INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL. 14, NO. 2, JUNE 2009, 141-148

# A Design Method of Two Degree-of-Freedom of Self-Tuning GPC Based on State Space Approach Using a Genetic Algorithm

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***Abstract*—In this paper, a new scheme of two degree-of-freedom of self-tuning Generalized Predictive Control (GPC) system is given by using a genetic algorithm for selection of integral gain. Although the author has proposed a design scheme of two degree-of-freedom GPC which reveals an effect of integral compensation only if there is modeling error or disturbance, this scheme has a problem that the integral gain must be selected by trial and error. For this problem, a genetic algorithm is introduced to find the best value of it.**

***Index Terms*—Generalized Predictive Control, Two degree-of-freedom, Self-tuning control, Genetic algorithm**

## 1. Introduction

GENERALIZED Predictive Control (GPC) has been proposed by Clarke and others[1]. This control method uses a performance index to obtain the control law. The performance index has some design parameters, which are called as prediction horizon, control horizon and weighting factor. The prediction horizon and the control horizon define the intervals to predict an output and to calculate the future control inputs respectively. The weighting factor is on the control inputs. The control input is calculated by minimizing the performance index and its minimization is repeated at each sampling step.

Due to these features, GPC has been accepted by many practical engineers and researchers[2], [3]. Although the controlled output can track to a step-type reference signal robustly by an integrator included in the controller, if the controlled plant is modeled accurately and there is no disturbance, it is able to track to the step-type reference signals without an integral compensation. That is, the integral compensation may have a worse effect on transient response or cause an increase of control input. Therefore it is desirable that the effect of integral compensation appears only if there is a modeling error or disturbance. In this paper, this feature is called as two degree-of-freedom system because the characteristics of output response and disturbance response can be designed independently. That is, the output response is designed by minimizing the performance index, and the disturbance response is tuned by an amount of integral compensation which is determined by an integral gain.

Although many papers have proposed two degree-of-freedom optimal servo systems[4], [5] and the author has proposed two degree-of-freedom of GPC based on state-space approach for single-input single-output systems[6], [7], there is a problem with a selection of the integral gain to give the amount of integral compensation. That is, the gain for integral compensation must be selected by trial and error. With this problem, although the author has proposed a selection method of the integral gain for two degree-of-freedom of GPC and self-tuning controller by a genetic algorithm[8], [9], the method has not been considered for the amount of the control input. Therefore, by including a term with control input for the fitness function of genetic algorithm[10], [11], [12], this paper newly proposes a design method of two degree-of-freedom of self-tuning GPC.

The design procedure of proposed method is on the following steps[6], [7]. The conventional GPC strategy, which was proposed by Clarke and others[1], has an integral compensation by including an integrator in the performance index. In this paper the amount of integral compensation is calculated analytically under the condition that there is neither modeling error nor disturbance. Therefore in the first step the controller is designed without an integral compensation in performance index. But if there is a disturbance, a steady state error remains. In the second step, a new controller is introduced by adding an integrator to the controller derived in the first step. The effect of its integral compensation can be designed by an integral gain introduced in this controller. And it always reveals the integral compensation and may cause an extra input because the integral action is merely added to the controller designed in the first step. In the third step, two degree-of-freedom of GPC is obtained by calculating the amount of integral compensation for the controller obtained in the second step under the condition that there is neither modeling error nor disturbance and subtracting its amount from the control input designed in the second step. By adding an adaptive observer, two degree-of-freedom of self-tuning GPC is obtained. Finally, the gain for the integral compensation is selected by using a genetic algorithm, that is, the proposed controller is given. If there is neither modeling error nor disturbance, the proposed controller generates the same control input as the controller derived in the first design step. It means that the control input has no integral compensation. And the proposed controller shows the effect of integral compensation if there is modeling error or disturbance.

The outline of this paper is as the followings. In section 2, two degree-of-freedom of GPC is shown. In section 3, self-tuning controller is obtained by an adaptive observer. In section 4, a search method of the solution of the integral gain is

Manuscript received June 19, 2009; revised September 18, 2009.
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shown by using a genetic algorithm. In section 5, the numerical examples are shown to verify the validity of the proposed method. Finally the conclusion is given.

## 2. Two DOF of GPC

### 2.1. Problem Statement

Consider a single-input single-output system as the following model,

$$\begin{aligned} x(t+1) &= Ax(t) + bu(t) && (1)\\ y(t) &= cx(t) && (2) \end{aligned}$$

where

$$\begin{aligned} A &= \begin{bmatrix} a_p & \begin{matrix} I_{n-1} \\ 0_{1\times(n-1)} \end{matrix} \end{bmatrix} \\ a_p &= \begin{bmatrix} a_1 \\ \vdots \\ a_n \end{bmatrix}, \quad b = \begin{bmatrix} b_0 \\ \vdots \\ b_{n-1} \end{bmatrix} \\ c &= [1 \ 0_{1\times(n-1)}] \end{aligned}$$

where $x(t)$, $u(t)$ and $y(t)$ denote a state vector, an input vector and an output vector. The dimensions of $A$, $b$ and $c$ are $n \times n$, $n \times 1$ and $1 \times n$ respectively. And it is assumed that

1) $(A, b)$ is stabilizable.
2) $(c, A)$ is detectable.
3) $\begin{bmatrix} A-I & b \\ c & 0 \end{bmatrix}$ has a full rank.

The integral action $w(t)$ is given by

$$w(t) = \frac{1}{\Delta} e(t) \qquad (3)$$

where

$$\Delta = 1 - z^{-1}$$

A tracking error is defined as a difference between a reference signal $r$ and the output, and given as follows.

$$e(t) = r - y(t)$$

In this paper, $z^{-1}$ denotes backward shift operator: $z^{-1}w(t) = w(t-1)$. The control objective is that the output $y(t)$ tracks to the reference signal $r$.

### 2.2. GPC without Integral Compensation

To obtain two degree-of-freedom of GPC, GPC without an integrator is firstly considered. The steady states of $x(t)$, $y(t)$ and $u(t)$ are denoted as $x_\infty$, $y_\infty$ and $u_\infty$ respectively. The steady states of the plant (1) and (2) are given as

$$\begin{aligned} x_\infty &= Ax_\infty + Bu_\infty && (4)\\ y_\infty &= cx_\infty && (5) \end{aligned}$$

Where it assumes that $y_\infty$ tracks to the reference signal $r$. Then the steady states of $x_\infty$ and $u_\infty$ are given by the following equations.

$$\begin{bmatrix} x_\infty \\ u_\infty \end{bmatrix} = \begin{bmatrix} A-I & b \\ c & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ r \end{bmatrix} \qquad (6)$$

Subtracting (4) and (5) from (1) and (2), it derives

$$\begin{aligned} x(t+1) - x_\infty &= A(x(t) - x_\infty) + b(u(t) - u_\infty) \\ y(t) - y_\infty &= c(x(t) - x_\infty) \end{aligned}$$

Therefore the deviations of $x(t)$, $y(t)$ and $u(t)$ are defined as follows.

$$\begin{aligned} \tilde{x}(t) &= x(t) - x_\infty \\ \tilde{y}(t) &= y(t) - y_\infty \\ \tilde{u}(t) &= u(t) - u_\infty \end{aligned}$$

Then the following deviation system is given.

$$\begin{aligned} \tilde{x}(t+1) &= A\tilde{x}(t) + b\tilde{u}(t) && (7)\\ \tilde{y}(t) &= c\tilde{x}(t) && (8) \end{aligned}$$

In order to find $j$-ahead prediction $\hat{\tilde{y}}(t+j|t)$ of this system, $j$-ahead output $\tilde{y}(t+j)$ is derived.

$$\tilde{y}(t+j) = cA^j\tilde{x}(t) + \sum_{i=1}^{j} cA^{i-1}b\tilde{u}(t+j-i) \qquad (9)$$

Because it is assumed that there is no disturbance, $j$-ahead prediction is derived as $\hat{\tilde{y}}(t+j|t) = \tilde{y}(t+j)$. Then the vector form of output prediction at each sampling time and the series of future inputs, and the matrices $H$ and $G$ are defined as follows.

$$\begin{aligned} \hat{\tilde{Y}}(t) &= \begin{bmatrix} \hat{\tilde{y}}(t+N_1|t) \\ \vdots \\ \hat{\tilde{y}}(t+N_2|t) \end{bmatrix}, \quad \tilde{U}(t) = \begin{bmatrix} \tilde{u}(t) \\ \vdots \\ \tilde{u}(t+N_u-1) \end{bmatrix} \\ H &= \begin{bmatrix} cA^{N_1} \\ cA^{N_1+1} \\ \vdots \\ cA^{N_2} \end{bmatrix} \\ G &= \begin{bmatrix} cA^{N_1-1}b & \cdots & cb & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ cA^{N_u-1}b & \ddots & \ddots & \ddots & cb \\ \vdots & & \vdots & & \vdots \\ cA^{N_2-1}b & \cdots & \cdots & \cdots & cA^{N_2-N_u}b \end{bmatrix} \end{aligned}$$

where $[N_1, N_2]$ expresses the prediction horizon and $[1, N_u]$ expresses the control horizon. Then the vector form of output prediction is given as follows.

$$\hat{\tilde{Y}}(t) = H\tilde{x}(t) + G\tilde{U}(t) \qquad (10)$$

To derive control law, consider the following performance index $J$.

$$J = \sum_{j=N_1}^{N_2} \tilde{x}^T(t+j)c^Tc\tilde{x}(t+j) + \sum_{j=1}^{N_u} \lambda_j \tilde{u}^2(t+j-1)$$

$J$ can be rewritten by the following vector form.

$$J = \tilde{Y}^T(t)\tilde{Y}(t) + \tilde{U}^T(t)\Lambda\tilde{U}(t) \tag{11}$$

where $\Lambda = \mathrm{diag}\{\lambda_1, \cdots, \lambda_{N_u}\}$. Since $\tilde{y}(t)$ means the tracking error, it is found that $J$ is square form of the tracking error and the deviation of control input. Substituting (10) for (11) and having partial derivative of $\tilde{U}(t)$, the series of the deviations of future control inputs can be derived.

$$\tilde{U}(t) = -(G^TG + \Lambda)^{-1}G^TH\tilde{x}(t)$$

Then the control law without an integral compensation can be derived as follows.

$$u(t) = F_0x(t) + H_0r \tag{12}$$

where $F_0$ and $H_0$ are defined by the following equations.

$$\begin{aligned} F_0 &= -[1\ 0\ \cdots\ 0](G^TG + \Lambda)^{-1}G^TH \\ H_0 &= -\left\{c(A - I + bF_0)^{-1}b\right\}^{-1} \end{aligned}$$

### 2.3. GPC with Integral Compensation

When there is modeling error or disturbance, the control law (12) can not achieve the control objective and leaves a steady state error between the output and the reference signal because it does not have an integral compensation.

Therefore an integral compensation $G_0w(t)$ is added to the control law (12), where it denotes the integral action as $w(t)$ and the integral gain as $G_0$. Then GPC controller with the integral action is derived as follows.

$$u(t) = F_0x(t) + H_0r + G_0w(t) \tag{13}$$

The control law derived here can achieve the control objective, that is, the output can track to the reference signal even if there is modeling error or step-type disturbance.

### 2.4. Two DOF Controller

Because the integral compensation in the control law (13) always acts, it may cause an extra input or have a worse change of the transient response. That is, it is desirable that two degree-of-freedom of GPC is designed, which has an effect of the integral compensation only if there is modeling error or disturbance. Two degree-of-freedom of GPC described in this paper can adjust the characteristics of the output response and the disturbance response independently. In this subsection, two degree-of-freedom of GPC controller is shown. At first, the control law is expressed as follows by including the integral compensation $z(t)$ and the integral gain $G_0$.

$$u(t) = F_0x(t) + H_0r + G_0z(t) \tag{14}$$

where $F_0$ and $H_0$ are the same coefficients as in (12).

Second, assuming that there is neither modeling error nor disturbance, the tracking error $e(t) = r - y(t)$ is calculated. By this assumption, the control law expressed here becomes the same controller of (12). Substituting (12) for (1) and subtracting $x(t)$ from it, the following equation is obtained.

$$x(t+1) - x(t) = (A - I + bF_0)x(t) + bH_0r$$

Therefore

$$\begin{aligned} x(t) &= (A - I + bF_0)^{-1}x(t+1) - (A - I + BF_0)^{-1} \\ &\quad \cdot x(t) - (A - I + bF_0)^{-1}bH_0r \end{aligned} \tag{15}$$

Substituting (15) for $e(t)$ and using $H_0$,

$$\begin{aligned} e(t) &= r - y(t) \\ &= r - cx(t) \\ &= r - c(A - I + bF_0)^{-1}x(t+1) + c(A - I \\ &\quad + bF_0)^{-1}x(t) + c(A - I + bF_0)^{-1}bH_0r \\ &= -c(A - I + bF_0)^{-1}(x(t+1) - x(t)) \end{aligned}$$

In the case that there is neither modeling error nor disturbance, the integration $w'(t)$ of tracking error can be given as follows. For simplicity of notation, it denotes $-c(A - I + bF_0)^{-1}$ as $\beta$.

$$\begin{aligned} w'(t) &= \frac{1}{\triangle}e(t) \\ &= -c(A - I + bF_0)^{-1}(x(t+1) - x(t)) \\ &\quad + w'(t-1) \\ &= \beta(x(t+1) - x(t)) + \beta(x(t) - x(t-1)) \\ &\quad + w'(t-2) \\ &= \beta(x(t+1) - \cancel{x}(t)) + \beta(\cancel{x}(t) - \cancel{x}(t-1)) + \cdots \\ &\quad + \beta(\cancel{x}(2) - x(1)) + w'(0) \\ &= -c(A - I + bF_0)^{-1}(x(t+1) - x(1)) \end{aligned}$$

where it is assumed that $w'(0) = 0$. Using the equation (15), the following equation is derived.

$$w'(t) = -c(A - I + bF_0)^{-1}(A + bF_0)(x(t) - x(0)) \tag{16}$$

The equation (16) stands for the integral compensation in the case that there is neither modeling error nor disturbance. Therefore the integral action $z(t)$ in two degree-of-freedom of GPC can be given as follows.

$$\begin{aligned} z(t) &= w(t) - w'(t) \\ &= w(t) + c(A - I + bF_0)^{-1}(A + bF_0)(x(t) \\ &\quad - x(0)) \end{aligned} \tag{17}$$

$z(t)$ is always set to be zero, that is, the integral compensation does not appear if there is neither modeling error nor disturbance. Therefore two degree-of-freedom of GPC law (14) is given by the integral compensation (17).

The extended system combined with the state $x(t)$ and the integral compensation $z(t)$ can be described as follows.

$$\begin{bmatrix} x(t+1) \\ z(t+1) \end{bmatrix} = \begin{bmatrix} A + bF_0 & bG_0 \\ 0 & 1 - H_0^{-1}G_0 \end{bmatrix} \begin{bmatrix} x(t) \\ z(t) \end{bmatrix} + \begin{bmatrix} bH_0 \\ 0 \end{bmatrix} r$$

If $A + bF_0$ is designed to be stable, the integral gain $G_0$ of the integral compensation can be chosen in the range that $1 - H_0^{-1}G_0$ is stable as follows.

$$\begin{aligned} 0 < G_0 < 2H_0 \quad (H_0 > 0) \\ 0 > G_0 > 2H_0 \quad (H_0 < 0) \end{aligned}$$

## 3. SELF-TUNING CONTROLLER

THIS section gives two degree-of-freedom of self-tuning GPC by applying the identified parameters $\hat{a}_p(t)$, $\hat{b}(t)$ of $a_p$, $b$ and the estimation $\hat{x}(t)$ of $x(t)$ from an adaptive observer. To construct the adaptive observer[13], the plant (1) is reformed to the following equations;

$$x(t+1) = Fx(t) + (a_p - f)y(t) + bu(t) \tag{18}$$

$$F = \left[ \begin{array}{cc} f & \begin{array}{c} I_{n-1} \\ 0_{1\times(n-1)} \end{array} \end{array} \right], \quad f = \left[ \begin{array}{c} f_1 \\ \vdots \\ f_n \end{array} \right]$$

Where $F$ is chosen as a stable matrix and its eigenvalues are the roots of the following polynomial.

$$f[z^{-1}] = 1 + f_1 z^{-1} + \cdots + f_n z^{-n}$$

$R_1(t)$ and $R_2(t)$ are defined as follows.

$$\begin{aligned} R_1(t+1) &= FR_1(t) + Iy(t),\ R_1(0) = 0 \\ R_2(t+1) &= FR_2(t) + Iu(t),\ R_2(0) = 0 \\ R(t) &= [R_1(t) \ \ R_2(t)] \end{aligned}$$

And the following signal vectors $\zeta_1(t)$, $\zeta_2(t)$ and $\zeta(t)$ are defined.

$$\begin{aligned} \zeta_1(t+1) &= F^T\zeta_1(t) + c^Ty(t),\ \zeta_1(0) = 0 \\ \zeta_2(t+1) &= F^T\zeta_2(t) + c^Tu(t),\ \zeta_2(0) = 0 \\ \zeta(t) &= \left[ \begin{array}{c} \zeta_1(t) \\ \zeta_2(t) \end{array} \right] \end{aligned}$$

Using $R_1(t)$ and $R_2(t)$, (18) and (2) can be expressed by the following equations.

$$x(t) = R(t)\theta \tag{19}$$

$$y(t) = \zeta^T(t)\theta \tag{20}$$

$$\theta = \left[ \begin{array}{c} a_p - f \\ b \end{array} \right]$$

where the terms with the initial state value $x(0)$ are removed from equations (19) and (20) since $x(0)$ decreases exponentially.

Replacing plant parameter vector $\theta$ with the identified value vector $\hat{\theta}(t)$ in equations (19) and (20), the adaptive observer is derived as

$$\hat{x}(t) = R(t)\hat{\theta}(t) \tag{21}$$

$$\hat{y}(t) = \zeta^T(t)\hat{\theta}(t) \tag{22}$$

Then the parameter identification law is given by

$$\hat{\theta}(t) = \hat{\theta}(t-1) - \Gamma(t-1)\zeta(t)\epsilon(t) \tag{23}$$

$$\Gamma(t) = \Gamma(t-1) - \frac{\Gamma(t-1)\zeta(t)\zeta^T(t)\Gamma(t-1)}{1 + \zeta^T(t)\Gamma(t-1)\zeta(t)} \tag{24}$$

$$\epsilon(t) = \frac{\hat{\theta}^T(t-1)\zeta(t) - y(t)}{1 + \zeta^T(t)\Gamma(t-1)\zeta(t)} \tag{25}$$

$$\Gamma(0) = \alpha I,\ 0 < \alpha < \infty$$

Therefore two degree-of-freedom of self-tuning GPC is obtained by replacing $a_p$, $b$ and $x(t)$ with the identified values $\hat{a}_p(t)$, $\hat{b}(t)$ and the state estimation $\hat{x}(t)$.

## 4. SEARCH FOR THE INTEGRAL GAIN BY A GENETIC ALGORITHM

IN the section 2, the range for the integral gain $G_0$ is given. In the two degree-of-freedom of GPC system[6], [7], its selection method is by trial and error. Therefore this section considers giving a best solution of the integral gain by a genetic algorithm.

In the first step, each genotype of individual of the integral gain $G_0$ represents in binary as strings of n bits. Each phenotype of individual of $G_0$, that is, the integral gain $G_0$ is calculated by converting the binary representation to the decimal representation in the range given in section 2.

In the next step, the fitness function to search the solution of $G_0$ is defined as the integral of a square error between the reference signal and the output, and a square of the control input.

$$f(G_0) = \sum_{t=1}^{N} \left[ \{r - y_{G_0}(t)\}^2 + \gamma u_{G_0}^2(t) \right] \tag{26}$$

where $y_{G_0}(t)$ and $u_{G_0}(t)$ are the plant output and the control input using $G_0$ searched by a genetic algorithm and $\gamma$ is a weighting factor. The solution of $G_0$ is searched by a genetic algorithm so that the fitness function $f(G_0)$ becomes small. In this paper, the fitness function is newly extended from the previous works[8], [9] in order to make not only a tracking error but also an extra input with an integral compensation small. And it is equal to the previous works when $\gamma = 0$.

The solution $G_0$ gives a disturbance response in the sense of minimization of $f(G_0)$. And the genetic algorithm in this paper is calculated as the following steps and repeated until a decided number of generations.

1) Initialization of population of genotype of $G_0$. The number of generation is set to be 1.
2) Evaluation of $f(G_0)$. It is repeated until a decided number of generations.
3) Creation of population of genotype of next generation by selection, crossover and mutation.
4) The number of generation is added to 1. Go to step 2.

## 5. NUMERICAL EXAMPLES

IN this section the numerical examples are shown to verify the validity of the proposed method.

Consider the controlled plant,

$$\begin{aligned} x(t+1) &= \left[ \begin{array}{cc} 0.8 & 1 \\ 0.4 & 0 \end{array} \right] x(t) + \left[ \begin{array}{c} 0.2 \\ 0.5 \end{array} \right] u(t) \\ y(t) &= \left[ \begin{array}{cc} 1 & 0 \end{array} \right] x(t) \end{aligned}$$

Simulation steps are 200. The initial values of the output and the input are assumed to be 0, and the nominal values of the plant parameters are set to be 0.8 $\times$ the true values. The white gaussian noise with the variance $\sigma^2 = 0.01$ is added to the plant output and the design parameters are given as follows.

$$N_1 = 1,\ N_2 = 10,\ N_u = 10,\ \lambda = 1$$

The reference signal is a rectangular signal with amplitude 1 and the period of 40 steps. The adaptive observer and the

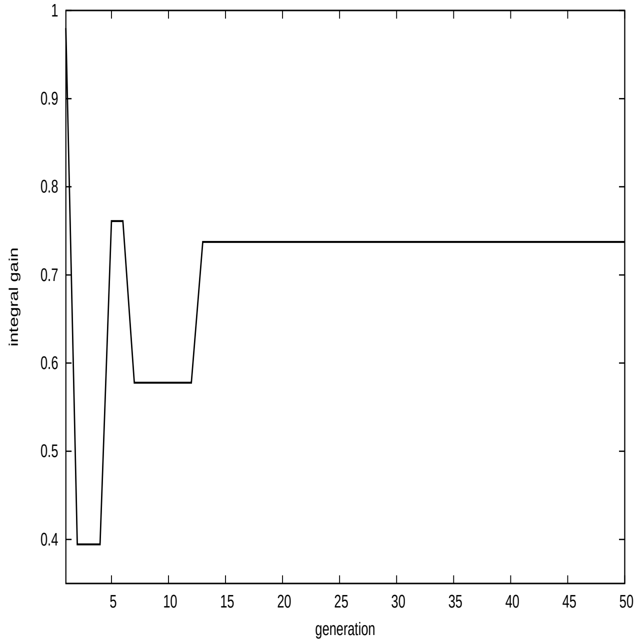


Fig. 1. Integral gain ($\gamma = 0.1$)

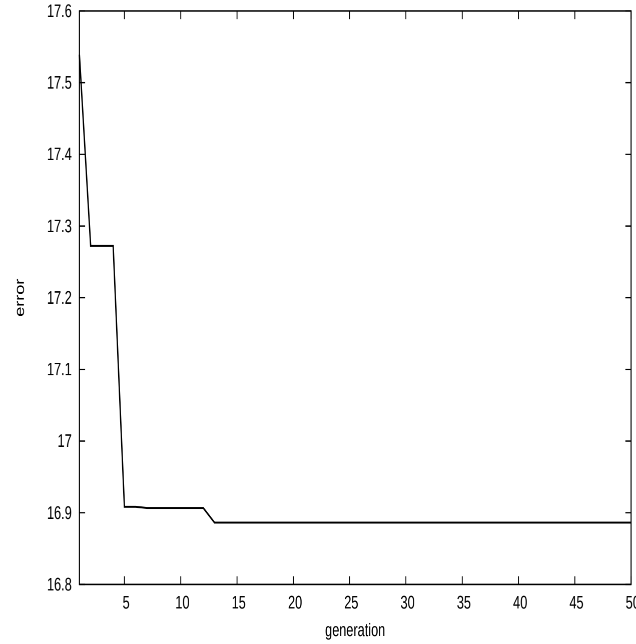


Fig. 2. Fitness value ($\gamma = 0.1$)

parameter identification law are chosen to $f = [0.1 \quad 0.2]^T$ and $\Gamma(0) = 100I$. The parameters of the genetic algorithm are given so that the number of individuals is set to be 50, the integral gain $G_0$ is represented in binary as strings of 8 bits, its phenotype is in the range given in section 2, the number of generations is set to be 50, the selection is chosen to roulette rule and the crossover is one-point crossover, and the probability of mutation is set to be 0.1.

In Fig.1 and Fig.2 the numerical example gives the minimal value of fitness function to 16.8863 and the integral gain to 0.7374 with $\gamma = 0.1$. On the other hand, Fig.7 and Fig.8 shows the minimal value of fitness function to 13.5731 and the integral gain to 0.9031 with $\gamma = 0$[9]. It is found that the proposed method in this paper can calculate a smaller integral gain than [9]. In Fig.4 and Fig.10, the absolute values of the plant input are $3.3272$ and $3.6601$ respectively. Therefore it is also found that the proposed method can generate a smaller input signal than [9].

Fig.3 and Fig.9 show the plant output and Fig.5, Fig.6, Fig.11 and Fig.12 show the identified values of plant $\hat{a}_p(t)$ and $\hat{b}(t)$. It is shown that the plant output can track to the reference signal by $G_0$ calculated by the genetic algorithm.

Fig.13 and Fig.14 show the plant output and the plant input adding the step-type disturbance with amplitude $0.3$ after 100th step instead of the gaussian noise. Although the parameter identification is not applied in these figures, because the two degree-of-freedom of GPC is obtained, the effect of the integral compensation appears when there is a disturbance.

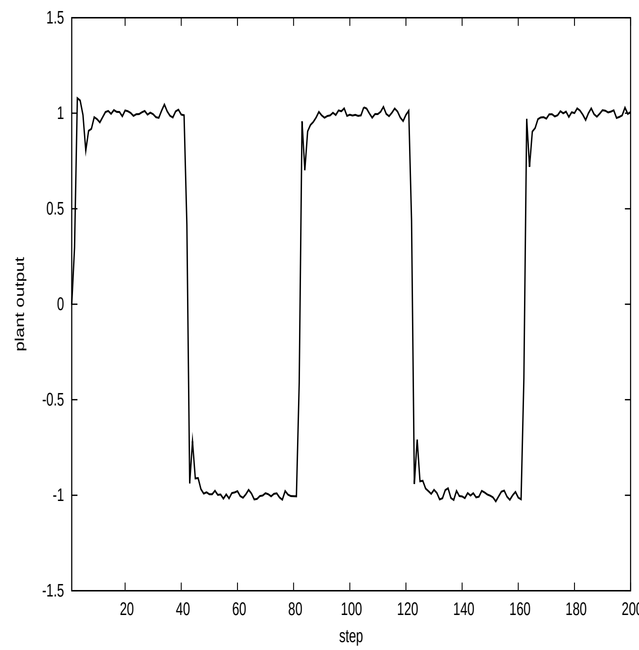


Fig. 3. Plant output ($\gamma = 0.1$)

## 6. Conclusion

In this paper, a selection method of the integral gain for two degree-of-freedom of self-tuning GPC based on state-space approach is given by using a genetic algorithm. And the numerical examples are shown to verify the validity of the proposed method. Although the gain for integral compensation must be selected by trial and error in the conventional method[6], [7], this paper gives its selection method by newly including the terms of a control input in the fitness function[8], [9].

As future works, there is an extension to MIMO systems of the proposed method and a problem to consider the relation between the parameter identification law and the tuning method of integral gain by a genetic algorithm.

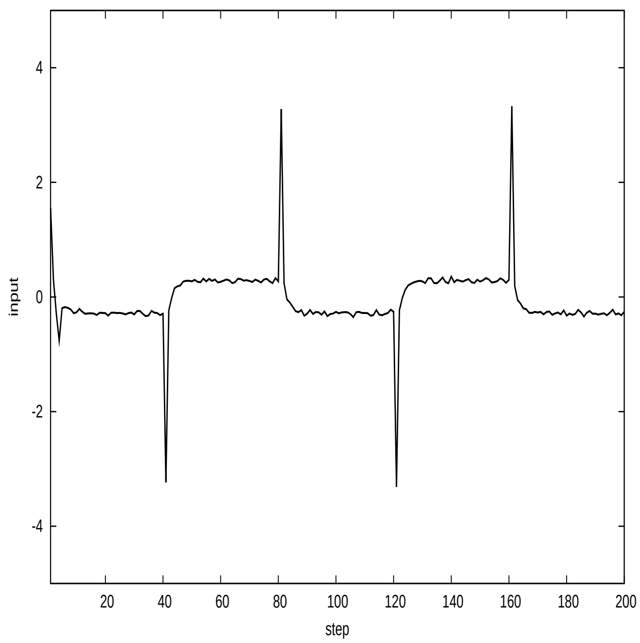


Fig. 4. Plant input ($\gamma = 0.1$)

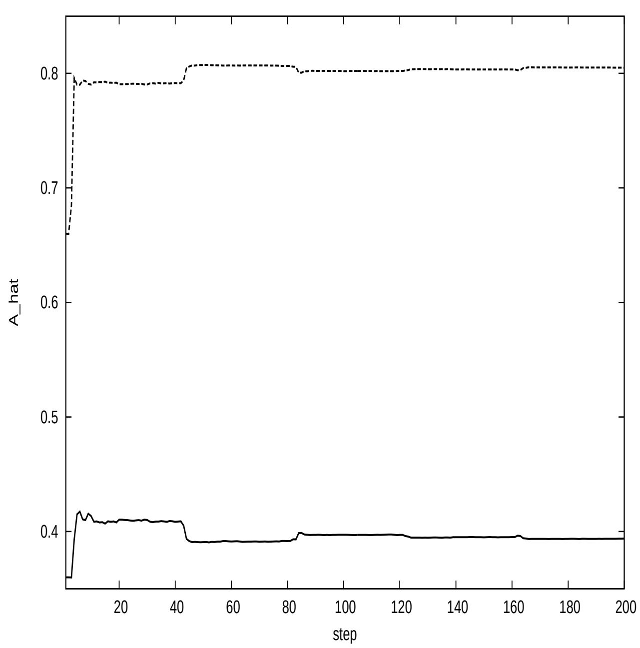


Fig. 5. Identified values of $\hat{a}_p(t)$ ($\gamma = 0.1$)

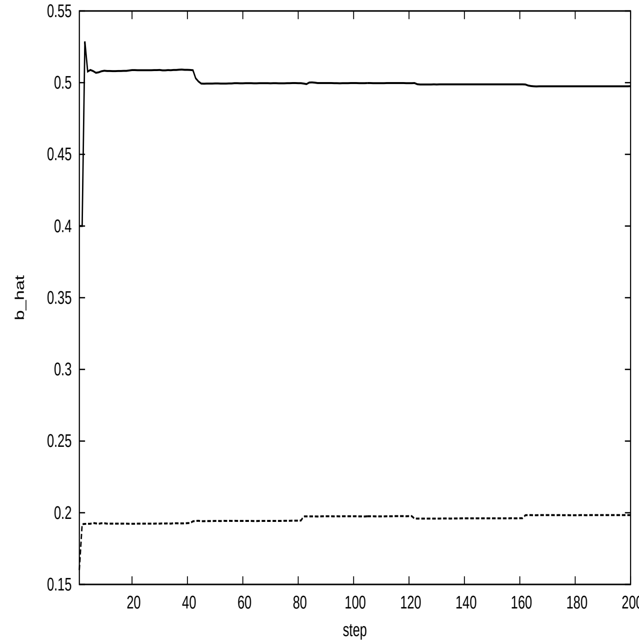


Fig. 6. Identified values of $\hat{b}(t)$ ($\gamma = 0.1$)

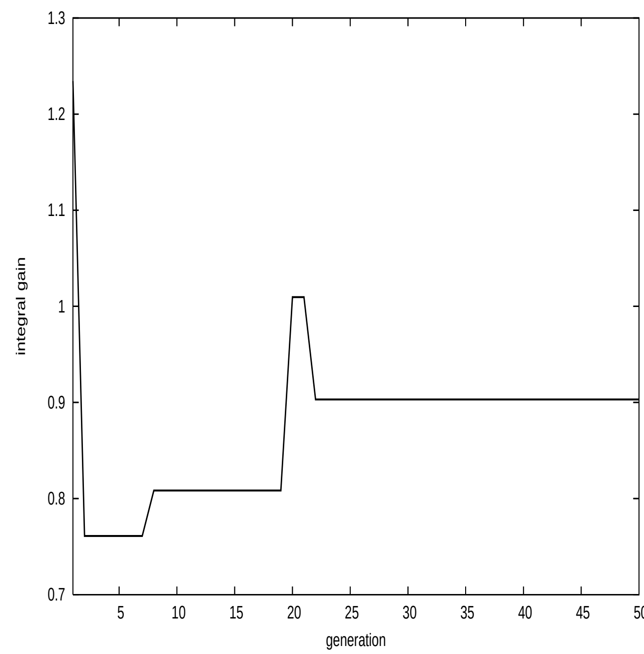


Fig. 7. Integral gain ($\gamma = 0$)


## ACKNOWLEDGMENT

The author is grateful to the anonymous reviewers and editor since their helpful comments have improved this paper.


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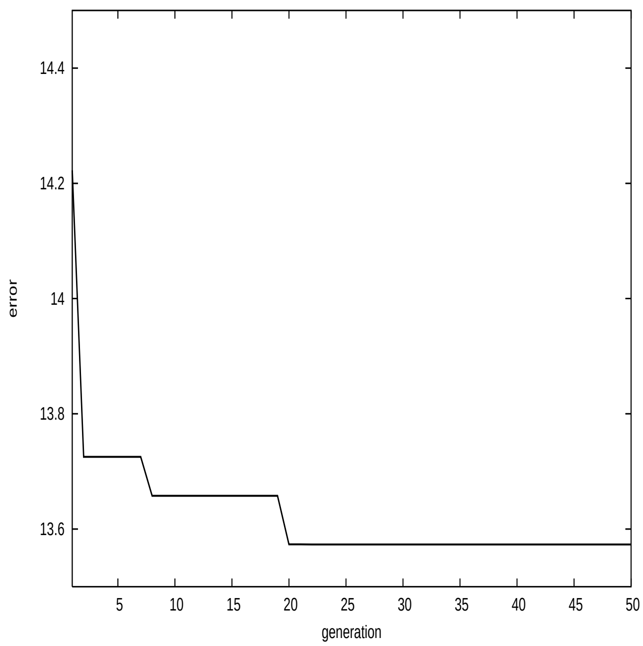


Fig. 8. Fitness value ($\gamma = 0$)

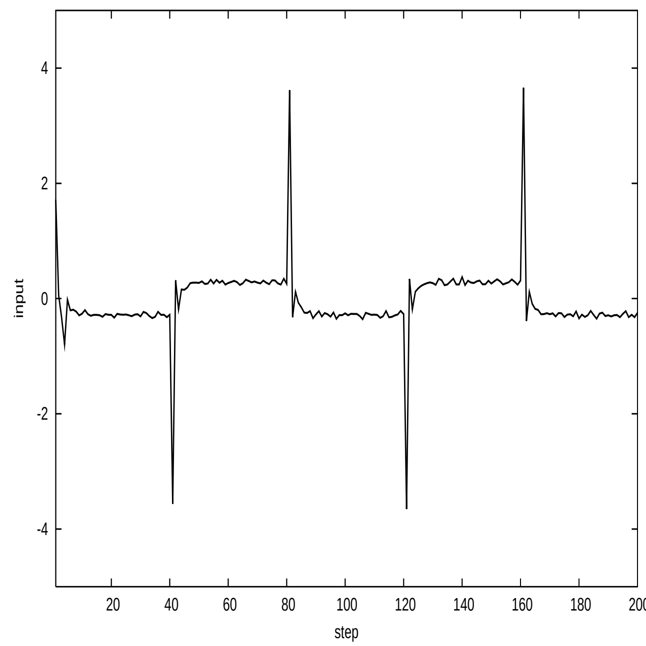


Fig. 10. Plant input ($\gamma = 0$)

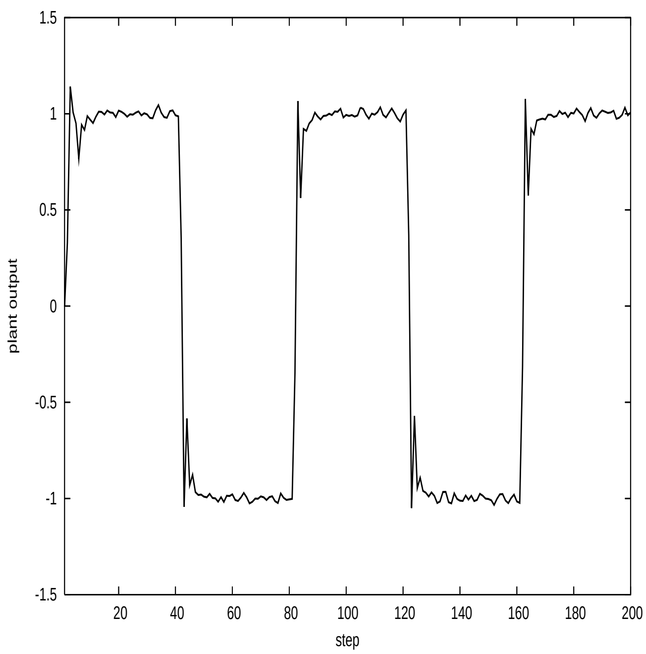


Fig. 9. Plant output ($\gamma = 0$)

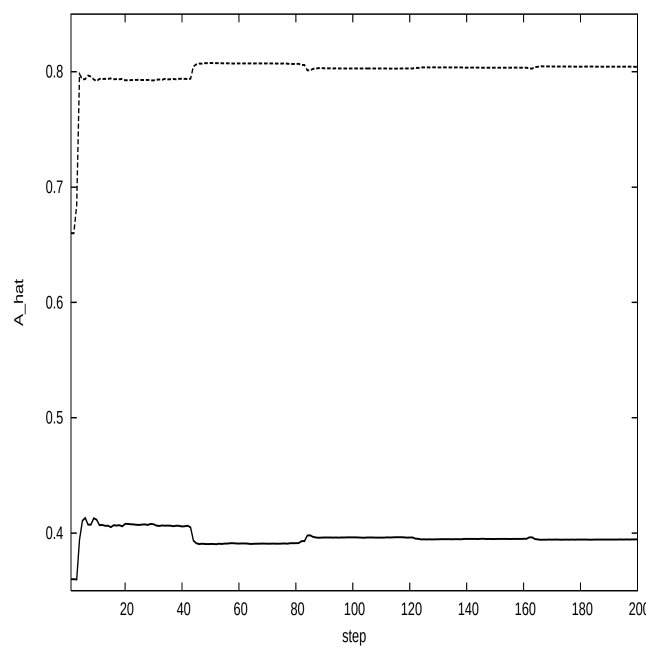


Fig. 11. Identified values of $\hat{a}_p(t)$ ($\gamma = 0$)


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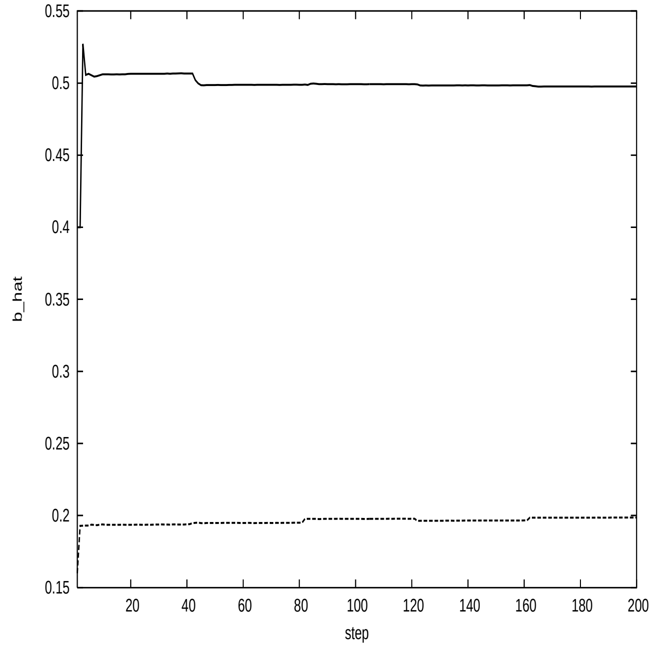


Fig. 12. Identified values of $\hat{b}(t)$ $(\gamma = 0)$

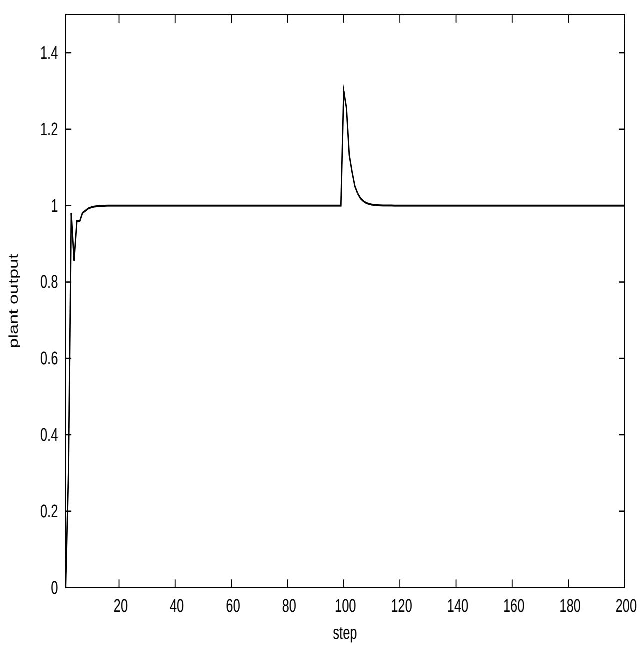


Fig. 13. Plant output with step-type disturbance

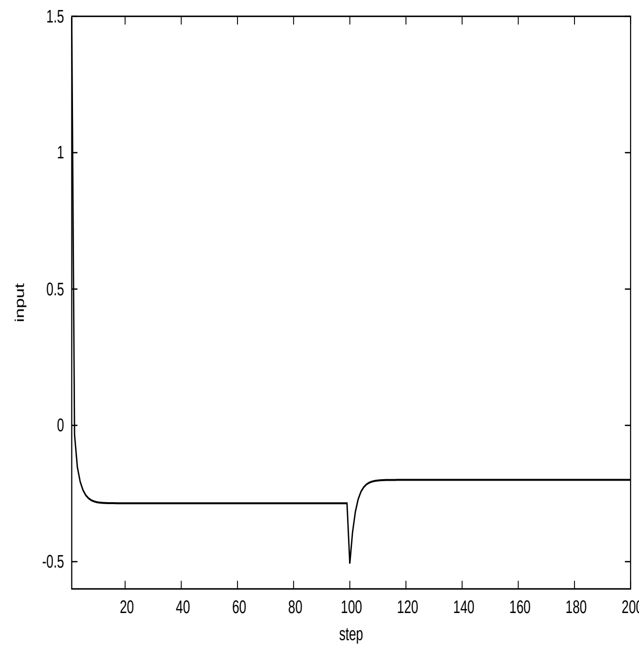


Fig. 14. Plant input with step-type disturbance

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