SELF-TUNING DECENTRALIZED CONTROLLER DESIGN OF WEB TENSION CONTROL SYSTEM

Kazuki Mizoguchi[1], **Tetsuzo Sakamoto**[2]

[1]Kyushu Institute of Technology, Graduate School of Engineering
Tobata, Kitakyushu 804-8550, Japan
[2]Kyushu Institute of Technology, Faculty of Engineering
Tobata, Kitakyushu 804-8550, Japan
sakamoto@cntl.kyutech.ac.jp(Tetsuzo Sakamoto)

Abstract

The paper deals with a self-tuning control design of a web tension control system. Based on the overlapping decomposition of the controlled system that we have proposed, we employ the generalized minimum variance control (GMVC) method combined with the particle swarm optimization to estimate the system parameters. The GMVC formulation of control input is then reduced to the PID structure to conform to a practical use. The results show that the decentralized control system works well under the uncertainties and variations of the system parameters and noise contained in the tension signals, converging to an optimum control state in terms of GMVC evaluation.

Keywords: web tension, decentralized control, overlapping decomposition, self-tuning, generalized minimum variance, PSO, PID.

Presenting Author's Biography

Tetsuzo Sakamoto. He received Dr. of Engineering degree from Kyushu University in Japan. In 1985, he joined the Faculty at Kyushu Institute of Technology as a Research Associate. Later he became Associate Professor at Kyushu Institute of Technology. Since 2002, he has been Professor in the Department of Control Engineering at Kyushu Institute of Technology. His research interests include electromagnetic analysis and control of linear synchronous motors and electrodynamic levitation, and the control system design of the web tension control system and the electromagnetic levitation system. He also wrote a book titled as 'Electrodynamics and Control of Electric Machines', which was published in 2007 by Morikita Publishing Company of Japan.

1 Preface

A web is a long, wide and thin material such as paper, film or fabric etc. In the web processing, the web material is delivered to the machines with many drive rolls and guidance rolls to control the web tension and its transfer speed. The web is elongated or broken if the tension is too high, while it has wrinkles or misguidance problems if the tension is too low. Since all the drive rolls are controlled separately at the same time, which is called decentralized control, significant mutual interactions exist between the drive rolls. This problem makes the web delivery and processing difficult. Moreover there exist uncertain dynamics caused by bearings of the drive roll and the frictional contacts between a web and rolls.

We have studied the modeling techniques and control methods about the web transfer system so far [1, 2, 3]. Due to the practical situation of setting up the web process machine, decentralized control is preferable because it can lead to less number of the order of the controlled system dynamics and shorter communication lines. If the centralized control structure is used, the controller design needs to take account of a larger number of dynamics of the controlled system, which is not practically feasible. If the overlapping decentralized control [3] is employed, then each subsystem can be regarded as an isolated SISO system so that the mutual interactions can become disturbances that have to be suppressed. Besides, in the web transfer systems the system parameters can change because of dealing with various web materials and mechanical bearings property uncertainties, and can have sensor noise resulting from drive systems. In this paper, we propose constructing a self-tuning decentralized PID control system comprised of the particle swarm optimization (PSO) and the generalized minimum variance control (GMVC), being based on the overlapping decentralized control methodology. The results show a robust performance even in the presence of system parameter uncertainties and noise.

2 Controlled system

2.1 System description

Fig.1 shows the schematic diagram of the controlled system, which has four drive rolls. The tension forces T_1 and T_2 are controlled respectively at the unwinder and the draw roll by using the corresponding drive torques u_1 and u_2, for which tension sensors are placed at lower places. The main web transfer speed is controlled at the leading section while winding speed is controlled at the winder.

Fig.2 shows the block diagram. In the diagram, r_1-r_4 are the radius of each roll, J_1-J_4 the moment of inertia of each roll, and L_1-L_3 represent the web length of the corresponding section, where $P(s) = A(\eta_v + G_v/s)$, A is the cross-sectional area, η_v the viscosity modulus, and G_v the elastic modulus of web material.

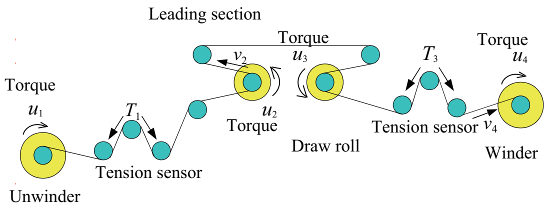

Fig. 1 Schematic diagram of the controlled system

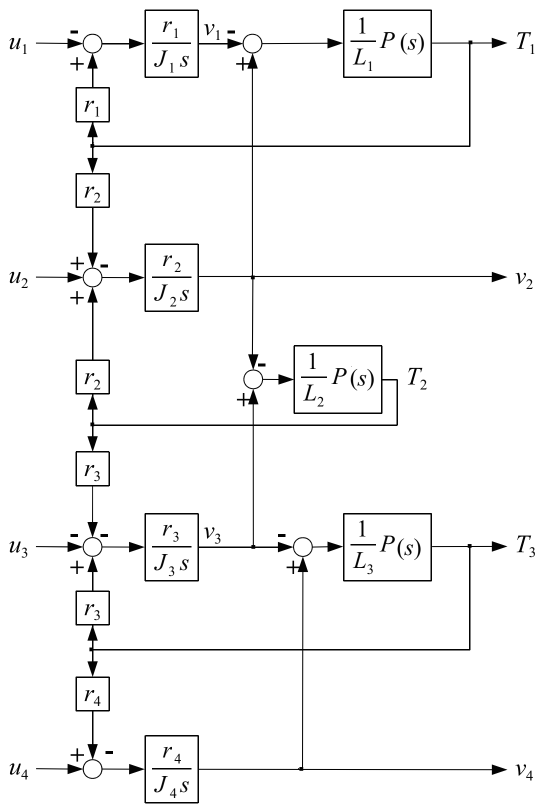

Fig. 2 Block diagram of the controlled object

2.2 Overlapping decomposition of controlled system

The tension force T_1 is established by the unwinder and the leading section roll physically, and thus we regard this combination as one subsystem, which is actually described by

$$T_1 = \frac{\frac{P(s)}{L_1}}{s + \frac{P(s)}{L_1}\left(\frac{r_1^2}{J_1} + \frac{r_2^2}{J_2}\right)} \left(\frac{r_1}{J_1}u_1 + \frac{r_2}{J_2}u_2\right) \quad (1)$$

On the other hand, the transfer speed is expressed by

$$v_2 = \frac{r_2}{J_2 s}u_2 \quad (2)$$

It is noticed that tensions forces are produced by two drive rolls, while speed is fundamentally determined by one drive roll. These relations lead to the concept of overlapping decomposition, and we define the virtual control input for the first subsystem as

$$\tilde{u}_1 = \frac{r_1}{J_1}u_1 + \frac{r_2}{J_2}u_2 \tag{3}$$

Finally we obtain the following relationship between the real and the virtual control inputs.

$$u = N\tilde{u} \tag{4}$$

where $u = (u_1, u_2, u_3, u_4)^T$, $\tilde{u} = (\tilde{u_1}, \tilde{u_2}, \tilde{u_3}, \tilde{u_4})^T$

$$N = \begin{pmatrix} \frac{r_1}{J_1} & \frac{r_2}{J_2} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{r_3}{J_3} & \frac{r_4}{J_4} \\ 0 & 0 & 0 & 1 \end{pmatrix}^{-1}$$

Thus, we obtain the overlapping decomposition that makes it possible to regard each subsystem as an SISO system. By applying the matrix N to the control input u, we have Fig.3 that shows the block diagram for decentralized controller design, in which mutual interactions are all disturbances to be suppressed.

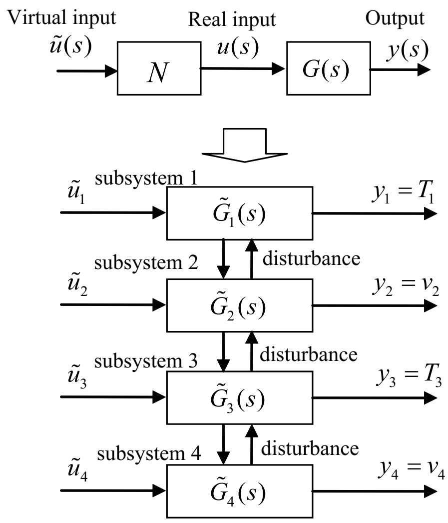

Fig. 3 Block diagram of the overlapping decomposition

3 Self-tuning decentralized control system

Fig.4 shows the decentralized controller block diagram which has a self-tuning function. The controller has a form of PID determined from the generalized minimum variance control (GMVC), in which the gains are tuned based on the particle swarm optimization (PSO).

3.1 GMVC design and its PID representation

We can design each decentralized controller for the corresponding subsystem transfer function obtained from

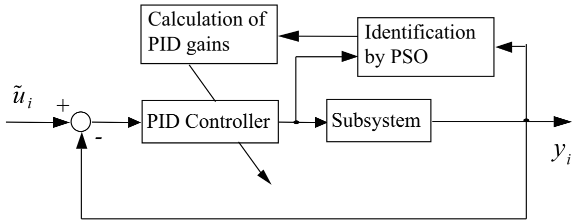

Fig. 4 Self-tuning control system

the overlapping decomposition. We here describe the subsystem using the Controller Auto-Regressive Moving-Average (CARMA) model:

$$A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k) + C(z^{-1})\xi(k) \tag{5}$$

z^{-1}: backward shift operator, $u(k)$: control input, $y(k)$: output, $\xi(k)$: zero-mean white noise, $E[\xi(k)] = 0$, d: time delay.

In our case, for each subsystem we can express the model and the polynomials as

$$\begin{aligned} \hat{A}(z^{-1})y(k) &= z^{-d}\hat{B}(z^{-d})u(k) + \xi(k) \\ \hat{A}(z^{-1}) &= 1 + \hat{a}_1 z^{-1} + \hat{a}_2 z^{-2} \\ \hat{B}(z^{-1}) &= \hat{b}_0 + \hat{b}_1 z^{-1} + \hat{b}_2 z^{-2} \end{aligned} \tag{6}$$

The cost function of the GMVC is given by

$$J = \mathrm{E}\left[h^2(k+d)\right] \tag{7}$$

where

$$\begin{aligned} h(k+d) := P(z^{-1})y(k+d) + Q(z^{-1})u(k) \\ -R(z^{-1})r(k+d) \end{aligned}$$

where $r(k)$ is the reference, and $P(z^{-1})$,$Q(z^{-1})$, $R(z^{-1})$ are the design polynomials given as

$$\begin{aligned} P(z^{-1}) &= 1 + p_1 z^{-1} + p_2 z^{-2} \\ Q(z^{-1}) &= -\hat{B}(z^{-1}) + \nu \\ R(z^{-1}) &= z^{-1}\hat{F}(z^{-1}) = P(z^{-1}) - \Delta\hat{A}(z^{-1}) \end{aligned} \tag{8}$$

The GMVC solution is obtained as the following control input[4] with assuming that the estimated values of system parameters are used.

$$u(k) = \frac{\hat{C}Rr(k+d) - \hat{F}y(k)}{\Delta\left(\hat{B}\hat{E} + \hat{C}Q\right)} \tag{9}$$

where "ˆ" indicates the estimated values obtained by using PSO, and $\Delta = 1 - z^{-1}$.

On the other hand, a general form of PID controller is expressed as

$$u(k) = \left(K_p + K_i\frac{T}{\Delta} + K_d\frac{\Delta}{T}\right)(r(k) - y(k)) \tag{10}$$

Substituting Eq.(9) into Eq.(10), we have the PID gains [6] as the GMVC control input:

$$\begin{aligned} K_p &= -\frac{p_2 + \hat{a}_1 + \hat{a}_2}{\nu} \\ K_i &= \frac{p_1 + p_2 + 1}{\nu T} \\ K_d &= \frac{\hat{a}_2}{\nu} T \end{aligned} \tag{11}$$

3.2 Identification by PSO

Particle swarm optimization (PSO) is a method to find an optimum solution so that the evaluation index is minimized. Each variable is called particle, and the group of particles defined in the problem space is called the swarm. We employ a particle composed of the subsystem parameters :

$$x = (\hat{a}_1\ \hat{a}_2\ \hat{b}_0\ \hat{b}_1\ \hat{b}_2)^T \tag{12}$$

The particle velocity and its position are updated by the following equation.

$$\begin{aligned} v_{ij}^{k+1} = w \cdot v_{ij}^k + C_1 \cdot rand_{1ij} \cdot (pbest_{ij} - x_{ij}^k) \\ + C_2 \cdot rand_{2ij} \cdot (gbest - x_{ij}^k) \end{aligned} \tag{13}$$

$$x_{ij}^{k+1} = x_{ij}^k + v_{ij}^{k+1} \tag{14}$$

where i: partical number, superscript k: search number, $rand_{1ij}$, $rand_{2ij}$: uniform random number distributed over [0,1], w, C_1, C_2: constants, $pbest_{ij}$: the best particle's position at the instant, $gbest$: the best particle's position in the swarm.

If we assume the time delay $d = 1$ and ignore the noise term of Eq.(5), then we get the following relationship.

$$\begin{aligned} y(k) = b_0 u(k-1) + b_1 u(k-2) + b_2 u(k-3) \\ -a_1 y(k-1) - a_2 y(k-2) \end{aligned}$$

Thus, the output with the estimated parameters using PSO is expressed as

$$\begin{aligned} y_{PSO}(k) = \hat{b}_0 u(k-1) + \hat{b}_1 u(k-2) + \hat{b}_2 u(k-3) \\ -\hat{a}_1 y(k-1) - \hat{a}_2 y(k-2) \end{aligned}$$

And we define the following evaluation index for the PSO [5] algorithm.

$$f(x) = \sum_{j=1}^{I-1} |y(k-j+1) - y_{PSO}(k-j+1)| \tag{15}$$

The particle swarm optimization is carried out with the information obtained from each particle and its swarm. After all, the PID gains of the controllers are automatically tuned by using the parameters obtained through the PSO optimization. We used the Gbest model as a means to exchange information between particles, and assumed that the number of swarm is 1.

Tab. 1 Dimensions of controlled object

Web		
Cross-sectional area	A	1.0×10^{-6} (m^2)
Elastic modulus	G_v	9.802×10^9 (N/m^2)
Viscosity modulus	η_v	9.164×10^8 (N· m^2)
Unwinder		
Radius	r_1	2.6×10^{-2} (m)
Moment of inertia	J_1	2.740×10^{-4} (N·m·s^2)
Span of the section	L_1	0.75 (m)
Leading section		
Radius	r_2	2.1×10^{-2} (m)
Moment of inertia	J_2	1.562×10^{-4} (N·m·s^2)
Span of the section	L_2	1.20 (m)
Draw roll		
Radius	r_3	2.1×10^{-2} (m)
Moment of inertia	J_3	1.493×10^{-4} (N·m·s^2)
Span of the section	L_3	1.25 (m)
Winder		
Radius	r_4	2.6×10^{-2} (m)
Moment of inertia	J_4	2.955×10^{-4} (N·m·s^2)

Tab. 2 System parameters ignored at controller design

Unwinder		
Viscous coefficient	k_1	3.841×10^{-3} (N·s)
Kinetic frictional torque	f_{d1}	5.478×10^{-2}(N·m)
Initial radius	r_{W1}	3.4×10^{-2}(m)
Leading section		
Viscous coefficient	k_2	1.610×10^{-3}(N·s)
Kinetic frictional torque	f_{d2}	4.158×10^{-2}(N·m)
Draw roll		
Viscous coefficient	k_3	3.899×10^{-3}(N·s)
Kinetic frictional torque	f_{d3}	2.030×10^{-2}(N·m)
Winder		
Viscous coefficient	k_4	1.908×10^{-3}(N·s)
Kinetic frictional torque	f_{d4}	3.990×10^{-2}(N·m)

4 Calculated results

Tab. 1 shows the dimensions of the web transfer system. In the simulations, we assumed static and dynamic friction forces and variable radius of the unwinder and winder, although these factors were not included in the controller design. Instead, the system is expected to work satisfactorily with the self-tuning function.

Some parameters in the controlled object were ignored at the stage of controller design to see the robustness of the self-tuning control system. The parameters shown in Tab.2 are not considered in the design, but included in the simulations.

Tab. 3 shows the controller design parameters.

Fig.5 and Fig.6 show respectively, the evaluation index $f(gbest_i)$ and the control output for the four subsystems when being given the radius change of the un-

Tab. 3 Control system parameters

Controller		
Sampling period	T	0.01(s)
parameter 1	σ	5×10^{-4}(s)
parameter 2	ν	$\hat{b}_0 + \hat{b}_1 + \hat{b}_2 + 2$
Reference of tension	T_{r1}	20(N)
Reference of speed	v_{r2}	0.5(m/s)
Reference of tension	T_{r3}	20(N)
Reference of speed	v_{r4}	0.5(m/s)
PSO for identification		
Number of particle	i_{max}	20
Velocity weight	w	0.729
Weight of $pbest$	C_1	1.4955
Weight of $gbest$	C_2	1.4955

winder (1st drive roll) and the winder (4th drive roll). It was found that step-wise reference may require severe demand for the self-tuning function. Thus, filters were included in the reference signals to have a soft start. The tension force and the speed references are 20N and 0.5m/s, respectively.

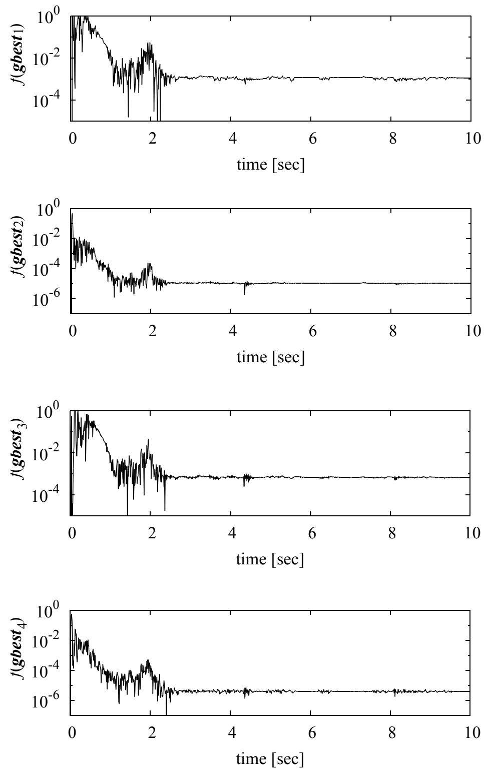

Fig. 5 PSO evaluation index for each subsystem

The results show that the evaluation indexes decrease in time on the whole to settle at a constant value in steady state, although the values are increased by the presence of the radius changes. There is a small delay in the unwinder tension from the reference, and a slight overshoot on the tension of the draw roll section. However, the system works well.

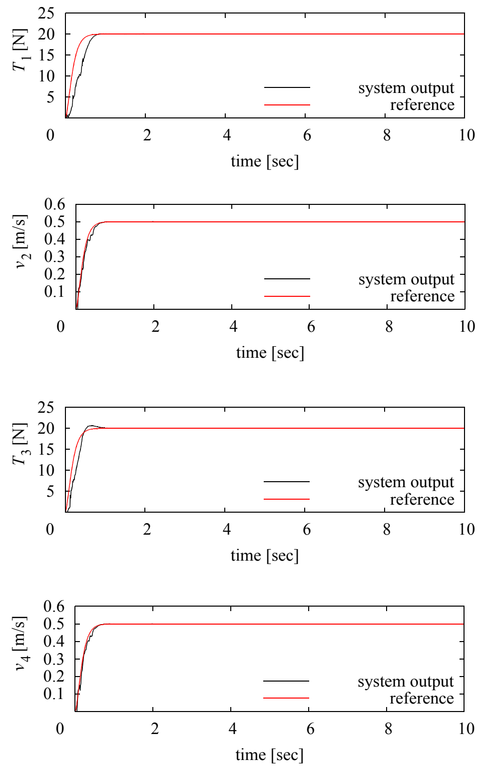

Fig. 6 Controlled variable of each subsystem

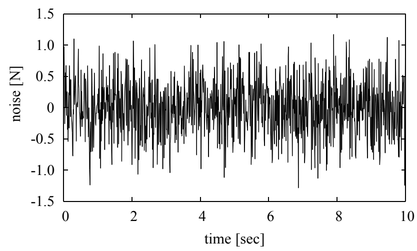

Fig. 7 White noise contained in the tension signals

Next, we consider the case of containing noise in the tension signals. The noise is shown in Fig.7, which is a zero-mean white noise. Fig.8 and Fig.9 show the simulation results. The evaluation indexes of the tension control subsystems, the unwinder and draw roll sections, don't decrease monotonously due to the presence of noise in the output signals. However, since the GMVC methodology takes account of the white noise, the self-tuning controller successfully works against the sensor noise and parameter uncertainties.

However, since the control system parameters are updated appropriately, the system behaviors are well controlled even under changing parameters and mutual interactions as a result. All the tension forces and roll peripheral speeds are controlled without overshoots or oscillations.

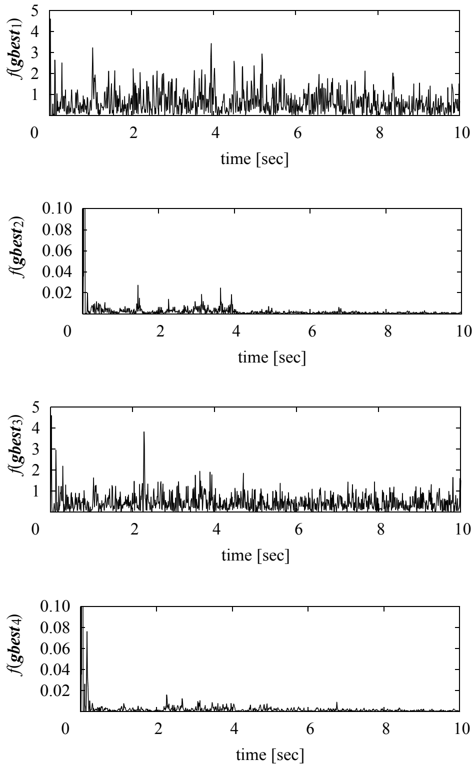

Fig. 8 PSO evaluation index for each subsystem

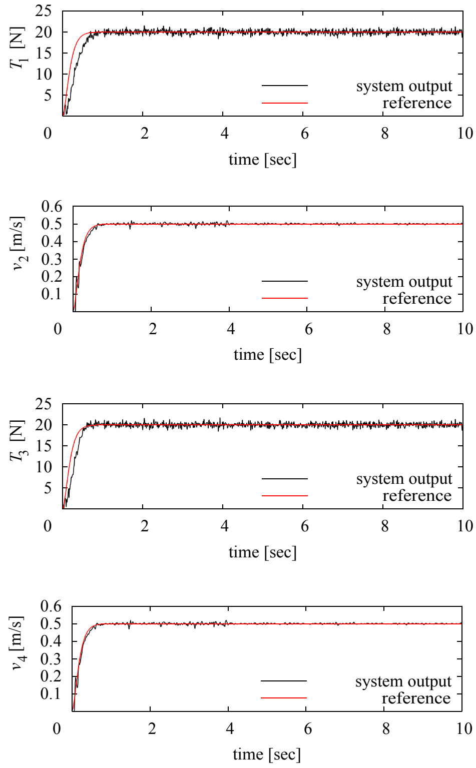

Fig. 9 Controlled variable of each subsystem

5 Conclusions

We have proposed a self-tuning decentralized control design for the web tension control system, which is characterized by the existence of significant mutual interactions among subsystems. The system parameters were estimated by the particle swarm optimization, while we employed the generalized minimum variance control to improve the control performance against sensor noise. In order to avoid the significant mutual interactions, we used the overlapping decomposition. Combined all those methodologies, we constructed a self-tuning decentralized PID controller. The simulation results show that the proposed system works well against the system parameter uncertainty and variations, and the output signals contaminated with irregular noise.

6 References

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