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Mathematical Modeling and Performance Analysis of Various Tuning Methods for PID Controller of Web Guide in Cold Rolling Mill using Particle Swarm Optimization Techniques

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Abstract
This work deals with design of controller for the intermediate web guide in a cold rolling mill using various tuning methods. Productivity in the web guide which relates the speed of the process and the position. Enhancing the productivity leads to a tangential misalignment of the web hence a tool for executive the position of the web is introduced. To locate the web on the part-way position of roller, a PID controller has been designed using various tuning methods. The web and guides are intended to use the geometrical relations by avoiding the stiffness and mass of the web. The particle swarm optimization (PSO) is used in this work for tuning the controller. The simulator using the PSO tuning methods was ripened to unzip the desired position tenancy of the web and the efficiency of the proposed tenancy is analyzed by relating with other tuning methods. It is shown from the simulation results that the performance with respect to the tuning using PSO tenancy scheme of the web is profoundly improved.

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1. Introduction

Rolling is the most widely used deformation process. It consists of passing metal between two rollers which shrink it to reduce its thickness. Cold rolling is one among the utmost vital processes in an combined steel works considering it improves the accuracy in executing the sizes and yields thinner gauge products with a unexceptionable plane surface. Compared to hot rolling, the sheets, strips and foils in cold rolling have largest dimensional accuracy, upper quality, surface finish and mechanical properties [1].

2. Mathematical Model

Displacement type web guide is shown in figure 1. The dynamic property of the mass is taken into consideration [20].

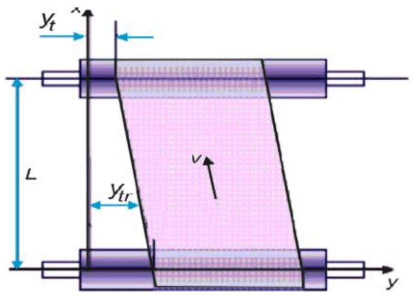

Figure 1: Displacement type web guide

L - Distance between two rollers, v - Line speed, θ_r - Angle between the roller and y axis, and θ_L is the web angle with respect to the x- axis.

$$\frac{\partial^4 y}{\partial x^4} - k^2 \frac{\partial^2 y}{\partial x^2} = 0, k = \sqrt{\frac{T}{EI}} \qquad \textbf{(1)}$$

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where, EI - bending stiffness of the web material. Assuming insignificant web mass and shear deflection with unvarying web thickness, the velocity and acceleration are given as,

$$\frac{dy_L}{dt} = v\left(\theta_r - \frac{\partial y}{\partial x}\right) + \frac{dz}{dt} \quad \textbf{(2)}$$

$$\frac{d^2y_L}{dt^2} = v^2\frac{\partial^2 y}{\partial x^2} + \frac{d^2z}{dt^2} \quad \textbf{(3)}$$

where, θ_r is the angle of downstream roller. There are two types of web guides namely the steering type and displacement type. In steering type, the inaccuracies of the web locus can be abridged by steering the upstream roller which travels linearly and rotationally. Displacement type guide has two cascaded type upstream rollers. With the lateral motion of the second upstream rollers z, the primary roller is horizontally moved to adjust the web.

Hence, $\frac{dy_L}{dt} = -v\frac{\partial z}{\partial x}$; Since $\theta_L = dy/dt$,

$$\theta_L = -\frac{1}{v}\frac{dy_L}{dt} \quad \textbf{(4)}$$

3. Lateral Position Control

Web guided systems are typically used to precise the lateral position error of a web. Mathematical models are essential for simulation work. Shelton[14] has developed a first order model of the web **beneath** the **precept** that the **web** span aligns themself vertically to the roller

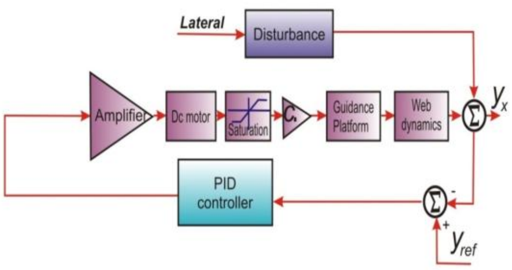

Figure 2: Simple block diagram of a web controller

Figure 2 shows the block diagram of the adjacent position control system. For the guiding system, the mathematical model of the motor is derived as,

$$G_m(s) = \frac{\theta(s)}{U(s)} = \frac{K/LJ}{s\left[s^2 + (\frac{b}{J} + \frac{R}{L})s + \frac{Rb+K^2}{LJ}\right]} \quad \textbf{(6)}$$

R- The Motor's armature resistance (Ohms), L-The Armature's inductance (Henry), b- Damping of the DC motor and accessories (Ns/rad). Where U is input voltage and θ is the motor angular position. The values of the motor parameter are given by,
Armature Resistance (R) - 0.6 Ohm; Armature Inductance (L) - 0.008 Henry
Ineria Constant (J) - 0.011 NM^2, Damping Constant (b)- 0.004 NM/Radiant / Sec
Torque Constant (K) - 0.55
The mathematical modelling for the displacement guide is given by,

$$\frac{Y_L(s)}{Z(s)} = \frac{\tau^2(L_2/L_p)s^2 + (1+L_2/L_p)\tau s + L_2/L_p}{\tau^2(L_2/L_p)s^2 + (1+L_2/L_p)\tau s + 1}, \quad \tau = \frac{L_2}{L_p} \quad \textbf{(7)}$$

where L_2 is the length of displacement guide 2, L_p is the guide roller distance from the center and z is the adjacent gesture of the downstream roller. For the monitor of DG2, z is proportional to θ.

$$z(s) = C_m\,\theta(s) \quad \textbf{(8)}$$

$$\theta(s) = \frac{K/LJ}{s\left[s^2 + (\frac{b}{J} + \frac{R}{L})s + \frac{Rb+K^2}{LJ}\right]}U(s) \quad \textbf{(9)}$$

Substituting $\theta(s)$ in equation 8, z(s) is obtained as,

$$z(s) = \frac{K/LJ}{s\left[s^2 + (\frac{b}{J} + \frac{R}{L})s + \frac{Rb+K^2}{LJ}\right]}U(s)*C_m \quad \textbf{(10)}$$

Combining the equations 8, 9 and 10, the calculated model of the translation guide can be written as,

$$\frac{Y_L(s)}{Z(s)} * \frac{Z(s)}{U(s)} = \left[\frac{\tau^2(L_2/L_p)s^2 + (1+L_2/L_p)\tau s + L_2/L_p}{\tau^2(L_2/L_p)s^2 + (1+L_2/L_p)\tau s + 1}\right]\left[\frac{K/LJ * C_m}{s\left[s^2 + (\frac{b}{J} + \frac{R}{L})s + \frac{Rb+K^2}{LJ}\right]}\right] \quad \textbf{(11)}$$

with the added derivative uncertainties, discounting the mass and stiffness, the active model of the web's guide is given by,

$$G_D(s) = \frac{\beta_{D3}s^3 + \beta_{D2}s^2 + \beta_{D1}s + \beta_{D0}}{s^5 + \alpha_{D4}s^4 + \alpha_{D3}s^3 + \alpha_{D2}s^2 + \alpha_{D1}s + \alpha_{D0}} \quad \textbf{(13)}$$

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where the coefficients are given by,

$$\beta_{D3} = K_D * (K/_{LJ} * C_m) \ ; \ \beta_{D2} = (K/_{LJ} * C_m) * \left[K + K_D \left(1 + \frac{(L_2/L_p)\tau}{\tau^2 (L_2/L_p)}\right) \right]$$

$$\beta_{D1} = (K/_{LJ} * C_m) * \left[\frac{K_D}{\tau^2} + \frac{(1 + (L_2/L_p))}{\tau^2 (L_2/L_p)} \right]$$

$$\beta_{D0} = \frac{K}{\tau^2} * (K/_{LJ} * C_m); \ \alpha_{D4} = \frac{\left[\left(\frac{b}{J} + \frac{R}{L} \right) + \tau \left(1 + \frac{L_2}{L_p} \right) \right]}{\tau^2 \frac{L_2}{L_p}};$$

$$\alpha_{D3} = \frac{\left[1 + \left(\frac{R_b + K^2}{LJ} \right) + \left(1 + \frac{L_2}{L_p} \right) \left(\frac{b}{J} + \frac{R}{L} \right) \right]}{\tau^2 \frac{L_2}{L_p}},$$

$$\alpha_{D2} = \frac{\left[1 + \left(\frac{R_b + K^2}{LJ} \right) * \left(1 + \frac{L_2}{L_p} \right) \tau + \left(\frac{b}{J} + \frac{R}{L} \right) \right]}{\tau^2 \frac{L_2}{L_p}},$$

$$\alpha_{D1} = \left(\frac{\frac{R_b + K^2}{LJ}}{\tau^2 \frac{L_2}{L_p}} \right)$$

where L_1, L_2 - Distance end to end of span , L_p - Length between roller to center point of the web , T – Tension , V- Online speed

Model reservations exists in the web speed V= [1,5]m/s and load pressure $P_L \in [20, 200]$ kg.f/cm^2. The coefficients of the displacement type web guide are given as intervals by,

$\beta_{D3} \in [3.5 \ \ 24]$; $\beta_{D2} \in [5 \ \ 29]$; $\beta_{D1} \in [0.9 \ \ 5]$; $\beta_{D0} \in [0.05 \ \ 3]$

α_{D4} [4 9] ; $\alpha_{D3} \in [4 \ \ 9]$; $\alpha_{D2} \in [0.7 \ \ 2]$; $\alpha_{D1} \in [0.03 \ \ 0.08]$; $\alpha_{D0} \in [0 \ \ 0]$

The mathematical model of the web guide system by considering the minimum, maximum and average values of the interval equation 13 is represented as model1, model2 and model3 respectively. The model1, model2 and model3 of the plant are given by,

Model1

$$= \frac{4.5s^3 + 5s^2 + 0.9s + 0.05}{s^5 + 4s^4 + 4s^3 + +0.7s^2 + 0.03s} \quad \textbf{(14)}$$

Model2

$$= \frac{24s^3 + 29s^2 + 5s + 0.3}{s^5 + 9s^4 + 9s^3 + 2s^2 + 0.08s} \quad \textbf{(15)}$$

Model3=

$$\frac{14.25s^3 + 17s^2 + 2.95s + 0.175}{s^5 + 6.5s^4 + 6.5s^3 + 1.35s^2 + 0.055s} \quad \textbf{(16)}$$

These models have been approximated to First order plus time delay with integrator (FOPTDI) system using the method described by Sundaresan and Krishnamoorthy (1978) [18,19]. Approximation is done by taking out 1/s from the actual model separately, and applying step input, the time constant τ is calculated by $\tau = 0.67(t_2 - t_1)$. The approximated (reduced) model transfer function for the web guide system is given by,

$$\text{Rmodel1} = \frac{1.667}{s(0.5584s+1)} e^{-0.3526s} \quad \textbf{(17)}$$

$$\text{Rmodel2} = \frac{3.75}{s(1.256s+1)} e^{-0.793s} \quad \textbf{(18)}$$

$$\text{Rmodel3} = \frac{3.1818}{s(1.0659s+1)} e^{-0.673s} \quad \textbf{(19)}$$

Controllers have been designed using various techniques for the approximated model transfer function for the web guide system since it is highly complicated to design the controller for the higher order mathematical model of the system. Controllers have been designed using various tuning methods like equating coefficient method (EQ), direct synthesis method (DS), model reference control (MRC) method and dual loop control (DLC) method implemented [11,12,15]. To enhance the performance further, in the present work PID controller is tuned using Ant colony optimization method. In order to demonstrate the effectiveness of the developed methods for set point tracking and disturbance rejection, the IMC and ZN tuning methodologies are chosen for comparison. The performance of the controller under uncertainty in model parameters has been analyzed and its robustness is verified.

4. Implementation of proposed system

Cost function

For the ACO method of tuning the PID parameters there are 3 different cost functions available.

$$f_1 = \int_0^\infty (e(t))^2 dt \quad \textbf{(21)}$$

Second cost function

Here the actual time domain specifications of the system with controller are used to find the cost functions, which is achieved by summing the errors from actual and the specified parameters of the system and is given by

$$f_1 2 = \frac{1}{([c_1 1(t_1 r - t_1 rd) + c_1 2(M_1 p - M_1 pd) + c_1 3(t_1 s - t_1 sd) + c_1 4(e_1 ss - e_1 ssd))} \quad \textbf{(22)}$$

Where c_1 to c_4 are positive constants (weighting factors), their values are chosen conferring to arranging their prominence, ($t_1 rd$) is the preferred rise time, ($M_1 pd$) is the preferred maximum overshoot, ($t_1 sd$) is the preferred settling time, and ($e_1 ssd$) is the preferred steady state error.

Third cost function

A performance criterion in the time domain is projected as given in eqn.23.

$$f_1 3 = \frac{1}{[(1-e^{\tau}(-\beta))(M_1 p + e_1 ss) + e^{\tau}(-\beta)(t_1 s - t_1 r))} \quad \textbf{(23)}$$

This cost function can fulfill the necessities using the weighting factor value β. The factor is fixed more than 0.7 to diminish the overshoot and steady-state error. Also it is set lesser than 0.7 to diminish the rise time and settling time. Hence all the cost functions are minimized subjected to,

$$k_p^{\min} \le k_p \le k_p^{max}$$
$$k_i^{\min} \le k_i \le k_i^{max}$$
$$k_d^{\min} \le k_d \le k_d^{max} \quad \textbf{(24)}$$

Particle Swarm Optimization: Overview

The particle swarm optimization (PSO) algorithm is a popular technique for solving computational problems is reduced in verdict good tracks over graphs. This algorithm is an associate of the ant colony algorithms family, in swarm intelligence techniques, and it institutes some meta heuristic optimizations [17]. The initial algorithm is to search a finest track through the graph based on the activities of the ants searching for a track that is suitable for them to reach their colony from the food source. In the ordinary world, ants (initially) roam aimlessly, and upon discovery of the food they return back to their colony by leaving pheromone trails. If any other ants discover such a path, they are not roaming aimlessly. They instead follow the trail, returning and supporting the trail if they finally find food. Later the pheromone trails gets evaporated, thus dropping its attractive power. Hence if it takes more time to travel through the preferred path and come back again the pheromones will evaporates and thus the path information will get lost. Thus a shortest path gets selected by the frequent usage which is identified by the pheromone concentration which becomes larger on shorter paths than the distant paths. A flow chart for this optimization is shown in figure 5.

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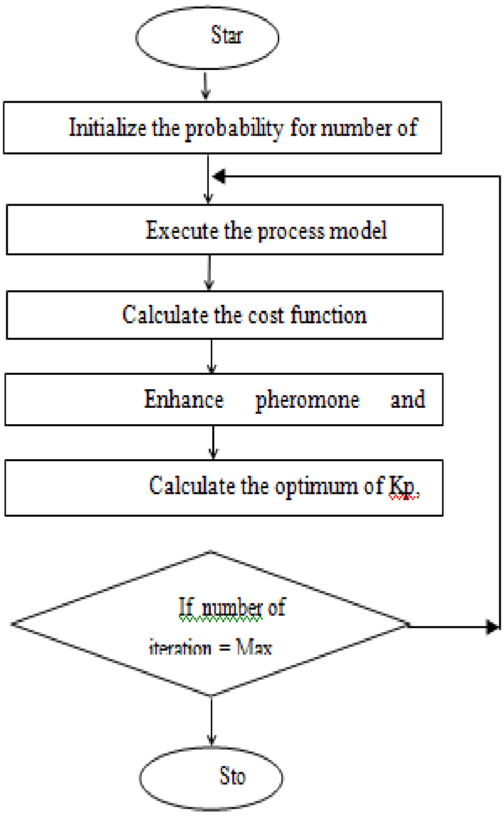

Figure 3: Flow graph of the proposed tuning system

$$p_{ij}(t) = \frac{\tau_{ij}(t)^{\alpha(\frac{1}{d_{ij}})^{\beta}}}{\sum_{j\in nodes}\tau_{ij}(t)^{\alpha(\frac{1}{d_{ij}})^{\beta}}}$$

$$\tau_i(t+1) = (1-\rho)\pi_{ij}(t) + \sum_{\substack{j\in colony\ that\\ used\ edge(i,j)}} \frac{Q}{L_m} \qquad \textbf{(25)}$$

5. Results and Conclusion

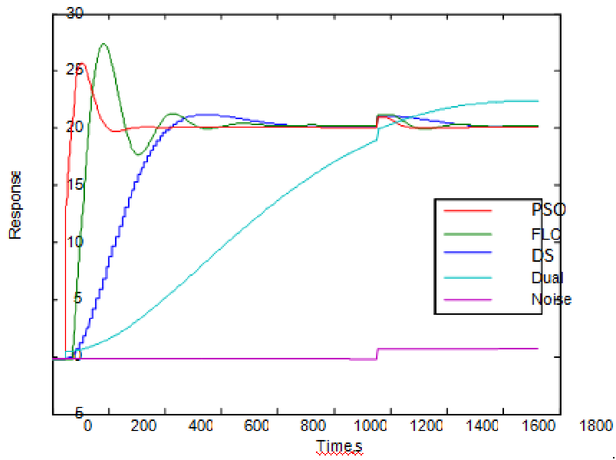

Figure 4: Servo Response of the system with added disturbance
(noise power =0.005 and sampling period=0.1)

The simulation results show the capability of controller tuned using various algorithms. Servo responses of the system with introduction of Gaussian noise is tested and the response is shown in the figure 6.

Table 1: Performance comparison of various tuning methods for servo response

	PSO	FLC	DS	DUAL
ISE	11.2	14.2	17.3	15.2
IAE	97.2	110	177	154
ITAE	88	105.2	116.1	112.5

When the DS and DUAL loop controller almost fails to cope with the added noise perturbation, the PSO controller provides good results. It can also be noticed that the response of the PSO method of tuning settles at the desired setpoint with minimum oscillations compared to other controllers where oscillations persist for quite long time. FLC seems to be on par with PSO with added minor oscillations.

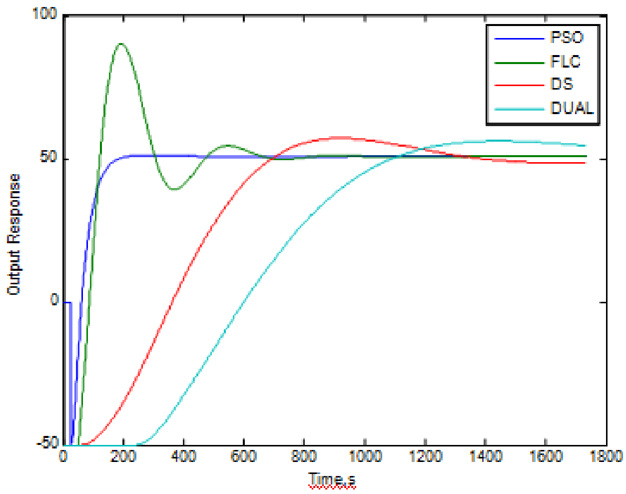

Figure 5: Regulatory response of the system

Table 2 and figure 7 shows the performance comparison of various tuning methods for regulatory response and manipulated variable response with respect to time respectively.

Table 2: Performance comparison of various tuning methods for regulatory response

	PSO	FLC	DS	DUAL
ISE	10.2	12.2	15.3	11.2
IAE	87.2	90	117	124

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ITAE	77	90.6	90.1	91.5

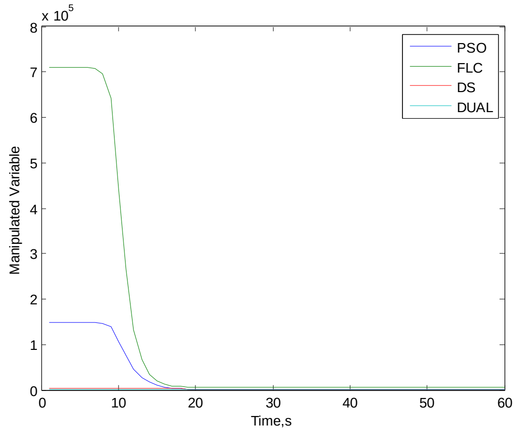

Figure 6: Manipulated Variable Vs Time

The behavior of manipulated variable versus time behavior is shown in Figure 6. In recent years the control system analysis by parametric uncertainties becomes more popular. Hence it is necessary to analyze the stability and robustness for any closed loop system with uncertainties in the method.

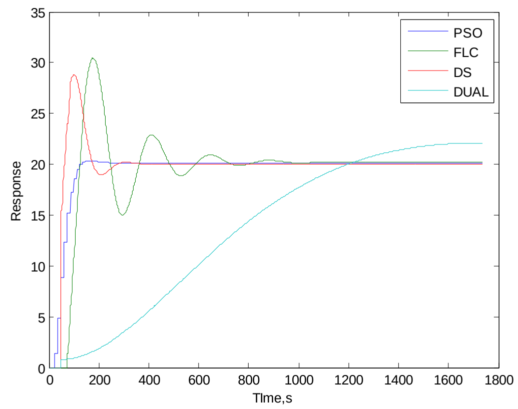

Figure 7: Servo Response of the system with +10% variation of Process Gain

In the figure 7, the process gain of the system is perturbed and the stability of the system is analyzed. In spite of various gain change the PSO settles at lesser time comparatively whereas others shows oscillatory response

Table 3: Performance analysis of various controller with +10% variation of Process Gain

	PSO	FLC	DS	DUAL
ISE	12.2	15.2	18.3	17.2
IAE	98.2	111	182	157
ITAE	89.1	115.2	118.1	122.5

From the Table 3, it is certainly observed that the performance characteristic parameters show better result for PSO method than that of other tuning methods. The controller robustness because of parametric uncertainties has been evaluated by making variation in process gain, time delay and time constant.

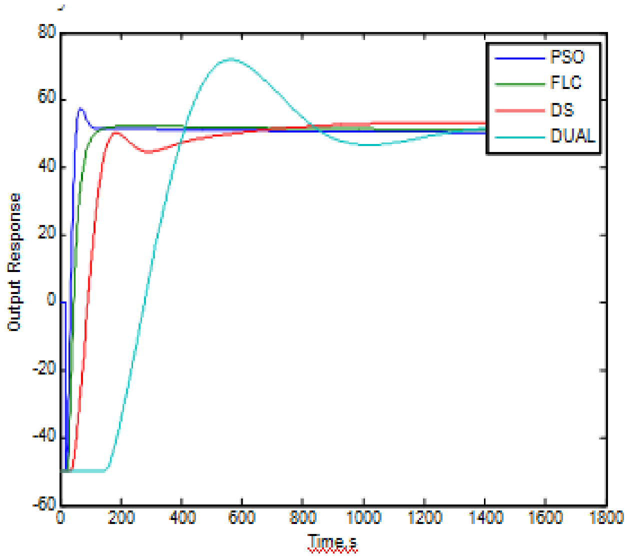

Figure 8: Servo Response of the system with +10% variations in Time constant

Table 4: Performance analysis of various controller with +10% variation in Time constant

	PSO	FLC	DS	DUAL
ISE	12.3	16.2	20	19.2
IAE	99.2	112	191	162
ITAE	89.3	107.2	200.1	114.5

From Figure 8 and its corresponding table 4, it is clearly observed that the response of the system for +10 % variations in time constant and its characteristic parameters respectively are better for the PSO and FLC method of tuning. Also servo response of the system with 10% time delay is depicted in figure 8.

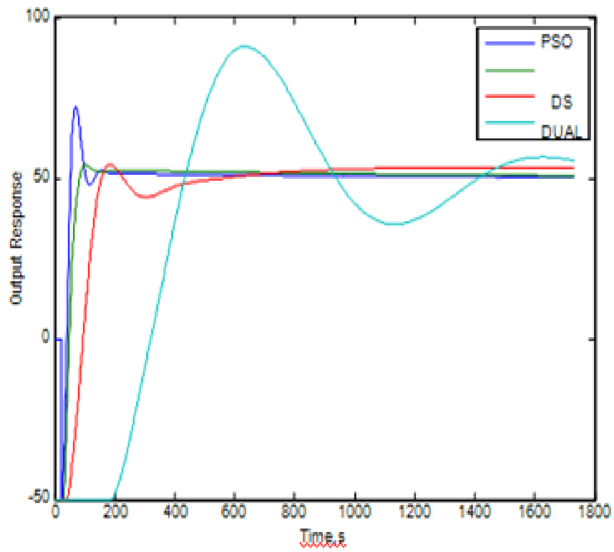

Figure 9: Servo Response with +10% time delay

Table 5. Performance analysis of various controllers with +10% changes in time delay

	PSO	FLC	DS	DUAL
ISE	11.7	16.2	17.3	15.2
IAE	97.8	110	177	154
ITAE	90.4	105.2	116.1	112.5

Simulation of the transfer function model of the web guide system has been tuned using PSO algorithm. The set point response and load disturbance response of the algorithm for the transfer function model of the web guide system have been compared with their corresponding responses obtained using other PID controllers tuned using various algorithms. Servo response of the system with -10% time delay is shown in Figure 10.

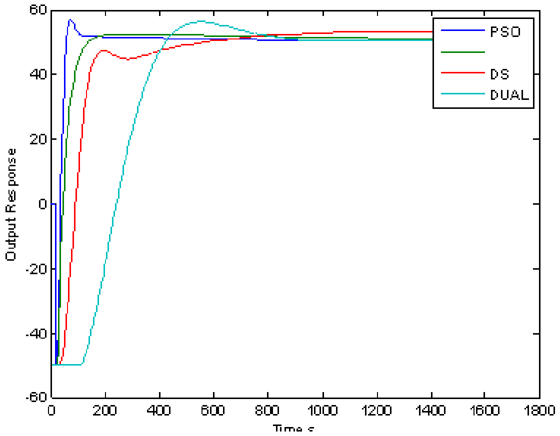

Figure 10: Servo Response with -10% time delays

Table 6: ISE, IAE and ITAE value comparison for various tuning methods for -10% time delays

	PSO	FLC	DS	DUAL
ISE	11.5	16.4	18.3	18.2
IAE	97.1	111.2	175	158
ITAE	90	104.2	115.1	118.5

The extent to which the system endures the ambiguity in model constraints is attained by changing the variable time delay by 10 % with the same controller parameters. The PSO and FLC loop controller settles at the faster rate without any overshoot whereas the DS and DUAL shows sluggish response. An examination of the performance characteristics for the control loops displays that the PSO method of tuning outclasses all the tuning practices. To overcome the problems of dealing with the model complexity and uncertainty, control researchers resorted to more advanced techniques such as the self-tuning (ST) adaptive PID control. In this work, various tuning method have been used to enhance the performance of the PID controller which is used to control the position of the web guide system whose mathematical model has been approximated to transfer function model of the system. The mathematical model of the cold rolling mill has been tuned using various methods like PSO, FLC, DS and Dual loop method of tuning. In this work, particle swarm optimization (PSO) method of tuning the PID controller is proposed and the simulated result is compared in terms of various performance indices like ISE, IAE and ITAE. Comparatively, the PSO method of tuning the PID controller provides improved performance assessment criteria with less Integral Square Error (ISE) and Integral Accumulated Error (IAE) values. In servo response with ±10% variation in time delay and +10% variation in time constant and process gain, PSO method shows marvelous result in terms of settling time and other performance indices as tabulated. Introduction of noise power of 0.005 also shows better performance in PSO and FLC method of tuning. It is concluded from the simulation that the PID controller tuning using the PSO scheme produce remarkable improvements in the performance compare to the conventional and other methods.

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