

Development of a Lateral Control Simulation Software for Roll-to-Roll Systems

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Abstract: This paper presents the development and simulation results of a computer simulation software for the lateral position control of a moving web in roll-to-roll (R2R) systems. Mathematical models of the web dynamics are described first to explain the lateral motion of a moving web. Based on the models, a controller that employs the PID control method is developed, and embedded in simulation software named LACOSIM. The software is for simulating the lateral dynamics of a moving web and controlling a lateral position error in R2R systems. Simulation results show that the software can be a useful tool for the development of a web guide system for R2R systems.

1. INTRODUCTION

Roll-to-roll (R2R) printing systems have been popularly used in the traditional packaging industry, but recently is found to have a great potential for the mass production of electronic devices including RFID, electronic paper, solar cells, and display. The R2R method in printed electronics (also known as e-printing) has great advantages in that it can be highly effective in the cost and also applicable to flexible and thin materials. However, unlike traditional printing processes, printed electronics requires the accuracy at a much higher level, and so the precision in the lateral position control of a moving web should be even more important for the success of R2R system in printed electronics.

In order to implement lateral position control methods, a mathematical model is described first to explain the lateral dynamics of a moving web. The model is based on web guide systems that are usually used to correct the lateral position error of a web in R2R systems.

The main work presented in the paper is the development of a simulation and control software for a web guide system. The software employs the mathematical model and PID control method in a graphical environment. The software unifies the simulation and control of lateral position of a web in a unique interface.

2. SYSTEM MODEL

In order for building a simulation and control system of lateral position, we introduce two mathematical models that describe the dynamics of a moving web. They are called Shelton's first and second order models. They present the relation of the lateral velocity to the longitudinal velocity, the

guide dynamics, and the input error at the previous roll in a single span guide.

2.1 First Order Dynamic Model of a Moving Web

The first order model is a simplified one based on the fundamental law of static steering, which is that the web in the entering span aligns itself perpendicularly to the roller. The model is built under the assumption that the mass and the lateral stiffness of the web are negligible. Accordingly the web is straight in each span and also it makes sharp angular breaks as it leaves each roller in a series of non-parallel rollers (Shelton J.J., 1968). Fig. 1 shows the idealized web behaviour with the input error.

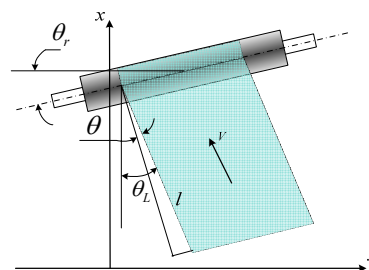


Fig. 1. Behaviour of idealized web.

The lateral displacement and the velocity are expressed in (1) and (2) when Δy is the lateral displacement, l is the distance between two rollers, θ_r is the angle between roller and y axis, θ_L is the web angle measured from the x axis, and v_L is the rate of lateral movement (Shelton J.J. and Reid K.N., 1971a).

$$\Delta y = l(\theta_L - \theta_r) \quad (1)$$

$$v_L = V(\theta_L - \theta_r) \quad (2)$$

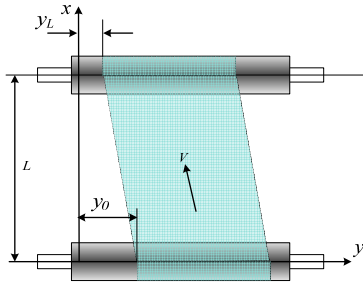


Fig. 2. Model of fixed parallel guides.

If the roller moves laterally and has a position z , this movement should be included in the velocity of web edge. As a result the first order equation of lateral velocity is obtained in (3).

$$\frac{dy}{dt} = V(\theta_L - \theta_r) + \frac{dz}{dt} \quad (3)$$

There is a specific case is where two rollers are parallel and fixed as shown in Fig. 2. Since there is no roller movement component, the following equation is obtained by taking the Laplace transform with zero initial condition:

$$sY_L(s) = -\frac{V}{L}Y_L(s) + \frac{V}{L}Y_0(s) \quad (4)$$

If we let $\tau = T/V$ be a time constant, the result is

$$\frac{Y_L(s)}{Y_0(s)} = \frac{1}{\tau s + 1} \quad (5)$$

2.2 Second Order Model

This model is for describing the lateral dynamics of a massless, moving web when the stiffness and several properties are considered (Shelton J.J. and Reid K.N., 1971b). Under the pure bending, the elastic deformation of a web can be described by the fourth-order differential equation:

$$\frac{\partial^4 y}{\partial x^4} - K^2 \frac{\partial^2 y}{\partial x^2} = 0, \quad K = \sqrt{\frac{T}{EI}} \quad (6)$$

where EI is the bending stiffness of web material. The general solution of linear ordinary differential equation is:

$$y = C_1 \sinh(Kx) + C_2 \cosh(Kx) + C_3 x + C_4 \quad (7)$$

Fig. 3 describes the boundary conditions of a basic free span web.

The total curvature equation of the web at downstream roller can be obtained

$$\frac{\partial^2 y}{\partial x^2} \Big|_L = \frac{f_1(KL)}{L^2}(y_0 - y_L) + \frac{f_2(KL)}{L}\theta_L + \frac{f_3(KL)}{L}\theta_0 \quad (8)$$

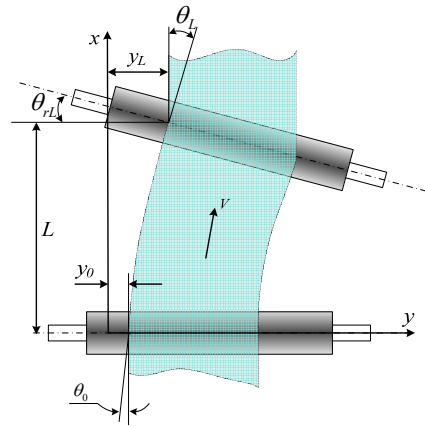


Fig. 3. Boundary condition of a basic free span web

$$\begin{aligned} f_1(KL) &= \frac{(KL)^2 (\cosh(KL) - 1)}{KL \sinh(KL) - 2 \cosh(KL) + 2} \\ f_2(KL) &= \frac{KL(KL \cosh(KL) - \sinh(KL))}{KL \sinh(KL) - 2 \cosh(KL) + 2} \\ f_3(KL) &= \frac{KL(\sinh(KL) - KL)}{KL \sinh(KL) - 2 \cosh(KL) + 2} \end{aligned} \quad (9)$$

Under the assumptions of negligible web mass and shear deflection, uniform web thickness, and no slip between the web and strip, the lateral velocity and acceleration are

$$\frac{dy_L}{dt} = V \left(\theta_r - \frac{\partial y}{\partial x} \Big|_L \right) + \frac{dz}{dt} \quad (10)$$

$$\frac{d^2 y_L}{dt^2} = V^2 \frac{\partial^2 y}{\partial x^2} \Big|_L + \frac{d^2 z}{dt^2} \quad (11)$$

where θ_r is the angle of downstream roller.

Fig. 4 shows a case in which two rollers are parallel and fixed, so the downstream roller does not move. As a result the roller velocity is dz/dt , the roller acceleration is d^2z/dt^2 and the roller angle is zero in (10) and (11).

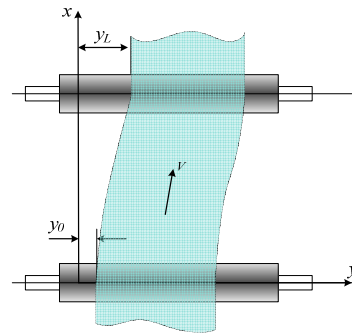


Fig. 4. Fixed parallel guides with real web

Therefore we get

$$\frac{dy_L}{dt} = -V \frac{\partial y}{\partial x} \quad (12)$$

Since θ_L is equal to dy/dt ,

$$\theta_L = -\frac{1}{V} \frac{dy_L}{dt} \quad (13)$$

Comparing (10), (11) and (13) yields

$$\frac{d^2 y_L}{dt^2} = \frac{V^2}{L^2} f_1(KL) y_0 - \frac{V^2}{L^2} f_1(KL) y_L - \frac{V}{L} f_2(KL) \frac{dy_L}{dt} \quad (14)$$

The transfer function of the second order model is attained by taking Laplace transform and rearrangement of (14):

$$\frac{Y_L(s)}{Y_0(s)} = \frac{\frac{f_1(KL)}{\tau^2}}{s^2 + \frac{f_2(KL)}{\tau} s + \frac{f_1(KL)}{\tau^2}}, \quad \tau = \frac{L}{V} \quad (15)$$

3. LATERAL POSITION CONTROL

In R2R systems, web guide systems are usually used to correct the lateral position error of a web. When a web is thin and flexible like plastic and the width is small, the displacement guide (DG) with a short span can be useful. Fig. 5 illustrates the web simulator model, which is used for our lateral position control. The web simulator system includes two displacement guides where DG2 is the main guide that corrects the lateral position error as the web runs through, while DG1 serves as a disturbance generation source to generate sine or step input errors (Shin K.H., *et al.*, 2004).

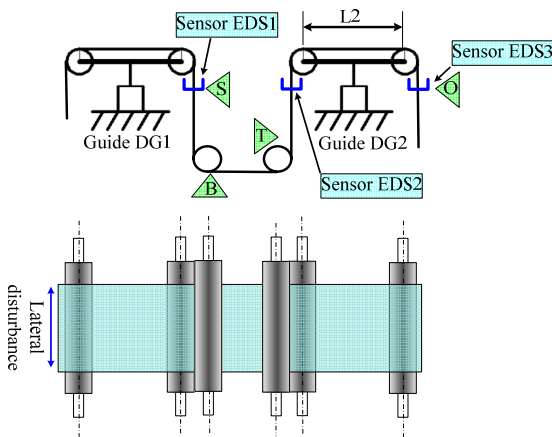


Fig. 5. Web simulator model

Three sensors are set at the points S, T, and O immediately after the exit of each guide. Sensors for the web guide system can be ultrasonic or infrared edge detect sensor (EDS). The sensor EDS1 at S measures the output from the guide DG1 then also gives the value of lateral error at this point, and the sensor EDS2 determines the lateral error at T. The sensors EDS1 and EDS2 are called observers. The sensor EDS3 is used for the feedback controller, i.e. the output value of this sensor is the lateral error at the controlled position, point O. the EDS3 signal is fed back to the controller. The lateral control acts on the guide DG2 to keep the lateral position at the controlled point, point O in Fig. 5 with any lateral disturbance input.

3.1 PID Controller

This section describes the design and simulation results of a PID Controller for the web guide system (Dorf R.C. and Bishop R.H., 2000). Fig. 6 shows the block diagram of the lateral control system where the guide system is the combination of a DC motor model, a guidance platform, and web dynamics model.

In the guide system, the mathematical model of motor is

$$G_m(s) = \frac{\theta(s)}{U(s)} = \frac{K/LJ}{s \left[s^2 + \left(\frac{b}{J} + \frac{R}{L} \right) s + \frac{Rb + K^2}{LJ} \right]} \quad (16)$$

where K , R , L , b and J are parameters of the motor and mechanics system and U is the input voltage and θ denotes the motor angular position.

The mathematical model for the displacement guide is

$$G_g(s) = \frac{Y_L(s)}{Z(s)} = \frac{\tau^2 (L_2/L_p) s^2 + (1 + L_2/L_p) \tau s + L_2/L_p}{\tau^2 (L_2/L_p) s^2 + (1 + L_2/L_p) \tau s + 1}, \quad \tau = \frac{L_2}{V} \quad (17)$$

where L_2 is the length of DG2, L_p is the distance from guide roller to the instant centre and z is the lateral motion of the downstream roller. In the guide DG2, z is proportional to θ .

$$Z(s) = C_m \theta(s) \quad (18)$$

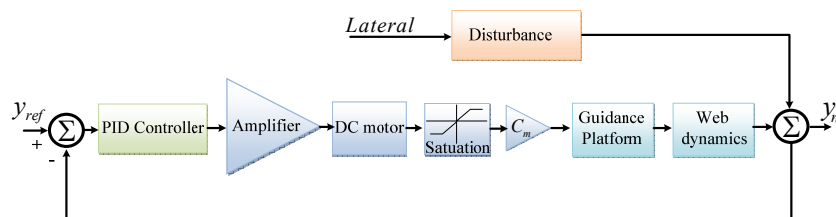


Fig. 6. PID control system for the web simulator

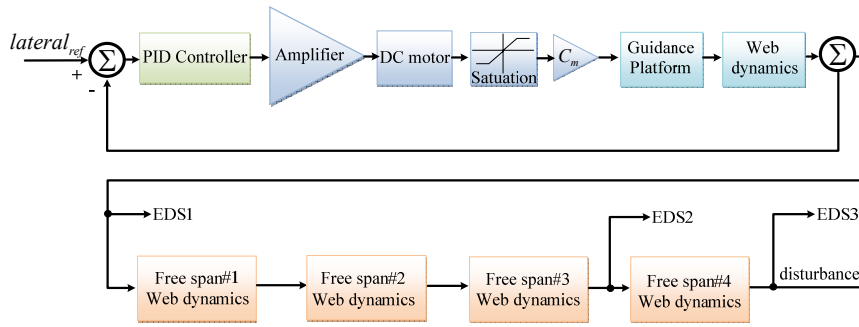


Fig. 7. Lateral disturbance generation and transport system

As described earlier, the lateral disturbance is generated by the guide DG1, and the same PID controller is applied for DG1 in order to make a desired lateral error. Fig. 7 displays the block diagram of lateral disturbance generation and transfer process. The lateral disturbance generated by DG1 is transferred to the downstream roller of guide DG2 through four free web spans, and the configuration of this span is considered similar to the fixed parallel rollers configuration, so the second order model in (18) will be applied for these spans.

3.2 Simulation Results

The simulation model for lateral position control in Fig. 6 and 7 is built in SIMULINK®. Parameters of the motor model are from DC brush motor ID23007 of MCG Motion control group. More detailed information is presented in Table 1.

Numerous simulations were conducted with the web simulator model and the PID controller. The operating tension and the line speed were set to be 3 kg and 2 m/sec, respectively (Shin K.H., *et al.*, 2004). Fig. 8 shows the step response in the simulation and Fig. 9 illustrates the response of system to sine input.

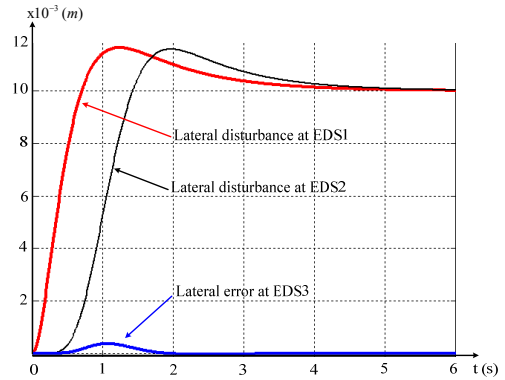


Fig. 8. Response of web simulator to step input

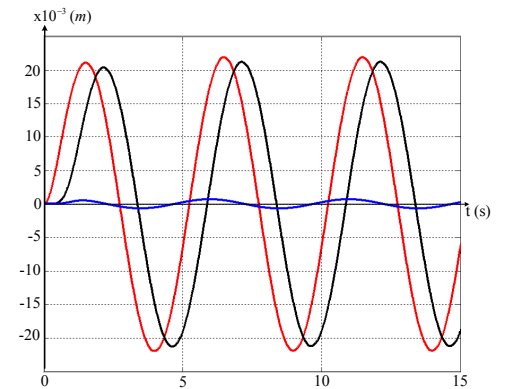


Fig. 9. Response of web simulator to sine input

Table 1. Simulation information

Parameter	Symbol	Value
Length span on guide	L1, L2	0.380 m
Distance from roller to centre point	Lp	0.380 m
Operating tension	T	3 kg
Web line speed	V	2 m/s
Web material		Polyester (P.E.T)
Frequency of sine lateral disturbance source	f	0.1 Hz
Amplitude of sine lateral disturbance source	A	0.02 m
P gain of PID controller	P	98
I gain of PID controller	I	21
D gain of PID controller	D	15

In the simulation work, the P, I and D gains of PID controller are set to be 98, 21 and 15, respectively. Simulation results show that the controller performs in a desired way for two kinds of input disturbance. As Fig. 8 and 9 shows, the lateral error at the downstream roller is about 5% of the input disturbance at the previous roll. The results verify that the PID controller performs successfully to reject the lateral disturbance in R2R systems.

4. LACOSIM – WEB LATERAL MOTION AND CONTROL SIMULATION SOFTWARE

Simulink of Matlab provides a large advantage in the simulation work due to numerous functions and toolbox. However, the software lacks visualization ability in the

simulation and is not easy to be connected to real control hardware. Several motion simulation softwares such as ADAMS, Nastran (MSC software corporation) or Recurdyn (FunctionBay, Inc.) can be useful for kinematics and dynamics analysis, but simulation work is usually more complicated and computationally expensive. In addition, the dynamics of a moving web is relatively complex, and the simulation model for R2R system is rarely found in motion simulation softwares.

Our software named LACOSIM (Lateral Motion and Control Simulation) has several fundamental functions: first it can implement the dynamics of a moving web and the mathematical model of a DC motor; second several control algorithms such as PID and fuzzy are applied in the software to control a virtual guide system in a web transport system; third LACOSIM itself can work as a control software for a real web guide system. Fig. 10 shows the interface of the LACOSIM software and Fig. 11 shows the software structure.

LACOSIM is constructed by C++ programming language with the graphic library OpenGL. The software interface includes components including the main view, graph windows, control bars and dialog systems. The main view window contains the 3D model of web guide system.

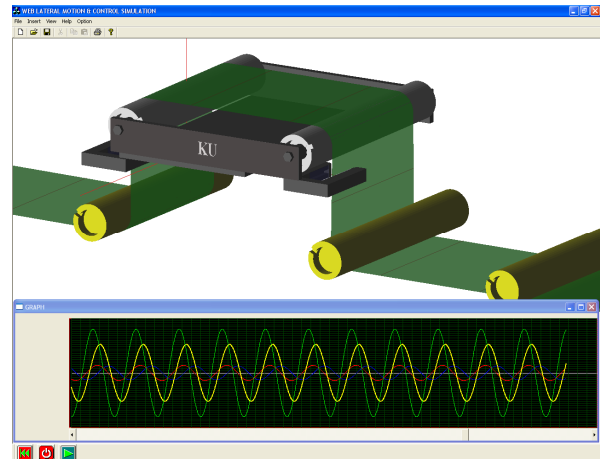


Fig. 10. Interface of LACOSIM software

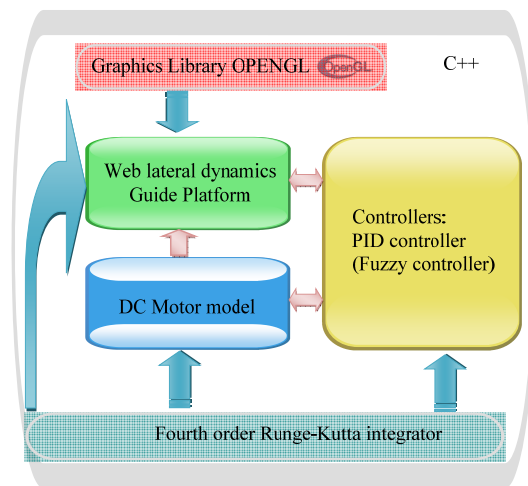


Fig. 11. Structure of LACOSIM software

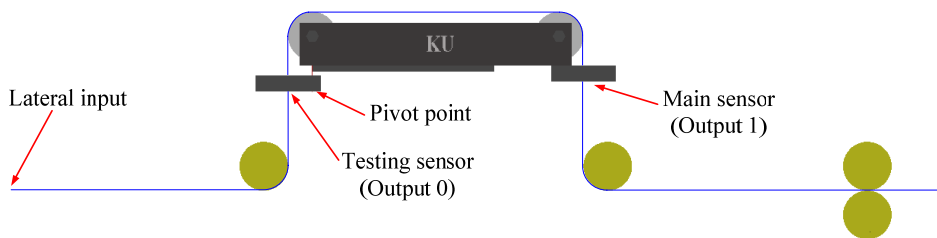


Fig. 12. Web guide model in LACOSIM

Compared with the web simulator model in Fig. 5 there is only one guide in this model in Fig. 12, i.e., the guide DG1 was removed from point B (see Fig. 5) and the disturbance is generated directly at B. The user interface system of LACOSIM allows users to set and change the parameters of guide system, web properties, and controller gains. The simulation results can be shown in graph windows and saved to files.

All the ordinary differential equations (ODE) in LACOSIM are solved by the fourth order Runge-Kutta numerical method

(RK4) (Johnston R.L., 1982), (Salleh S., Zomaya A.Y., Olariu S, Sanugi B., 2005). RK4 method is known to be very accurate and well-behaved for a wide range of problems. Since all the ODEs of mathematical models in the web simulator system are of higher order, RK4 could not be applied directly. Therefore the mathematical models were converted to state variable forms and KR4 method was implemented.

The results from solving ODE of mathematical models combined with the output of the controllers become the

motions of guide and web in 3D graphics environments. As a result, both the real motion and response graph can be observed.

Several simulations were done in the same condition shown in Table 1, and Fig. 13 shows the response of system to the step input and Fig. 14 displays the result of sine signal. Compared with the results in Fig. 8 and Fig. 9, the lateral error in the LACOSIM software is a little larger because the lateral disturbance is applied directly at the point B which is near the position O, where we want to reject the lateral error. In a real web transport system, a web guide should be set up immediately before the process position.

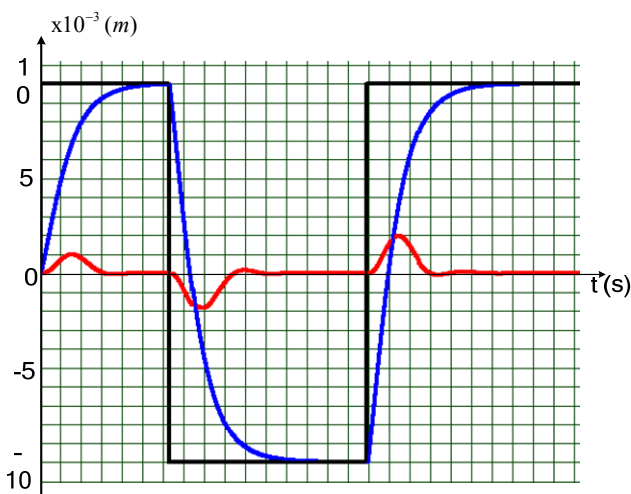


Fig. 13. Simulation result of web guide in LASOSIM with step input.

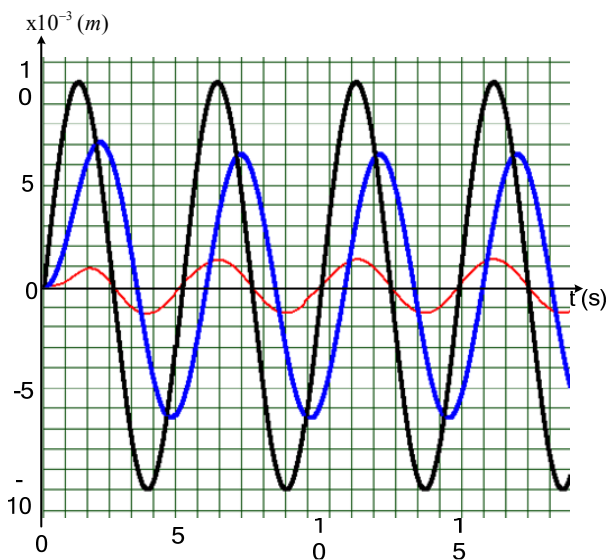


Fig. 14. Sine response of LACOSIM.

5. CONCLUSIONS

A web simulator model and a control method for the lateral position control of a moving web in R2R systems are reported in the paper. The suggested PID controller produced a good result when it was implemented in the web simulator. The LACOSIM software which combines modelling, simulation, and controller in a unique interface also showed a successful performance. The web simulator model and LACOSIM are considered as an important step toward building a web guide system in R2R process. In particular, as R2R methodology is considered as an ideal solution to the mass production of electronic devices and the new application requires a higher accuracy in the control, our software can be quite a useful tool.

However some aspects still need to be improved. A combination of several guides to eliminate the large amplitude and high frequency error can be applied and a fuzzy controller is planned to be added to the LACOSIM software.

REFERENCES

- Shelton J.J. (1968). *Lateral dynamics of moving web*, Ph.D, dissertation, Dept. Mech., Eng., Oklahoma State Univ., Stillwater, Oklahoma.
- Shelton J.J and Reid K.N. (1971). *Lateral dynamics of an idealized moving web*, Trans. ASME, J. Dyn. Syst. Meas. Control, ser. G, no. 3, pp. 187-192.
- Shelton J.J and Reid K.N. (1971). *Lateral dynamics of a real moving web*, Trans. ASME, J. Dyn. Syst. Meas. Control, ser. G, no. 3, pp. 180-186.
- Shin K.H., Kwon S.O., Kim S.H, and Song S.H. (2004). Feedforward control of the lateral position of a moving web using system identification. *Industry Application, IEEE Transaction*, Vol. 40, 1637-1643.
- Dorf R.C. and Bishop R.H. (2000). *Modern control system*, 174-784. Prentice Hall International.
- Johnston R.L. (1982). *Numerical methods A software approach*, Chap. 2, 6. John Wiley. USA.
- Salleh S., Zomaya A.Y., Olariu S, Sanugi B. (2005). *Numerical simulations and case studies using Visual C++.Net*, Chap. 4, 5. John Wiley. New Jersey.