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Optimal design of the PID Controller using a predictive control method

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Abstract

This paper is concerned with the design of a predictive PID controller, which has similar features to the model-based predictive controller. A PID type control structure is defined which includes prediction of the outputs and the recalculation of new set points using the future set point data. The optimal values of the PID gains are pre-calculated using the values of gains calculated from an unconstrained generalized predictive control algorithm. Simulation studies demonstrate the performance of the proposed controller and the results are compared with generalized predictive controller and the results are compared with generalized predictive control solutions.

Key words : PID control, Predictive control, time delay, motor control

1. Introduction

Proportional-Integral-Derivative (PID) controller is the control algorithms commonly found in industrial applications.

The popularity of PID controller is due to their functional simplicity. They provide robust and reliable performance for most systems if the PID parameters are determined or tuned to ensure a satisfactory closed-loop performance.

Gaining the optimal parameter in the controller's performance is worthy of study and It has been studied up to these days. Explicit relations for tuning PID controllers were proposed in (Ziegler and Nichols) (Cohen and Coon)[1-2]. Astrom and Hagglund developed a relay feedback technique for auto tuning PID controllers. Because of its simplicity and efficiency, relay based auto-tuning methods have been integrated into commercial controllers, which have been successful in many process control applications (Astrom and Hagglund)[3-4]. The structure of PID controllers is discussed in (He and Garvey, 1996) with respect to self-tuning algorithms and automatic selection of structures. On the other hand, the GPC method was proposed by Clarke et al. (1987) and this has become one of the most popular Model Predictive Control (MPC) methods both in industry and academia[5-6]. The GPC provides an analytical solution, it can deal with unstable and non-minimum phase plants. The GPC is an optimal method which incorporates the concept of a control horizon as well as the consideration of weighting of control increments in the cost function. Because of wide application of the PID controllers, many researchers have attempted to use advanced control techniques such as optimal control and GPC to restrict the structure of these controllers to retrieve the PID controller.

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Revera et al. introduced an IMC based PID controller design for a first order process model[7]. Chien extended IMC-PID controller design to cover the second order process model[8]. Morari and Zafiriou have shown that Internal Model Control (IMC) leads to PID controllers for virtually all models common in industrial practice[9]. In Wang et al. a least square algorithm was used to compute the closest equivalent PID controller to an IMC design and a frequency response approach is adopted[10]. However, the design is still ineffective when applied to time-delay and unstable systems. Marques and Fliess have developed a simple approach for PID control of linear continuous systems based on flat output trajectory generation. Important characteristics of model predictive control methods have been combined with PID control properties by considering flatness based predicted trajectories. In Rusnak's works [14-15] the linear quadratic regulator(LQR) theory has been used to formulate tracking problems and to show those cases when the solution gives PID controllers. This avoided heuristics and gives a systematic approach to the explanation of the good performance of the PID controllers. In Rusnak the generalised PID structure had been introduced and applied up to a fifth order system. Tan et al. have also presented a PID control design based on a GPC approach. The real time application results showed that their method is applicable and efficient.

This paper presents a new PID controller based on the GPC approach. Objective of PID controller design can apply for low order, high order and non-minimum phase process, but existing predictive control studies tended to research theoretical approach and failed to notice about experiment. So, goal of this paper is design of a new PID controller that is applicable to both time delay and unstable real system. Main idea in this paper is based on PID parameter computing from GPC control law.

2. Predictive Controller

2.1 Predictive control

Controller needs an operation of a prediction for elimination an Error and an oscillation. Namely, the error is predicted by not the error in control period but difference in model with reference in point of set in future and then fitness output is calculated.

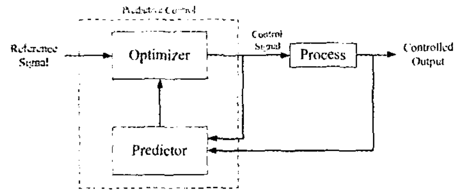

Fig 2.1 Basic Structure of Predictive Controller

The solution derived objective function optimization problem in time k, in other words, control input in current and the future has the following form

u(k),u(k+1),..., u(k+M-1)

And, first input, that is, current control input u(k) uses in time [k,k+1] to control the plant only. Next, control and prediction period move forward a point of time, and control input u(k) and control input derived from new optimization problem in predicted initial condition induced by system output y(k+1) are obtained. Fig. 2.2 show an algorithm of predictive control

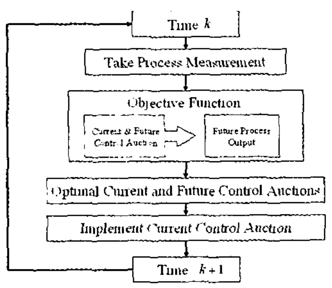

Fig 2.2 Algorithm of Predictive Control

2.2 Control method of Predictive Control

Generally, the control method in predictive control uses Receding Horizon Control (RHC). First, RHC compute u(k|k),u(k+1|k),u(k+2|k),...,u(k+N-1|k) which are optimal control inputs, considering in time from k to [k, k+N].

And then, we can predict u(k | k) using process. And next, calculate optimal control input u(k+1|k+1),u(k+2|k+1),..., u(k+N|k+1) considering [k+1,k+N+1] horizon in k+1 time. And then use process u(k+1|k+1) again. Namely, Process controlled using current control input u(k|k) in time k and next, control horizon and predict horizon are moved forward one step, and control input is derived from new optimal problem, which have Predicted initial condition that is derived from control input u(k|k) and system output y(k+1).

3. Design of predictive controller

3.1 General form of PID

A discrete PID controller has the following form:

$$\tilde{u}(k)=k_P e(k)+k_I\sum_{j=1}^{k}e(j)+k_D[e(k)-e(k-1)] \tag{3.1}$$

Where k_P, k_I and k_D are the proportional, integral and derivates gains, respectively. Fig 3.1 show the PID controller.

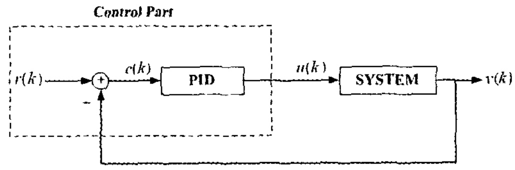

Fig 3.1 PID Controller

Taking the difference on both sides of Eq. (3.1) at step k and k+1 leads to :

$$\begin{aligned}\Delta\tilde{u}(k)&=\tilde{u}(k)-\tilde{u}(k-1)\\&=k_P[e(k)-e(k-1)]+k_I e(k)+\\&\quad k_D[e(k)-2e(k-1)+e(k-2)]\end{aligned} \tag{3.2}$$

Transforming equation (3.2) into z domain gives:

$$\tilde{U}(z)=\frac{[q_0+q_1z^{-1}+q_2z^{-2}]}{1-z^{-1}}E(z) \tag{3.3}$$

where:

$q_0=(k_P+k_I+k_D)$, $q_1=-(k_P+2k_D)$, $q_2=k_D$

3.1 Predictive PID controller

A type of predictive PID controller is defined as follows:

$$u(k)=\sum_{i=0}^{M}\left(k_P e(k+i)+k_I\sum_{j=1}^{k}e(j+i)+k_D[e(k+i)-e(k+i-1)]\right) \tag{3.4}$$

The controller consists of M parallel PID controllers as shown in Fig.3.2. For M = 0, the controller is identical to the

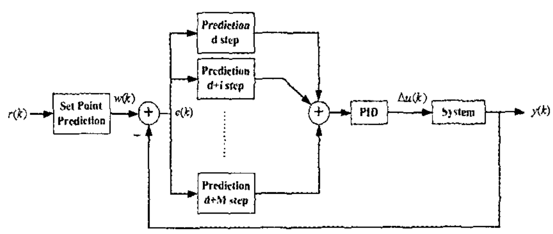

Fig 3.2 Basic Algorithm of Predictive PID Controller

conventional PID. For M > 0, the proposed controller has predictive capability similar to MBPC where M is prediction horizon of PID controller.

Using Eq. (3.1), Eq. (3.4) can be decomposed into M control signal as follows:

$$u(k) = \tilde{u}(k) + \tilde{u}(k+1) + ... + \tilde{u}(k+M) \quad (3.5)$$

where:

$$\tilde{u}(k+i) = k_P e(k+i) + k_I \sum_{j=1}^{k} e(j+i) + k_D[e(k+i) - e(k+i-1)]$$
$$(i = 0,..,M)$$

It is assured that $e = y_{set} - y = -y\ (y_{set} = 0)$ and if incremental form of control signal is considered, $\Delta u(k) = u(k) - u(k-1)$, and after some straightforward algebra, the control signal can be written as:

$$\Delta u(k) = \Delta\tilde{u}(k) + \Delta\tilde{u}(k+1) + ... + \Delta\tilde{u}(k+M) \quad (3.6)$$

where:

$$\tilde{u}(k+i) = k_P[w(k) - y(k+i)] + k_I \sum_{j-1}^{k}[w(k) - y(j+i)]$$
$$+ k_D[w(k) - y(k+i) - w(k) + y(k+i-1)] \quad (3.7)$$
$$(i = 0,..,M)$$

In compact $\Delta\tilde{u}(k+i)$ form can be written as:

$$\Delta\tilde{u}(k+i) = -KY(k+i)$$

where:

$$K = [k_D \quad -k_P - 2k_D \quad k_P + k_I + k_D]$$
$$Y(k+i) = [y(k+i-2) \quad y(k+i-1) \quad y(k+i)]^T$$

Using Eq. (3.7) in Eq. (3.5):

$$\Delta u(k) = \Delta\tilde{u}(k) + \Delta\tilde{u}(k+1) + ... + \Delta\tilde{u}(k+M)$$
$$= -K\{Y(k) + Y(k+1) + ... + Y(k+M)\} \quad (3.8)$$

This implies that the current control signal value is a linear combination of the future predicted outputs. The i th step ahead prediction of output can be obtained from the following equation[18]

$$y(k+i) = [g_{i1} \ g_{i2} \ ...... \ g_0]\begin{bmatrix} \Delta u(t) \\ \Delta u(t+1) \\ ...... \\ \Delta u(t+i-1) \end{bmatrix} + [f_{i1} \ f_{i2} \ ...... \ f_{i(n_a+1)}]\begin{bmatrix} y(t) \\ y(t-1) \\ ...... \\ y(t-n_a) \end{bmatrix}$$
$$+ [g'_{i1} \ g'_{i2} \ ...... \ g'_{n}]\begin{bmatrix} \Delta u(t-1) \\ \Delta u(t-2) \\ ...... \\ \Delta u(t-n_b) \end{bmatrix} \quad (3.9)$$

Therefore, the output prediction for i th PID will be:

$$\begin{bmatrix} y(k+i-2) \\ y(k+i-1) \\ y(k+i) \end{bmatrix} = \begin{bmatrix} g_{i3} & \cdots & g_0 & 0 & 0 \\ g_{i2} & g_{i3} & \cdots & g_0 & 0 \\ g_{i1} & g_{i2} & g_{i3} & \cdots & g_0 \end{bmatrix}\begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ ...... \\ \Delta u(k+N_u-1) \end{bmatrix}$$
$$+ \begin{bmatrix} f_{(i-2)1} & f_{(i-2)2} & \cdots & f_{(i-2)(n_a+1)} \\ f_{(i-1)1} & f_{(i-1)2} & \cdots & f_{(i-1)(n_a+1)} \\ f_{i1} & f_{i2} & \cdots & f_{i(n_a+1)} \end{bmatrix}\begin{bmatrix} y(k) \\ y(k-1) \\ ...... \\ y(k-n_a) \end{bmatrix} \quad (3.10)$$
$$+ \begin{bmatrix} g'_{(i-2)1} & g'_{(i-2)2} & \cdots & g'_{(i-2)n_b} \\ g'_{(i-1)1} & g'_{(i-1)2} & \cdots & g'_{(i-1)n_b} \\ g'_{i1} & g'_{i2} & \cdots & g'_{in_b} \end{bmatrix}\begin{bmatrix} \Delta u(k-1) \\ \Delta u(k-2) \\ ...... \\ \Delta u(k-n_b) \end{bmatrix}$$

In equation (3.10), future control inputs are needed to calculate $\{\Delta u(k+i) \quad i = 1:(N_u - 1)\}$.

Rewriting the output prediction in compact form gives:

$$Y(k+i) = G_i \Delta\hat{u}(k) + F_i y_0(k) + G'_i \Delta u_0(k) \quad (3.11)$$

where:

$$G_i = \begin{bmatrix} g_{i-3} & \cdots & g_0 & 0 & 0 \\ g_{i-2} & g_{i-3} & \cdots & g_0 & 0 \\ g_{i-1} & g_{i-2} & g_{i-3} & \cdots & g_0 \end{bmatrix}$$
$$F_i = \begin{bmatrix} f_{(i-2)1} & f_{(i-2)2} & \cdots & f_{(i-2)(n_a+1)} \\ f_{(i-1)1} & f_{(i-1)2} & \cdots & f_{(i-1)(n_a+1)} \\ f_{i1} & f_{i2} & \cdots & f_{i(n_a+1)} \end{bmatrix}$$
$$G'_i = \begin{bmatrix} g'_{(i-2)1} & g'_{(i-2)2} & \cdots & g'_{(i-2)n_b} \\ g'_{(i-1)1} & g'_{(i-1)2} & \cdots & g'_{(i-1)n_b} \\ g'_{i1} & g'_{i2} & \cdots & g'_{in_b} \end{bmatrix}$$

$$\Delta\hat{u}(k) = [\Delta u(k) \quad \Delta u(k+1) \ \ldots \ \Delta u(k+N_u-1)]^T$$
$$\Delta u_0(k) = [\Delta u(k-1) \quad \Delta u(k-2) \ \ldots \ \Delta u(k-n_b)]^T$$
$$y_0(k) = [y(k) \quad y(k-1) \ \ldots \ y(k-n_a)]^T$$
$$Y(k+i) = [y(k+i-2) \quad y(k+i-1) \quad y(k+i)]^T$$

substituting Eq. (3.11) in Eq. (3.8):

$$\Delta u(k) = -K\sum_{i=0}^{M} Y(k+i)$$
$$= -K\{\sum_{i=0}^{M} G_i \Delta\hat{u}(k) + \sum_{i=0}^{M} F_i y_0(k) + \sum_{i=0}^{M} G'_i \Delta u_0(k)\} \quad (3.12)$$

Rewriting the control signal in compact form for PID type predictive control gives:

$$\Delta u(k) = -K\{\alpha\Delta\hat{u}(k) + F_f y_0(k) + G_g \Delta u_0(k)\} \quad (3.13)$$

where:

$$\alpha = \sum_{i=0}^{M} G_i \qquad F_f = \sum_{i=0}^{M} F_i \qquad G_g = \sum_{i=0}^{M} G'_i \quad (3.14)$$

For system with time delay, d, the output of the process will not be affected by $\Delta u(k)$ until the time instant (k+d +d), the previous outputs will be a part of the free response and there is no point in considering them as part of the objective function. In this case the first PID predicts d step ahead and last PID predicts (d+M) step ahead Fig 1. The control signal can be written as:

$$\Delta u(k-d) = -K\{\alpha \Delta \hat{u}(k-d) + F_f y_0(k) + G_g \Delta u_0(k)\} \tag{3.15}$$

Shifting the control signal for d step ahead gives:

$$\Delta u(k) = -K\{\alpha_d \Delta \hat{u}(k) + F_{fd} y_0(k) + G_{gd} \Delta u_0(k)\} \tag{3.16}$$

where coefficient matrices are:

$$\alpha_d = \sum_{i=0}^{d+M} G_i \qquad F_{fd} = \sum_{i=0}^{d+M} F_i \qquad G_{gd} = \sum_{i=0}^{d+M} G_i'$$

3.3 Optimal values of Predictive gains

To obtain the optimal values of the gains, the Generalised Predictive Control(GPC) algorithm is used. For process control, default settings of output cost horizon $\{N_1 : N_2\} = \{1 : N\}$, and the control cost horizon $N_u = 1$ can be used in GPC to give reasonable performance. GPC consists of applying a control sequence that minimizes the following cost function:

$$J(1,N) = \sum_{i=1}^{N} [y(k+d+i) - w(k+d+i)]^2 + \lambda \Delta u(k) \tag{3.17}$$

The minimum of J (assuming there are no constraints on the control signals) is found as follow[]:

$$\Delta u(k) = \left(G^T G + \lambda I\right)^{-1} G^T \left[w - F y_0(k) + G' \Delta u_0(k)\right] \tag{3.18}$$

which can summarized (assuming the future set point w(t+i) = 0):

$$\Delta u(k) = -K_{GPC}[-F \quad G]\begin{bmatrix} y_0(k) \\ \Delta u_0(k) \end{bmatrix} = -K_0 \begin{bmatrix} y_0(k) \\ \Delta u_0(k) \end{bmatrix} \tag{3.19}$$

where:

$$K_0 = -K_{GPC}[-F \quad G] \qquad K_{GPC} = \left(G^T G + \lambda I\right)^{-1} G^T$$
$$y_0(k) = [y(k) \quad y(k-1) \quad \ldots \quad y(k-n_a)]^T$$
$$\Delta u_0(k) = [\Delta u(k-1) \quad \Delta u(k-2) \quad \ldots \quad \Delta u(k-n_b)]^T$$

To compute the optimal values of predictive control PID gains with $N_u = 1$ $[\hat{u}(k) = u(k)]$, the PID control signals should be made the same as GPC controller. This means using Eq. (13) and Eq. (19) and solving the following optimal problem:

$$Min_{K \in K_{PID}^s, M} J(K.K_0)$$

where:

$$J(K.K_0) = \left\| -(1+K\alpha)^{-1} K [F_f \quad G_g] Z(K) + K_0 Z(K_0) \right\|_2$$

$K_{PID}^s =$ Set of stability gain for PID

$Z = (y_0(k) \; \Delta u_0(k))^T$ is depend on the controls gains used. Write $Z(k) = Z(k_0) + \Delta Z$. Inserting N_u=1 in Eq. (13), then the optimization problem will be:

$$\begin{aligned} J(K.K_0) &= \left\| -(1+K\alpha)^{-1} K [F_f \quad G_g](Z(K_0+\Delta Z)) + K_0 Z(K_0) \right\|_2 \\ &\le \left\| \left(-(1+K\alpha)^{-1} K [F_f \quad G_g] - K_0\right) Z(K_0) \right\|_2 \\ &\quad + \left\| -(1+K\alpha)^{-1} K [F_f \quad G_g] \Delta Z \right\|_2 \\ &\le \left\| \left(-(1+K\alpha)^{-1} K [F_f \quad G_g] - K_0\right) \right\|_2 \left\| Z(K_0) \right\|_2 \\ &\quad + \left\| -(1+K\alpha)^{-1} K [F_f \quad G_g] \right\|_2 \left\| \Delta Z \right\|_2 \end{aligned}$$

Thus:

① A minimum norm solution is sought from:

$$\left\| -(1+K\alpha)^{-1} K [F_f \quad G_g] - K_0 \right\|_2$$

this is found as

$$-(1+K\alpha)^{-1} K [F_f \quad G_g] = K_0$$

② It is assumed that it is possible to find suitable gain K close to K_0 so that $\|\Delta Z\|_2$ is suitable small.

The solution for K can be found in terms of K_0 as:

$$K_0 = -(1+K\alpha)^{-1} K [F_f \quad G_g] \rightarrow K_0 = -(1+K\alpha)^{-1} K S_0 \tag{3.20}$$

$$K_0(1+K\alpha) = K S_0 \rightarrow K(S_0 - \alpha K_0) = K_0 \tag{3.21}$$

where:

$$S_0 = [F_f \quad G_g]$$

A unique solution to Eq. (3.20) always exist and takes the form:

$$K = K_0 (S_0 - \alpha K_0)^T \left[(S_0 - \alpha K_0)(S_0 - \alpha K_0)^T\right]^{-1} \tag{3.22}$$

For second order system one level of PID (M=0) is enough to achieve the GPC performance. For higher order systems, M will be selected to find the best approximation to GPC solution.

3.4 Set Point Rebuilt

In GPC algorithm the information about N horizon of set point are used to calculate the control sequence. In the proposed method the new set point is generated to save the information about the future set point. The new set point, r(k), is calculated form future set point, w(k), as:

$$r(1) = \sum_{i=1}^{N} \frac{w(i)}{N}$$
$$r(i) = r(i-1) + w(i+N-1) - w(i-1) \qquad i = 2 \ldots\ldots n \tag{3.23}$$

The rebuilt set point is average of set point in N next steps. The Proposed method uses these generated set points to achieve the GPC performance. Another alternative to rebuild new set point is:

$$r(k) = K_{GPC} W(k) \qquad k = 1, \ldots\ldots, n \tag{3.24}$$

where:

$$W(k) = [w(k) \quad w(k+1) \quad \ldots \quad w(k+N)]$$

K_{GPC} is the GPC gains calculated from Eq. (3.19) and w(k) is future set point of system.

4. EXPERIMENT AND ANALYSIS

4.1 Simulation

Predictive controller is composed as Fig. 4.1.

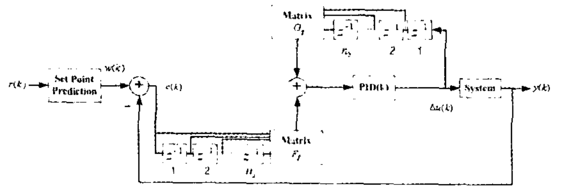

Fig.4. 1 The Structure of Predictive PID Controller

Simulation in this paper takes noticed of output variation following Prediction Horizon M. First, transfer function in Eq. (4.1) is selected in order to compare with composed predictive controller performance.

$$G(z)=\frac{0.033z^{-4}-0.0328z^{-3}-0.0348z^{-2}+0.0346z^{-1}}{0.0330z^{-4}-0.9559z^{-3}+2.8115z^{-2}-2.8885z^{-1}+1} \quad (4.1)$$

In Fig.4.2, Outputs of Predictive PID controller According to M obtain variable. As M is increased, overshoot is decreased. But time delay due to much computation amount is increase. So it need to select the optimal value of M.

Initial PID parameters in this system is tuned by using Zeigler Nichols method.

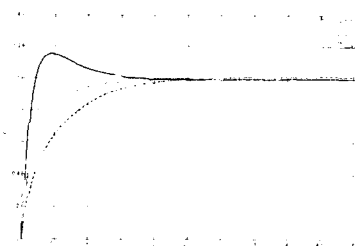

Fig.4.2 Simulation results

Table 4.1 Predictive PID Gain

M	Gain
PID(0)	[0.88 0.18 1.13]
3	[1.14 0.22 0.52]
5	[1.35 0.29 0.37]
7	[1.42 0.33 0.31]
9	[1.50 0.39 0.29]

4.2 Experiment results

In this paper, experiments equipments are composed as Fig. 4.3.

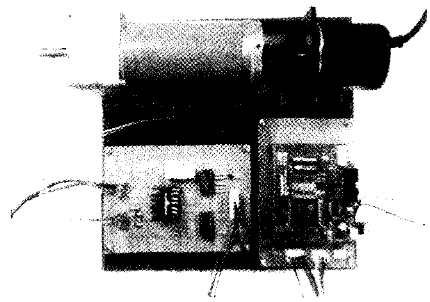

Fig.4.3 Hardware Construction of Controller System Configuration [Cpu: TMS320LF2407, Motor driver : L6203 Encoder: 1000pulse/cycle]

First, convergence values about general motor are comparison with simulation results. Fig 4.4 shows the motor response according to M value increases.

As M value is increased, oscillation is decreased and stable convergence value is obtained. However, time delay due to predict time addition is occurred

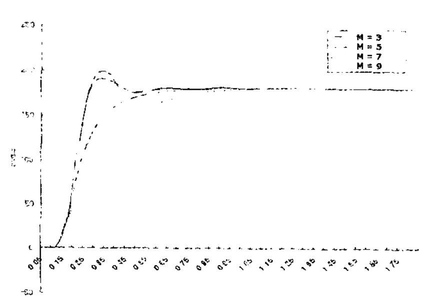

Fig.4.4 Step response in proportion of M value

Fig. 4.5 shows impulse response according to M value variance. The results are obtained similarly.

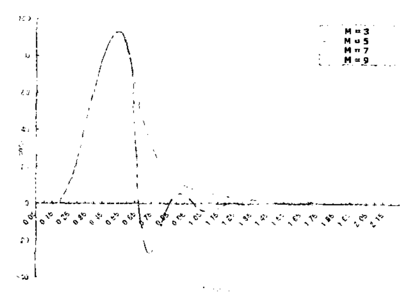

Fig.4.5 Impulse response in proportion of M value

As considering results in proportion to M values in Fig 4.4 and Fig. 4.5, M value which controller performs the best efficiency is 5. But, predict time may differ with motor's characteristic.

4.3 Performance comparison with predictive PID controller and Fuzzy controller

For comparing predictive PID controller with Fuzzy controller, Fuzzy controller is composed as follow. Table 4.2 shows whole fuzzy set about error **e** and a mount of error variation **ce** which are used the motor control.[18]

Table 4.2 Fuzzy control rules

e \ ce	NB	NM	ZO	PM	PB
NB	NG	NB	NM	NS	ZO
NM	NB	NM	NS	ZO	PS
ZO	NM	NS	ZO	PS	PM
PM	NS	ZO	PS	PM	PB
PB	ZO	PS	PM	PB	PG

NG: Negative Great　NB: Negative Big
NM: Negative Medium　NS: Negative Small
ZO: Apporoximately Zero　PS: Positive Small
PM: Positive Medium　PB: Positive Big
PG: Positive Great

In this experiments, Predict time M is 5. Fig 4.6 shows step responses with three controllers (PID controller, fuzzy controller and predictive PID controller.) and impulse responses in Fig 4.7.

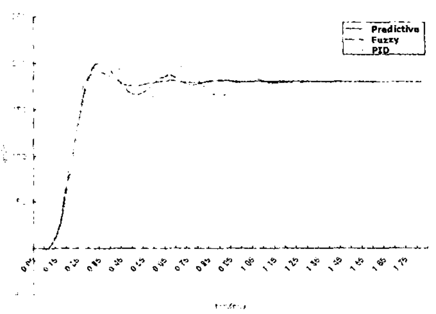

Fig.4.6 Step response in comparison with other controllers

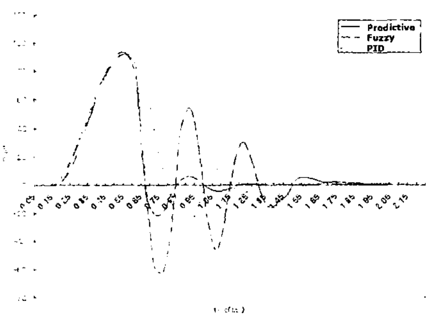

Fig.4.7 Impulse response in comparison with other controllers

As Fig.4.6, Fig.4.7 shows, general PID controller has overshoot and robustness about disturbance problems though it has fast initial response time. And fuzzy controller has robustness about disturbance comparison with general PID controller. However, initial response time is delayed.

Predictive PID controller has better performance than fuzzy and general PID controller.

5. CONCLUSION

We suggested the method which improve generally well known PID controller using predictive PID controller. General form of PID controller has defects in comparison with predictive PID controller.

First, about diversity of process step response, PID controller controls for the first order delay function and others control by feedback. So it makes oscillation inevitably. Second, u(k), fundamental to compute control, refer to declination obtained through computation. So, compensation of feedback control may produce oscillation and its damping is eigenvalue of PID. Improving these defects, we design the predictive PID controller and bring to conclusion as following through experiment result and consideration. Predictive PID controller's performance differs with the number of prediction time. The controller proposed in this paper, we find that controller is best performance when M is 5, and controller' performance become deteriorated when M is bigger than 7. We obtained same result both simulations and experiments. However, it may occur different results in different hardware feature. Additionally, for measuring controller performance, we compared with fuzzy controller and confirmed that predictive PID controller is better when M is 5.

In future, it needs to study a decrease amount of calculation which is origin complexity of prediction process and derive optimal M value from application in several systems.

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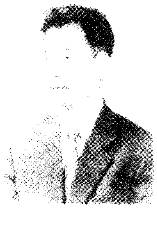

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