Auto-Tuning Adaptive Control System Using Fuzzy Inference

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ABSTRACT

In the present paper, the practical design method of a strongly stable system for the adaptive control is proposed. When the system parameter changes greatly, a series compensator having unstable poles appears in an adaptive pole placement control system frequently, even if the closed-loop system is designed to be an optimal servo system. However, the appearance of an unstable series compensator in this control system is undesirable in terms of stability. The strongly stable adaptive control system is achieved, by adjusting automatically the weight of a performance index in the optimal control on the basis of the stability index. Furthermore, the fuzzy inference is effectively introduced into this adaptive control system in order to adjust the performance weight appropriately. In addition, numerical simulation is used to prove that the proposed method provides sufficient performance regarding both tuning and control.

1. INTRODUCTION

Many control systems that the dynamic characteristics of controlled process greatly change exist in industry fields. For example, the parameter of mechanical system on motor control field changes over a wide range. Furthermore, the speed control system on the rolling lines of steel mills is a plant whose load inertia fluctuation is very large. Accordingly, control performance usually deteriorates when applying many conventional control methods with fixed parameter as controller. Therefore, that an adaptive control [1], [2], is a very effective method for such systems is known. Furthermore, the realization of auto-tuning on the motor control system is tried actively in industries at present.

By the way, when the system parameters change over a wide range, a series compensator having an unstable pole appears in the adaptive pole placement control system frequently, even if the closed-loop was designed as a stable system. The appearance of the unstable compensator is not desirable with respect to both stability and reliability. The unstable controller is reluctantly used, especially if the plant itself is a stable system. Therefore, in order to obtain a stable controller over the full range of parameter change, appropriate selection of the pole of a closed-loop system is required. However, selecting the closed-loop pole ensuring the stability of compensator under condition of parameter change over a wide range is very difficult in the pole placement control. In other words, in practice it is easily proved that designer cannot select this closed-loop pole as the fixed constant value. Therefore, the construction of a strongly stable system [3] is facilitated if designer is able to adjust the stable poles of the closed-loop system recursively according to the change of plant parameter. Such research is an indispensable significant theme to the development of intelligent auto-tuning technology. However, few design methods consider the robustness and the relative stability of adaptive control system itself, although some studies [4], [5], with respect to robustness of the adaptive algorithm have been reported as a recent trend of adaptive control. Furthermore, the report that discussed the tuning strategy of both controller and closed-loop poles according to the parameter change of plant is little found.

Recently, authors announced an effective design method [6] that constructs a strongly stable system with respect to the adaptive pole placement, even if the plant parameter changes greatly. This presented method does not only ensure the stability of both closed-loop system and controller but also can achieve fine control performance. Furthermore, That in an adaptive pole placement system the design method evaluates by introducing a stability index the relative stability of both series compensator and closed-loop system is main characteristic. A stability index is the evaluation that was introduced in the coefficient diagram method [7], [8], it is also known as a useful index in the case that a robust controller of low dimension is derived in robust control design. In addition, a binomial coefficient polynomial was selected by considering the easiness of tuning algorithm, although designer is able to choose an optional stable polynomial in order to specify the poles of a closed-loop system.

The procedure of this proposed method is summarized as follows. The adaptive identification is first performed in this tuning system in order to complete the original design even if the plant parameter changes and simultaneously the characteristic polynomial of an optimal servo system [9] is recursively calculated. The series compensator is secondly constructed by solving *Bezout* identity on the basis of this characteristic polynomial. New resultant index is selected as the scaling factor of fuzzy inference [10] from these stability indices of series compensator in order to evaluate relation between the stability of a controller and the performance of a closed-loop system and simultaneously it can be related to the weight of performance index in optimal control. By considering these relations, appropriate tuning system of the performance weight based on relation between stability index and membership function is automatically achieved.

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Therefore, the proposed method automatically adjusts the weight of a performance index so that the adaptive system can place the stability index of the series compensator into the specified area. Because an optimal servo system is recursively calculated to an estimated plant model in this approach the proposed method has such characteristic that the control purpose is theoretically evident; however, calculation algorithm is a little complicated in comparison with previous report.

2. STRONGLY STABLE ADAPTIVE CONTROL SYSTEM

The model reference adaptive control system can be constructed by utilizing the pole-zero cancellation if the discrete-time model of a controlled process does not have the unstable zeros. However, it is difficult in many discrete-time systems really to avoid an unstable zeros. The adaptive pole placement control system in this approach adjusts automatically the control system by repeating the estimation and the control alternately, it has the characteristic that the structure of estimation and control are separating. Furthermore, the designer need not consider the problem of the unstable zeros because this system does not use unstable pole-zeros cancellation.

In addition, the closed-loop characteristic polynomial of an optimal servo system is recursively calculated by the concept of LQG (linear quadratic Gaussian). The strongly stable optimal servo system is constructed automatically by updating the weight of performance index in an optimal system on the basis of a stability index of the derived controller. A fuzzy inference is used like [6] in the present paper, although there are several methods in an update of the weight of performance index.

2.1 Control system

The adaptive control system of this research is constructed by means of the adaptive pole placement control system introduced with an integrator in order to reject stationary disturbance. At this time, the plant is given by ARX (auto-regressive exogenous) system described according to the following:

$$A(q^{-1})y(k) = q^{-d}B(q^{-1})u(k) + w(k) \ , \quad (1)$$

where $u(k)$ and $y(k)$ represent the input and output for the plant, respectively, and $w(k)$ is the white noise having zero mean value, and the integer d is the time delay. Furthermore, by using the delay operator q^{-1}, the plant denominator $A(q^{-1})$ and numerator $B(q^{-1})$ are given by the following polynomials:

$$A(q^{-1}) = 1 + a_1 q^{-1} + \cdots + a_n q^{-n} \ , \quad (2)$$

$$B(q^{-1}) = b_0 + b_1 q^{-1} + \cdots + b_m q^{-m} \ . \quad (3)$$

Furthermore, when the input and output regarding the reference model are expressed by using $u_m(k)$ and $r_m(k)$, respectively, reference signal is generated in accordance with the following:

$$A_m(q^{-1})r_m(k) = q^{-d}B_m(q^{-1})u_m(k) \quad (4)$$

$$A_m(q^{-1}) = 1 + a_{m1}q^{-1} + \cdots + a_{ml}q^{-l} \ , \quad (5)$$

$$B_m(q^{-1}) = b_{m0} + b_{m1}q^{-1} + \cdots + b_{ml}q^{-l} \ . \quad (6)$$

At this time, the regulation performance of stable closed-loop system is specified by the following polynomial:

$$D_o(q^{-1}) = 1 + d_1 q^{-1} + \cdots + d_{nd}q^{-nd} \ , \quad nd \le n + m + d \ . \quad (7)$$

In addition, the tracking performance of control system is generally achieved using prefilter $T(q^{-1})$, either the constant such as

$$T(q^{-1}) = D_o(1)/B(1) \quad (8a)$$

or the polynomial such as

$$T(q^{-1}) = D_o(q^{-1})/B(1) \ . \quad (8b)$$

Here, let us consider the error described by

$$e(k+d) = D_o(q^{-1})y(k+d) - T(q^{-1})B(q^{-1})r_m(k+d) \ . \quad (9)$$

The variance of (9) is defined as the performance index:

$$J = E[e^2(k+d)] \ , \quad (10)$$

where $E[*]$ represents the expectation operation. Then, the optimal actuating value $u(k)$ that minimizes a performance index J is constructed by means of the following signal:

$$u(k) = \frac{T(q^{-1})r_m(k+d) - R(q^{-1})y(k)}{(1-q^{-1})S(q^{-1})} \ , \quad (11)$$

where $S(q^{-1})$ and $R(q^{-1})$ are given by the polynomials:

$$S(q^{-1}) = 1 + s_1 q^{-1} + \cdots + s_{ns}q^{-ns} \ , \quad ns = m + d - 1 \ , \quad (12)$$

$$R(q^{-1}) = r_0 + r_1 q^{-1} + \cdots + r_{nr}q^{-nr} \ , \quad nr = n \ . \quad (13)$$

Furthermore, $S(q^{-1})$ and $R(q^{-1})$ can be derived by solving the *Diophantine* equation (or the *Bezout* identity):

$$D_o(q^{-1}) = (1-q^{-1})A(q^{-1})S(q^{-1}) + q^{-d}B(q^{-1})R(q^{-1}) \ . \quad (14)$$

2.2 Identification system

When the parameter of ARX system of (1) is unknown or greatly changeable, the estimated value of a parameter is substituted in such control system as mentioned at previous section. If the signal to noise (S/N) ratio of ARX system is a good condition, least-squares estimation has few bias with respect to the estimated value. A generalized adaptive identification based on a reliable least-squares estimation is described below.

Now, let us use (1) mentioned previously as the same plant. If the parameter vector θ and the regression vector $\varphi(k)$ constructed by measurement data are defined as

$$\theta^T = \{a_1, a_2, \cdots, a_n, b_0, b_1, \cdots, b_m\} \quad (15)$$

and

$$\varphi^T(k) = \{-y(k-1), -y(k-2), \cdots, -y(k-n), u(k-d), u(k-1-d), \cdots, u(k-m-d)\} \ , \quad (16)$$

respectively, then the plant output $y(k)$ is expressed as follows:

$$y(k) = \varphi^T(k)\,\theta + v(k) \ . \quad (17)$$

Here, let us use the notation $\hat{y}(k|\theta)$ as the one-step-ahead prediction value, then it is given by the linear formula with respect to the parameter vector θ as follows:

$$\hat{y}(k|\theta) = [1 - A(q^{-1})]y(k) + B(q^{-1})u(k) = \varphi^T(k)\,\theta \ . \quad (18)$$

Therefore, the estimate model output $y_m(k)$ is constructed according to

$$y_m(k) = \varphi^T(k)\,\hat{\theta}(k) \ , \quad (19)$$

where the estimate vector of the parameter is defined as follows:

$$\hat{\theta}^T(k) = \{a_1(k), a_2(k), \cdots, a_n(k), b_0(k), b_1(k), \cdots, b_m(k)\} \ . \quad (20)$$

In conclusion, a generalized adaptive identification algorithm based on least-squares method that minimizes the square sum-mation of prediction error $\{y(k) - y_m(k)\}$ is completed by means of the following formulation:

parameter adjusting:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \lambda_2(k)P(k)\varphi(k)\varepsilon(k) \quad (21)$$

adaptive gain:

$$P(k) = \frac{1}{\lambda_1(k)}\left\{P(k-1) - \frac{\lambda_2(k)P(k-1)\varphi(k)\varphi^T(k)P(k-1)}{\lambda_1(k) + \lambda_2(k)\varphi^T(k)P(k-1)\varphi(k)}\right\}, \quad (22)$$

apriori error:

$$\varepsilon(k) = y(k) - \varphi^T(k)\hat{\theta}(k-1) \quad (23)$$

where weighting sequences $\lambda_1(k)$ and $\lambda_2(k)$ in (21) and (22) are

$0 < \lambda_1(k) \le 1$ and $0 \le \lambda_2(k) < 2$, respectively. Furthermore, the designer can obtain other adaptive gain that has the typical characteristic by selecting the appropriate values for $\lambda_1(k)$ and $\lambda_2(k)$.

2.3 Characteristic polynomial based on optimal servo

A discussion progressed by applying a binomial coefficient polynomial to simplify the tuning algorithm in the previous paper, as the regulation performance of a closed-loop system that is specified with (7). Type-1 optimal servo based on the state-space approach is tried without using a binomial polynomial in this paper. After the parameter estimation, a state-space description with respect to ARX system of (1) is given by ignoring the disturbance noise $w(k)$ as $\Sigma : (\bar{A}, \bar{B}, \bar{C})$. The controllable canonical form and so on, for example, is adopted as the state-space description for the optimal design. Type-1 servo system that considered the computation time delay to the system Σ as shown in Fig.1 is constructed. Here, the quadratic type performance index is defined as

$$J = \sum_{k=0}^{\infty} \{\tilde{x}^T(k) Q \tilde{x}(k) + R \tilde{v}^2(k)\} , \quad R > 0 , \qquad (24)$$

where $\tilde{x}(k)$ and $\tilde{v}(k)$ represent the states and actuating value for the extended deviation system, respectively, and Q is a semi-positive definite matrix. A type-1 optimal servo having one sample controller delay that minimizes a performance index of (24) is given as follows:

***Riccati* equation:**

$$P = Q + \bar{A}^T P \bar{A} - \bar{A}^T P \bar{B}(R + \bar{B}^T P \bar{B})^{-1} \bar{B}^T P \bar{A}, \quad P > 0 \qquad (25)$$

Optimal feed-back gain:

$$F = (R + \bar{B}^T P \bar{B})^{-1} \bar{B}^T P \bar{A} \qquad (26)$$

Controller parameters:

$$g = F \bar{B} + 1 \qquad (27)$$

$$[H, K] = [F\bar{A}^2, F\bar{A}\bar{B} + F\bar{B} + 1] E^{-1} \qquad (28)$$

$$E = \begin{bmatrix} \bar{A} - I & \bar{B} \\ \bar{C} & 0 \end{bmatrix} \qquad (29)$$

Furthermore, the state-space description of this servo system is expressed as follows:

$$\begin{bmatrix} x(k+1) \\ u(k+1) \\ z(k+1) \end{bmatrix} = \begin{bmatrix} \bar{A} & \bar{B} & 0 \\ -H & -g & K \\ -\bar{C} & 0 & 1 \end{bmatrix} \begin{bmatrix} x(k) \\ u(k) \\ z(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} r(k) . \qquad (30)$$

Therefore, the characteristic polynomial $D_o(q^{-1})$ of closed-loop system is, for example, calculated by *Faddeev*'s algorithm from the system matrix of (30).

2.4 Strongly stable adaptive control based on stability index

In this section a tuning method of the strongly stable adaptive pole placement control based on the stability index is discussed. The proposed method recursively updates an optimal servo system, simultaneously it has a characteristic that ensures the stability of a series compensator. First, The stability index is introduced in order to evaluate the relative stability of the control system. In the following n^{th}-order characteristic polynomial of the continuous time transfer function:

$$p(s) = f_n s^n + \cdots + f_1 s + f_0 , \qquad n \ge 2 , \qquad (31)$$

the stability indices γ_i are generally defined as follows:

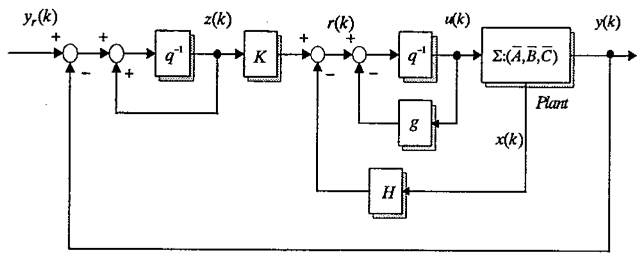

Fig.1 Type-1 optimal servo system having one sample delay.

$$\gamma_i = f_i^2 / f_{i+1} \cdot f_{i-1} , \qquad (i = 1, \cdots, n-1) . \qquad (32)$$

A series compensator $[S(q^{-1})]^{-1}$ is derived by solving (14), according to the characteristic polynomial $D_o(q^{-1})$ that is obtained with an optimal design of the previous section.

Next, in order to apply a stability indices γ_i to the discrete-time series compensator $[S(q^{-1})]^{-1}$, it is transformed into the continuous-time transfer function $S_c(s)$ using the inverse bilinear transformation

$$q = (2 + Ts)/(2 - Ts) , \qquad (33)$$

where T is the sampling period.

After the bilinear transformation, the stability indices γ_i in terms of the denominator polynomial of the continuous-time compensator $S_c(s)$ are calculated. Furthermore, such new index that evaluates relation between the stability of a controller and the performance of a closed-loop system is able to be composed of these stability indices γ_i.

In the present paper, only the simplest resultant stability index γ is selected and is given by the algebraic product of the stability indices γ_i:

$$\gamma = \prod_{i=1}^{n-1} \gamma_i . \qquad (34)$$

This new index γ can be related to the weight R of a performance index in the optimal control. Furthermore, the index γ is related to each characteristic, whether open-loop, such as gain-phase margin, or close-loop, such as settling time. Appropriate auto-tuning of weight R based on the resultant stability index γ is achieved, by considering the relations as mentioned above. At the same time, the resultant stability index γ is selected as the scaling factor, and the fuzzy inference is introduced to adjust the weight R of a performance index in the optimal control.

In addition, in order to complete the defuzzification of the inference result, the consequent of fuzzy inference is executed using the min-max-gravity method of *Mamdani*:

$$u_g(k-1) = \{\sum x_j \cdot \mu(x_j)\} / \sum \mu(x_j) \qquad (35)$$

where x_j is the nonfuzzy value, $\mu(x_j)$ is the value of the membership function, and $u_g(k-1)$ is the inference result.

In order to place the resultant stability index γ of the series compensator $S_c(s)$ into the specified area, the weight R of a performance index in the optimal control system is adjusted by means of the following recursive formula:

$$R(k) = R(k-1) \cdot 10^{\beta(k-1)} \qquad (36)$$

$$\beta(k-1) = c \cdot u_g(k-1) , \quad c : any\ constant . \qquad (37)$$

These details are shown in a design example in the following section. Furthermore, the block diagram of the proposed adaptive control system is shown in Fig.2.

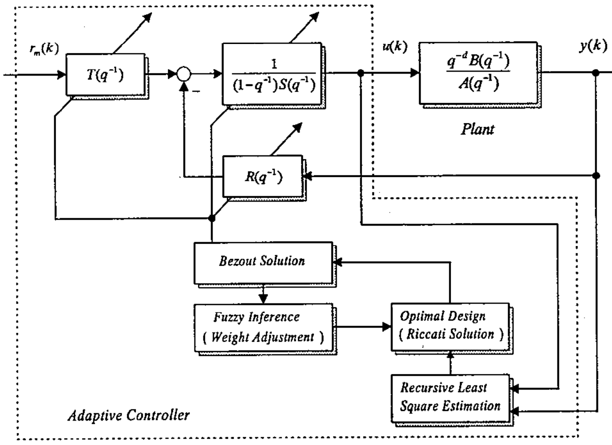

Fig.2. Block diagram of proposed adaptive control system.

3. DESIGN EXAMPLE

A 3^{rd}-order continuous-time plant is chosen as the controlled process according to the following:

$$G(s)=\frac{K\omega_n^{\,2}}{(s+d)(s^2+2\varsigma\omega_n s+\omega_n^{\,2})}\,, \qquad (38)$$

where K and d are assigned to a constant value of 50 in order to simplify the calculation similarly to [6]. The design is performed according to the procedure described below. The controllers for both of the plant pairs, $\Sigma_f(\varsigma=0.1,\omega_n=60)$ and $\Sigma_s(\varsigma=0.4,\omega_n=20)$, are designed. The plant Σ_f is a typical plant that has a fast response, and also the plant Σ_s is a typical plant, yet has a slower response than the plant Σ_f. First the plant Σ_f described above is transformed into a discrete-time system, because the digital controller is designed using a discrete-time model. Therefore, for sampling time $T=0.02$[sec], the 3^{rd}-order discrete-time model is transformed from continuous-time plant of (38) as follows:

$$G(q^{-1})=\frac{q^{-1}(0.16573+0.46092q^{-1}+9.0122\times10^{-2}q^{-2})}{1-1.0206q^{-1}+1.0267q^{-2}-0.28938q^{-3}}\,. \qquad (39)$$

Due to the computation time delay, d should be increased by 1, yielding $d=2$.

Here, let us consider the controllable canonical form of a state-space description with respect to (39) as the object of a optimal servo design. For example, a type-1 optimal servo controller having one sample controller delay is calculated under the condition that the weights of performance index of (24) are $Q=diag$ (100,100,100) and $R=10^3$.

When *Riccati* equation of (25) is first solved, a positive definite solution is derived as follows:

$$P=\begin{bmatrix}1.3400\times10^2 & -1.0886\times10^2 & 6.8613\times10\\ -1.0886\times10^2 & 5.7559\times10^2 & -2.9854\times10^2\\ 6.8613\times10 & -2.9854\times10^2 & 6.8367\times10^2\end{bmatrix}. \qquad (40)$$

Therefore, the optimal feed-back gain of (26) is given as

$$F=[\,1.1751\times10^{-1}\quad -3.7617\times10^{-1}\quad 2.3710\times10^{-1}\,]\,, \qquad (41)$$

the controller parameters are then obtained, respectively, as

$$g=1.2371,\quad H=[\,4.4541\times10^{-1}\quad -4.4633\times10^{-1}\quad 1.1029\,],$$
$$K=9.6992\times10^{-1}. \qquad (42)$$

At the same time, by using *Faddeev*'s algorithm, the characteristic polynomial $D_o(q^{-1})$ of an optimal servo system is calculated as follows:

$$D_o(q^{-1})=1-7.8348\times10^{-1}q^{-1}+6.5057\times10^{-1}q^{-2}-1.7188\times10^{-1}q^{-3}$$
$$-7.4890\times10^{-16}q^{-4}+1.9485\times10^{-17}q^{-5} \qquad (43)$$

The order nd of the characteristic polynomial is equals to 5 theoretically. However, it is actually possible to process the order of polynomial $D_o(q^{-1})$ as $nd=3$, because both coefficients of the fourth and fifth order term in (43) are very small. When (14) is solved after the characteristic polynomial $D_o(q^{-1})$ is substituted to it, the pole placement controllers $S(q^{-1})$ and $R(q^{-1})$ are derived, respectively, as

$$S(q^{-1})=1+1.2371q^{-1}+9.1316\times10^{-1}q^{-2}+1.4628\times10^{-1}q^{-3} \qquad (44)$$
$$R(q^{-1})=1.1449-1.3117q^{-1}+1.6064q^{-2}-4.6971\times10^{-1}q^{-3}. \qquad (45)$$

Furthermore, when $[S(q^{-1})]^{-1}$ is transformed into the continuous-time transfer function $S_c(s)$ by means of the inverse bilinear transformation, the stability indices $\gamma_i(i=1,2)$ and the scaling factor γ are obtained, respectively, as

$$\gamma_1=1.960\,,\quad \gamma_2=1.086\,,\quad \gamma=2.129\,. \qquad (46)$$

At this time, in order to confirm the absolute stability of $S_c(s)$, *Hurwitz* determinant H_2 is calculated as the following value:

$$H_2=1.9712\times10^6. \qquad (47)$$

Next, when the frequency response is calculated from the loop transfer function of this discrete-time system, the gain margin g_m and the phase margin p_m are calculated to be

$$g_m=7.86\ [dB]\quad,\quad p_m=62.0\ [\text{deg}] \qquad (48)$$

respectively. In addition, through a step response simulation of only closed-loop system, settling time ST is confirmed as follows:

$$ST=14\ [sample]\,. \qquad (49)$$

Similarly, when the calculation is repeated changing R continuously, using fixed Q in terms of both weights, Q and R, in a performance index, each significant characteristic is obtained. First, the index γ of series compensator for the weight R of a performance index of both plants, Σ_f and Σ_s, is shown in Fig.3. Furthermore, *Hurwitz* determinant H_2 to the weight R of a performance index is shown in Fig.4. The diagrams in terms of the characteristics of the gain-phase margin and the settling time are omitted in this paper.

Next, the relation of both performance weight R and stability index γ having good performance for the control system of Σ_f

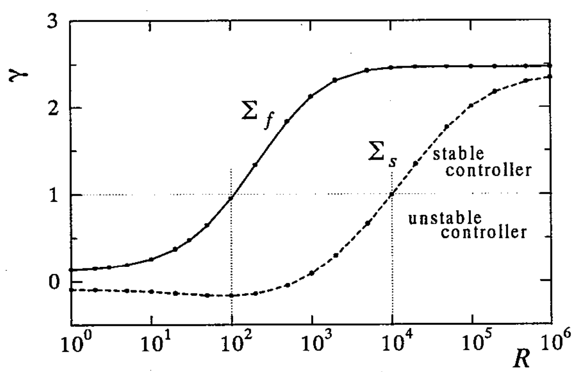

Fig.3. Each index γ of plants Σ_f and Σ_s to the weight R.

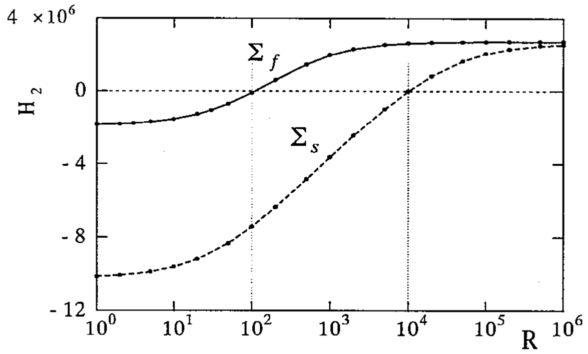

Fig.4. Each *Hurwitz* determinant H_2 to the weight R.

and Σ_s is examined, respectively, in these figs. 3 and 4. Let us first think about the stability of series compensator for both of the plants. Each range of the performance weights that meet a condition $H_2 > 0$ is estimated in Fig.4 as

$$10^2 \le R_f , \qquad 10^4 \le R_s , \tag{50}$$

where R_f and R_s represent the range of performance weight regarding the plants Σ_f and Σ_s, respectively. Therefore, in consideration of (50) with respect to Fig.3, the range of the index having a stable compensator is given as $1 < \gamma$. Furthermore, let us think about the control performance of closed-loop system. When the settling time for both of plants, Σ_f and Σ_s, is estimated about 10 sample and 21 sample respectively, the weights of a performance index for the plants, Σ_f and Σ_s, are about

$$R_f \fallingdotseq 5\times10^2 , \qquad R_s \fallingdotseq 5\times10^4 , \tag{51}$$

respectively.

At this time, designer is able to choose the range flexibly as a suitable area of both stability and settling time by considering Fig.3. However, the selection of a wide range is not appropriate for the purpose of auto-tuning. For example, the vicinity of each stability index corresponding to R_f and R_s is selected as one of the appropriate ranges according to the following:

$$\left.\begin{array}{lll} l_f \le \gamma_f \le u_f , & l_f = 1.5 , & u_f = 2.0 \\ l_s \le \gamma_s \le u_s , & l_s = 1.7 , & u_s = 1.8 \end{array}\right\} . \tag{52}$$

Thus, many degrees of freedom are given to the designer on the occasion of a decision of l_f, u_f and l_s, u_s in (52). Fuzzy inference is used to ensure the resultant stability index γ of the series compensator $[S(q^{-1})]^{-1}$ within the specified area.

The fuzzy variable γ used in the antecedent of the fuzzy rule has a trapezoidal membership function, as shown in Fig.5. In addition, the membership function used in the consequent of the fuzzy rule has a triangular form, as shown in Fig.6. The horizontal scale in the membership function of Fig.5 can be selected as

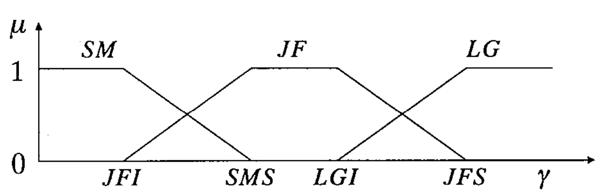

Fig.5 Membership function of antecedent.

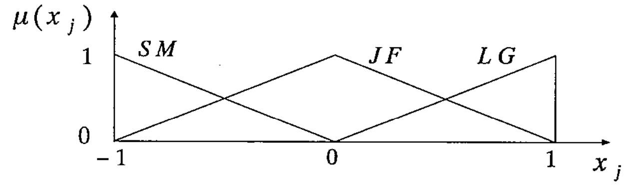

Fig.6 Membership function of consequent.

$$JFI = \min(\gamma_f \cup \gamma_s) , \quad SMS = \min(\gamma_f \cap \gamma_s)$$
$$LGI = \max(\gamma_f \cap \gamma_s) , \quad JFS = \max(\gamma_f \cup \gamma_s) . \tag{53}$$

The complete inference is found by calculating the center of gravity of (35) in terms of membership function shown in Fig.6.

4. SIMULATION RESULTS

The simulation result that a control system having strongly stable and simultaneously good performance can be easily achieved by using the proposed method is shown, even if the unstable compensator is guided on the conventional adaptive pole placement control system in the case that the plant parameter changes greatly. The simulation result of the conventional adaptive pole placement control having the closed-loop pole designed by an optimal servo is shown in this section. After that the auto-tuning simulation of adaptive control system is shown.

It is assumed that the prefilter of (8a) is specified and also the reference signal of $r_m(k) = u_m(k)$ without reference model is used for the plant of (38). Furthermore, when the weights of performance index of (24) are chosen to be constant values of $Q = diag$ (100,100,100) and $R = 10^3$, the simulation result of the adaptive pole placement control by the conventional method is first shown in Figs. 7 through 9. The plant output is shown in Fig. 7, and the index γ and the adaptive manipulated variable $u(k)$ are shown in Figs. 8 and 9, respectively. The plant parameter has been changed to $\Sigma_s(\varsigma = 0.4, \omega_n = 20)$ from $\Sigma_f(\varsigma = 0.1, \omega_n = 60)$ at a step of 400 and a minimal disturbance noise of variance $\sigma_n{}^2 = 5\times10^{-6}$ has been added to the simulation. The control result appears to be good according to Fig.7; however, Fig.8 reveals that the index γ is very small in the area of the Σ_s plant and that the series compensator $[S(q^{-1})]^{-1}$ is unstable. When an unstable compensator appears in the pole placement system, Fig.9 reveals that the manipulated variable is greatly disturbed even for a minimal random disturbance. Consequently, a strongly stable system is not achieved using the conventional method even if optimal servo system is designed to the given plant and the selection of an appropriate closed-loop pole becomes difficult.

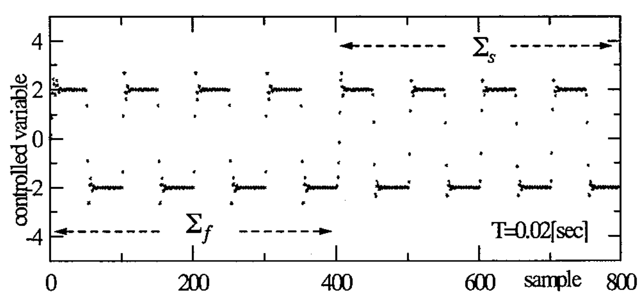

Fig.7 Controlled variable, in case of conventional adaptive control.

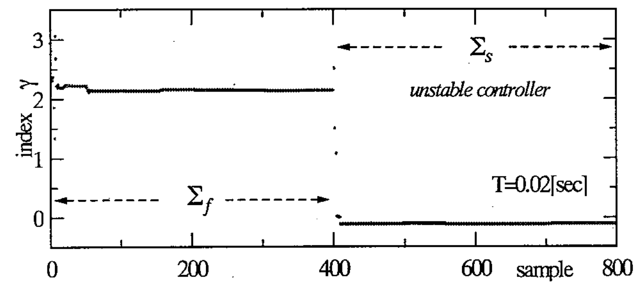

Fig.8 Index γ , in case of conventional adaptive control.

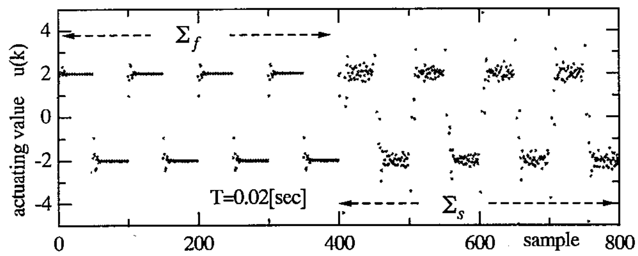

Fig.9 Actuating value $u(k)$, in case of conventional control.

The simulation result obtained in same condition mentioned above using the proposed method is next shown in Figs.10 through 12. The controlled variable $y(k)$ of the plant is shown in Fig.10, and the performance weight R in optimal servo and the resultant index γ are shown in Figs. 11 and 12, respectively. That the performance weight R is adjusted appropriately and simultaneously the occurrence of unstable controller is prevented in accordance with the proposed method, even after the plant parameters are changed greatly at a step of 400 in Fig.11 is obvious. Furthermore, Fig.12 reveals that the proposed adaptive control system is appropriately adjusted by means of fuzzy inference as the stability index γ is put in the specified area.

5. CONCLUSION

This paper has proposed a useful method for automatically con-

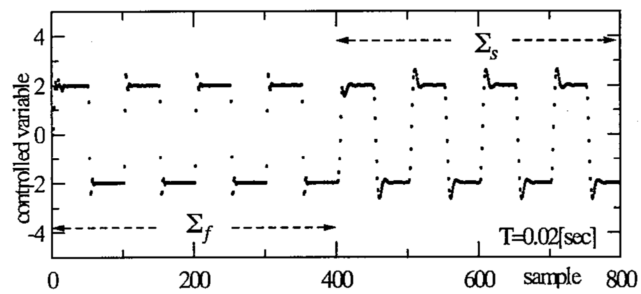

Fig.10 Controlled variable $y(k)$, in case of proposed method.

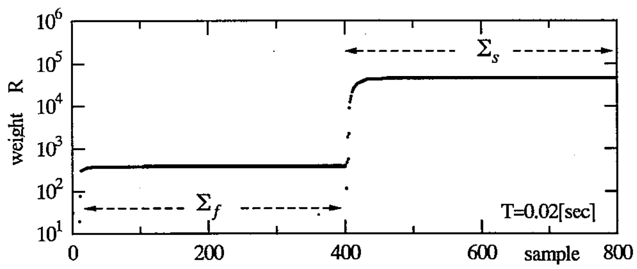

Fig.11 Performance weight R, in case of proposed method.

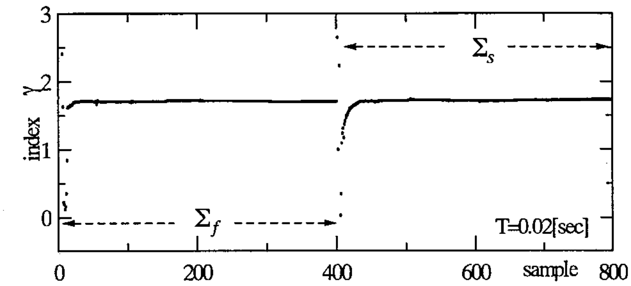

Fig.12 Index γ , in case of proposed method.

structing the strongly stable adaptive control system. An original and evident solution for the control purpose is derived like previous report by applying the proposed scheme in terms of this problem; however, the unstable series compensator is guided into the control system on the occasion of the use of the conventional method. The proposed method was applied to a 3^{rd} -order plant similar to previous report as a design example, and that usefulness was demonstrated by the present simulation.

Both are recursively repeated in this research; however, it does not necessarily require that the estimation and the control is performed on every control interval in the auto-tuning of adaptive control system. Therefore, it was able to inspect the real time performance regarding the proposed algorithm through this simulation too. In other words, the proposed method was able to confirm even that is sufficiently applicable to practical machine.

6. REFERENCES

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