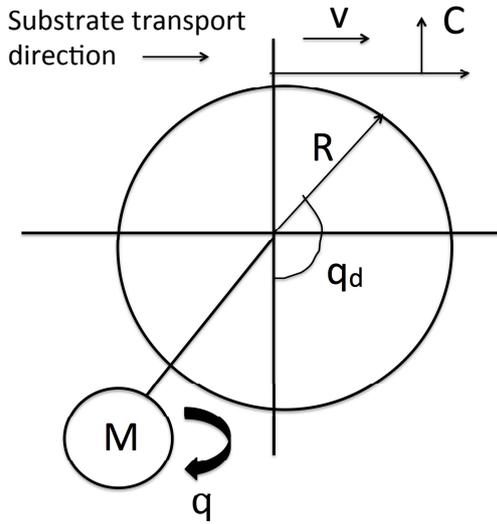


Fig. 5: Load torque with tension C

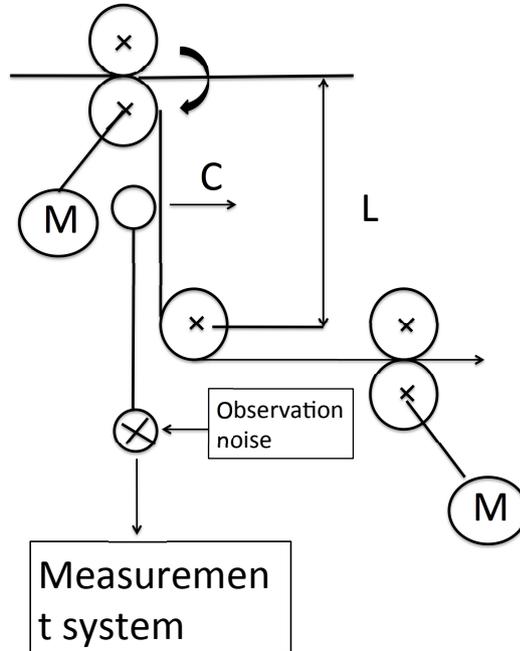


Fig. 6: Stochastic measurement system

Table. 2: Physical meaning of each symbol

W	Substrate width
h	Thickness of substrate
R	Radius of drive roll
v	Circumferential speed
C	Tension
q	Electric motor

With respect to Fig.5, the variables are described as Table.3. The circumferential speed v is

$$v = \frac{2\pi R}{J} \int (q - WhRC) dt \quad (3.2)$$

where, J indicates a hard to rotate larger[14, 19].

Then, the circumferential speed v , the substrate speed w_0 and let the forward slip as f [3, 15].

$$v_0 = (1 + f)v \quad (3.3)$$

where, the forward slip f changes due to the tension. Though the circumferential speed v is constant, a variation of f occurs the substrate speed v changing[11, 15].

Then, let a degree of influence as K_{v_c} ,

$$K_{v_c} = v_0 \frac{\partial f}{\partial C} \quad (3.4)$$

where,

$$C = \frac{E}{L} \int (v - K_{v_c} c) dt \quad (3.5)$$

From Eqn.(3.5),

$$\frac{dC(t)}{dt} = \frac{E}{L} \int (v - K_{v_c} c) \quad (3.6)$$

A tension at stage is depend on the circumferential speed v of drive roll[3, 7, 11].

Therefore, the mathematical model of tension at stage are reasonable as Eqs.(2.27) and (2.28). Here, we simplify Eqn.(2.27).

$$\frac{\partial C(t)}{\partial t} = a_c \cdot C(t) \quad (3.7)$$

where, a_c is a comprehensive parameter.

Then, we proposed the approximation model of distributed parameter system[3]. We describe the model as

$$\frac{dC_i(t)}{dt} = \lambda_i C_i(t) + r_1 \varphi_i(0) v_f(t) - r_2 \varphi_i(L_1) v_b \quad (3.8)$$

Compare with Eqn.(3.8), when we add a external force $f_{ex}(t)$ to Eqn.(3.7), we obtain

$$\frac{\partial C(t)}{\partial t} = a_c \cdot C(t) + b f_{ex}(t) \quad (3.9)$$

Eqn.(3.9) is similar to Eqn.(3.8). Please refer to our paper about physical meaning of each variable in Eqn.(3.8)[3].

4 Stochastic measurement problem of tension

Fig.6 shows the concept of stochastic measurement system. Applying Assumption 2.4, we represent a stochastic model of tension generating mechanism as following. Please see Eqs.(3.8) and (3.9) for reference.

$$dC(t) = a_c \cdot C(t) + b_\sigma dW_\sigma(t) \quad (4.1)$$

Moreover, we represent a measurement system as

$$d\xi(t) = g \cdot C(t)dt + b_m dW_m(t) \quad (4.2)$$

where, $g \equiv a(K_b - K_f)$.

We apply Kalman Filter Theory to estimate a tension by using Eqs.(4.1) and (4.2). With respect to a tension, It's average and volatility are

$$\mu(t) = E[C_t | \mathcal{F}_t^W] \quad (4.3)$$

$$v = V[C_t | \mathcal{F}_t^W] \quad (4.4)$$

A detailed definition for this system is omitted[18].

Then, A Riccati equation for $v(t)$ is

$$\frac{dv}{dt} = 2a_c v(t) - \frac{g^2}{b_m^2} v^2(t) + b_\sigma^2 \quad (4.5)$$

where,

$$v(0) = E[(\sigma_0 - E[\sigma_0])^2] = c^2 \quad (4.6)$$

The explicit solution of Eqs.(4.5) and (4.6) is

$$v(t) = \frac{\alpha_1 - K \cdot \exp\left\{\frac{(\alpha_2 - \alpha_1)}{b_m^2} t\right\}}{1 - K \cdot \exp\left\{\frac{(\alpha_2 - \alpha_1)}{b_m^2} t\right\}} \quad (4.7)$$

where,

$$\alpha_{1,2} = g^{-2} \cdot \left(ab_\sigma^2 \mp b_m \sqrt{a^2 b_m^2 + g^2 b_\sigma^2} \right) \quad (4.8)$$

$$K = \frac{c^2 - \alpha_1}{c^2 - \alpha_2} \quad (4.9)$$

Then, let $h(t)$ to the following.

$$h(t) = a - \frac{g^2}{b_m^2} v(t) \quad (4.10)$$

With respect to $\mu(t)$, $\mu(t)$ satisfy

$$d\mu(t) = h(t)\mu(t)dt + \frac{g^2}{b_m^2} v(t)d\xi(t) \quad (4.11)$$

where, $\mu(0) = E[\sigma_0]$

Applying Ito's Theorem to Semi martingale $\{\mu(t), t\}$ and the function $f(t, x) = x \cdot \exp\left\{-\int_0^t h(u)du\right\}$,

$$\begin{aligned} \mu(t) \cdot \exp\left\{-\int_0^t h(u)du\right\} - \mu_0 &= \int_0^t (-h(s) \exp\left\{-\int_0^s h(u)du\right\}) \cdot \mu(s) ds \\ &\quad + \int_0^t \exp\left\{-\int_0^s h(u)du\right\} d\mu(s) \\ &= \int_0^t \exp\left\{-\int_0^s h(u)du\right\} \cdot \frac{g^2}{b_m^2} v(s) d\xi(s) \end{aligned} \quad (4.12)$$

Therefore, $\mu(t)$ is

$$\mu(t) = \mu_0 \cdot \exp\left\{\int_0^t h(u)du\right\} + \frac{g}{b_m^2} \int_0^t \exp\left\{\int_0^t h(u)du\right\} \cdot v(s)d\xi(s) \quad (4.13)$$

From the definition of stochastic integration, as $t \rightarrow \infty$,

$$v(t) \simeq v \quad (4.14)$$

Substitute Eqn.(4.14) to Eqn.(4.13).

$$\mu(t) = \mu_0 \cdot \exp\left\{\left(a_c - \frac{g^2 \cdot v}{b_m^2}\right)t\right\} + \frac{g^2 \cdot v}{b_m^2} \cdot \int_0^t \exp\left\{\left(a_c - \frac{g^2 \cdot v}{b_m^2}\right)(t-s)\right\} d\xi(s) \quad (4.15)$$

Then, let $-\beta = a_c - \frac{g^2 \cdot v}{b_m^2}$, Eqn.(4.15) is deformed.

$$\mu(t) = e^{-\beta t} \left(\mu_0 + \frac{g^2 \cdot v}{b_m^2} \cdot \int_0^t e^{\beta s} d\xi(s) \right) \quad (4.16)$$

The estimation variable $\mu(t)$ of a tension $C(t)$ is represented by Eqn.(4.16).

Therefore, the estimation variable $\mu(t)$ of a tension $C(t)$ is a parameter.

$$\begin{aligned} a_c &\equiv a(\hat{K}_b - \hat{K}_f) \times \frac{E}{L} \\ \hat{K}_b &= a_b(1 + \xi_b) \\ \hat{K}_f &= a_f(1 + \xi_f) \end{aligned}$$

where, a is a parameter of substrate, \hat{K}_b is a parameter of backward drive roll and \hat{K}_f is a parameter of forward drive roll.

5 Numerical simulation

Fig.7 shows a solution process of tension C described by Eqn.(4.1). Fig.8 shows a solution process of Brownian motion $W_\sigma(t)$ in Eqn.(4.1). Fig.9 shows a measurement process $\xi(t)$ obtained by Kalman Filter in Eqn.(4.2). Fig.10 shows an estimation process $\mu(t)$ obtained by Kalman Filter in Eqn.(4.15). Table.3 represents each parameter of Fig.7-10 used in the numerical simulation.

Table. 3: Description of Figure 7– 10

Fig.No.	Fig.7	Fig.8	Fig.9	Fig.10
Average	$a_c = 0.14$	-	$a_c = 0.14$	$a_c = 0.14$
Volatility	$b_\sigma = 0.02$	-	$b_\sigma = 0.02, b_m = 0.2$	$b_\sigma = 0.2, g = 0.1596$

6 Results

By treating the roll-transport system as a lumped kinetic model on drive rolls between stages, we were able to clarify the tension point origin (or drive roll point). We proposed a mathematical model of the system and a highly feasible tension control system design. The mathematical model

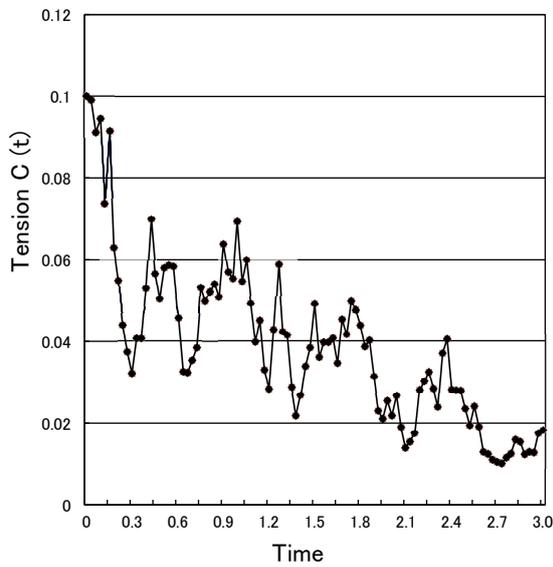


Fig. 7: Solution process tension C of stochastic differential equation

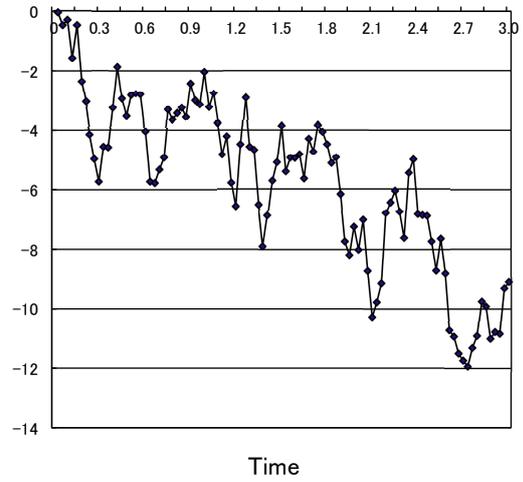


Fig. 8: Solution process $W_\sigma(t)$ of Brownian motion

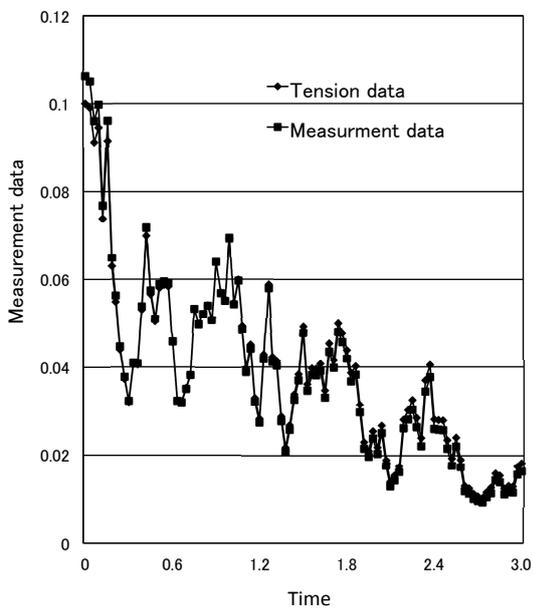


Fig. 9: Measurement process $\xi(t)$ by Kalman Filter

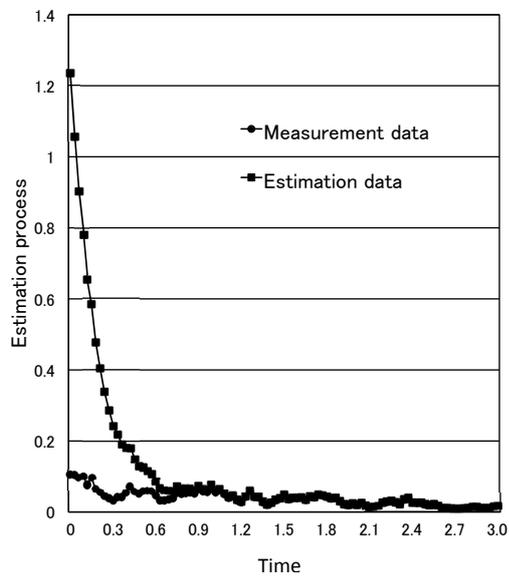


Fig. 10: Estimation process $\mu(t)$ by Kalman Filter

considered the tension that occurred at the stands between rolls, and the tension control system was a lumped parameter model described by the ODE. The ODE was derived from certain equilibrium conditions that balance the spatial forward deviation at the stands between rolls with the temporal variation of the tension.

The main problem occurred with slipping in the driving roll that is attached to the sheet transport system, creating slackening (back tension) or heightening of tension (tension). The tension was quantified on the basis of Young's modulus acting as a macro parameter and on the speed deviation between separate rolls.

In designing an optimal estimation system, a tension model was required for the peripheral speed difference of rolls between the drive roll and the variable. We proposed a tension estimation method using the Kalman filter theory in optimal control theory. We verified that our theory was reasonable by demonstrating numerical simulation.

References

- [1] Kenji Shirai and Yoshinori Amano: Mathematical Analysis of Vapor Diffusion Process for Impregnated Solvent on Sheet-Type Films-Diffusion Status Model for Designing a Control System Configuration-; Niigata University of International and Information Studies Bulletin, 2013, No.16, p.117-133
- [2] Kenji Shirai and Yoshinori Amano: State Estimation of Impregnated Sheet Substrates in a Drying Oven Niigata University of International and Information Studies Bulletin, 2014, No.16, p.117-133
- [3] Kenji Shirai and Yoshinori Amano: A dynamic span model and associated control strategy for roll transport systems for sheet-type materials (Part I) ; Niigata University of International and Information Studies Bulletin, 2014, No.16, p.117-133
- [4] Osamu Takehira: Transport simulation of sheets; Ricoh Technical Report, 1999, No.25
- [5] Jun Yanagimoto: Rolling theory(Elementary level) ; Institute of Industrial Science, University of Tokyo, p.3-77
- [6] Yanagimoto: Rolling theory(Intermediate level) ; Institute of Industrial Science, University of Tokyo, p.78-104
- [7] Ken Nishida, etc: Film transport and control of speed and tension in the winding; Technical Information Institute, 2013, p.47-56
- [8] Shoichirou Koide: Physics; Shokabo,co, LTD, 2003
- [9] Cheng Hui,etc: Development of A Simulation System for Sheet Transport Path, The Japan Society of Mechanical Engineers, 2006, vol.72, no.722, p.3162-3169,
- [10] Hitoshi Kushida, etc: Sizing Mill Rolling Technology for Close-tolerance Wire Rod; Kobe Steel Ltd. R and D Kobe Steel Technical Report, 2000, vol.50, no.1, p.25-28
- [11] Ichirou Hasegawa, etc: A model for estimation of forward slip rate and investigation of model accuracy; Development of forward slip rate control II(Shaping and Fabrication • Instrumentation and Control, The 111th ISIJ Meeting), 1986, p.376
- [12] Katuya Takada, etc: Tension Control Technology for Wire Rod Rolling; Kobe Steel Ltd. RD Engineering Report, 2006, vol. 56, no. 3

- [13] kazuya Asano, etc: Stabilization of Tension Control in Reverse Rolling by Using State Feedback; JFE Technical report, 2007, no.15, p.12-17
- [14] Jun Yanagimoto: The thickness of the tandem mill and Tension control; University of Tokyo Press, 1999
- [15] Takayuki Koizumi, etc: Analysis of A Slip-Phenomenon of Paper Feeding System, The Japan Society of Mechanical Engineers, Dynamics and Design Conference, 2000, no.00-6
- [16] Kenji Shirai and Yoshinori Amano, etc: Mathematical Model of Thermal Reaction Process for External Heating Equipment in the Manufacture of Semiconductors(Part1); International Journal of Innovative Computing, Information and Control, 2013, vol.9, no.4, p.1557-1571
- [17] Kenji Shirai and Yoshinori Amano, etc: Mathematical Model of Thermal Reaction Process for External Heating Equipment in the Manufacture of Semiconductors(Part2); International Journal of Innovative Computing, Information and Control, 2013, vol.9, no.5, p.1889-1898
- [18] Kenji Shirai, Yoshinori Amano and Sigeru Omatu: Throughput Analysis for Manufacturing Process by Using a Kalman Filter Theory under Uncertainty based on Physical Approach; International Journal of Innovative Computing, Information and Control, Volume 9, Number 11, pp.4431-4445, November, 2013
- [19] Japan Society of Mechanical Engineers: Mechanical Engineering Encyclopedia; Maruzen co.Ltd, 2007