Use of an Adaptive Window in PID-plus Bang-Bang Control: A Motor Control Experiment

S. H. Jung, K.-H. Cho, S.-H. Lee, T. G. Kim, and J.-T. Lim

Abstract

PID-type controllers have been widely used in many industrial applications. Regulation properties of those can be improved through the addition of the Bang-Bang action. In spite of the potentials of this PID-plus Bang-Bang controller, their regulation properties are still limited if a fixed window limit is used in selection of a control action between PID and Bang-Bang action. Thus, this paper proposes an approach to improving regulation properties. Our approach changes window limits adaptable to plant dynamics by use of a Gradient Based Prediction Model. We experimented our control scheme with a DC servo-motor system. It has been shown through the experiment that our control scheme outperformed than existing one in terms of overshoot, rise time, and settling time.

I. Introduction

Although there exist so many modern control algorithms, PID-type controllers are most commonly used in most practical application areas. It may be regarded as an experimental evidence for their usefulness that the large number of PID controllers are used routinely for process control applications. To improve the regulation properties of those PID-type controllers, several methods have been proposed. Especially, a PI-plus Bang-Bang(BB) action [1] has been proposed to overcome the difficulties due to the integral wind-up of a controller with the PI-action.

In [1], the controller employs the PI-action if an error between a reference signal and a controlled output signal is smaller than a prescribed window limit. Otherwise, the controller produces a maximum allowable control signal. The proposed method solved the problems arising from the integral wind-up. Since the method employed a window with fixed limits, regulation properties are limited as the plant dynamics changes.

Nowadays various self-tuning expert PID-type controllers are developed by using intelligent control methodologies [2]-[4]. A method employing an adaptive window has been proposed to overcome the limited regulation properties due to fixed values of a window limit [5,6]. In [5,6], an adaptive window limit is realized with a Neural Network predictive model. However, it has some limitations in real-time control arising from heavily computation time for the predictive model. To overcome such limitations, this paper proposes a faster prediction algorithm, based on the Gradient Based Prediction Model(GBPM), than the complicated Neural Network predictive model. The usefulness of this method is small computation time, thus being possible in real-time control.

Improvement of some regulation properties for the proposed algorithm is validated through position control experiments for a DC servo-motor system.

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II. PD-Plus Bang-Bang Control

To concentrate on regulation properties, i.e., transient error dynamics, only a PD-action is considered in PID-type controllers.

A PD-plus BB control algorithm is illustrated in Fig. 1.

As shown in the figure, the next control action is determined based on the magnitude of the present error. That is, the controller employs the PD-action if the magnitude of an error between a reference signal(y_r) and a controlled

output signal($y(t)$) is smaller than the prescribed window limit (W_l). Otherwise, the controller produces the maximum allowable
control signal($\pm u_m$). It can be summarized as follows.

Existing PD−plus BB control scheme ;

$$u(t+T_s)=\begin{cases} PD-action & : \text{if } |e(t)| < W_l \\ \pm u_m & : \text{if } |e(t)| \geq W_l \end{cases}$$

where $e(t)=y_r-y(t)$ and T_s is a sampling time.

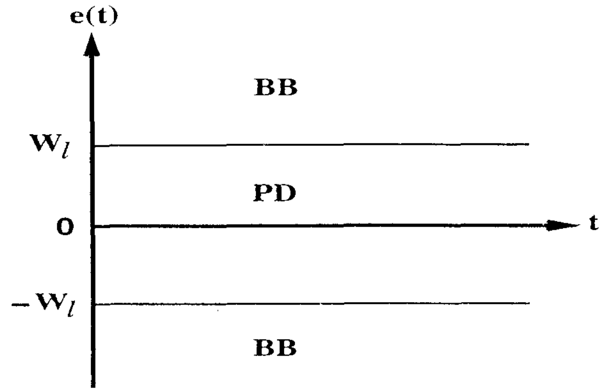


Fig. 1. PD-plus BB control (e(t) : error, W_l : window limit).

III. Adaptable PD-plus BB Control

To see the need for an adaptive window, consider a step response of a SISO (Single-Input Single-Output) system as shown in Fig. 2. The window limits considering a set point (y_r) can be rewritten as follows.

$$\begin{aligned} W_l^{upper} &= y_r + W_l \\ W_l^{lower} &= y_r - W_l \end{aligned}$$

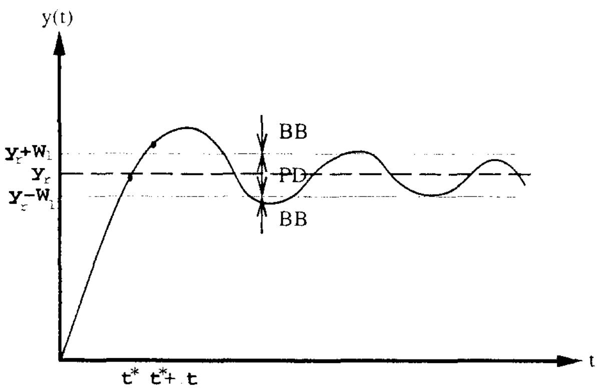


Fig. 2. Typical step response in SISO system.

As the output reaches near the set point, y_r at t^*in Fig. 2, the next control action, a PD-action, will be taken based only on the present error. Deciding the action by such a way causes a large overshoot as shown in Fig. 2. However, if an output at the near future, say at $t^*+\Delta t$, is predictable, a BB action will be taken at the next control step. Surely the action results in a smaller overshoot than the former case. This is because the BB control action near the set point will suppress the output much faster.

Thus, if a PD-plus BB controller uses a predictive error, instead of a present error, in determining the next control action, some classical figures of merit related to regulation properties, such as overshoot, rise time, and settling time can be much more improved. Note that the use of predictive errors is identical to the use of variable window limits in which the window limits are changed based on the plant dynamics.

The control scheme can be summarized as follows.

Proposed *Adaptable PD−plus BB control scheme* ;

$$u(t+T_s)=\begin{cases} PD-action & : \text{if } |e_p(t)| < W_l \\ \pm u_m & : \text{if } |e_p(t)| \geq W_l \end{cases}$$

where $e_p(t)=y_r-y_p(t+\Delta t)$.

The overall proposed control structure is shown in Fig. 3.

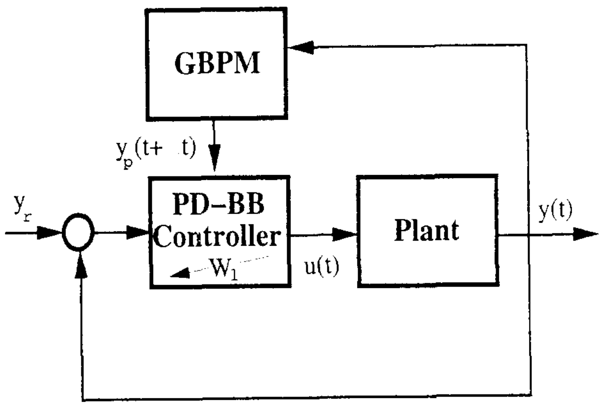


Fig. 3. The overall structure of the GBPM based PD-plus BB control system.

IV. Gradient Based Prediction Model

A predictive output($y_p(t+\Delta t)$) can be obtained by the GBPM as:

$$\begin{aligned} y_p(t+\Delta t) &= y(t)+\Delta y(t) \\ \Delta y(t) &= y(t)\frac{y(t)-y(t-T_s)}{T_s}\Delta t \\ \Delta t &= T_s k_{pr} \end{aligned}$$

where T_s is sampling time and k_{pr} ranged 0 to infinite is prediction gain. In the equation, Δt composed of T_s and k_{pr} is a time constant used to predict the plant output. If the k_{pr} is zero, then the Δt becomes zero and the $y_p(t+\Delta t)$ is always the same as $y(t)$. In the case, the operations of the proposed scheme are the same as those of original PD-Plus BB control scheme. Similarly, if the k_{pr} is infinite, then the Δt becomes ∞ and the $y_p(t+\Delta t)$ is always $\pm\infty$. In the case, the proposed scheme will act as the BB control scheme. k_{pr} should be selected carefully because this factor affects the performance of this scheme.

The optimal value of the prediction gain k_{pr} is determined by the dynamics of a given plant.

If a controlled plant have very large inertia, then the k_{pr} should have a large value. Otherwise, the k_{pr} can be a small value.

This is because if the k_{pr} is a large value, then the proposed scheme will act BB action faster than the case that k_{pr} is a small value. This operation makes it possible to reduce the large overshoot of a large inertia plant. Further research to find the optimum value of K_{pr} is needed.

To obtain the predictive plant output, we first must know the change of plant output during Δt. The change of plant output during Δt is simply given as $\frac{y(t)-y(t-T_s)}{T_s}\Delta t$. This equation can not be applied to highly nonlinear plants. If a plant is highly nonlinear, then another scheme [6]---which is very similar to this scheme except for using neural networks for predicting the plant output---can be used. We multiply $y(t)$ to the change of plant output because if the $y(t)$ reaches near at $\pm u_m$, then the BB action should be fast applied to the plant for reducing the overshoot.

The use of predictive errors causes the variation of window limit.

The adaptive window limits are given by

$$\begin{aligned} W_l^{upper}(t) &= W_l^{upper} - \Delta y(t) = y_r + W_l - \Delta y(t) \\ W_l^{lower}(t) &= W_l^{lower} - \Delta y(t) = y_r - W_l - \Delta y(t) \end{aligned}$$

where $W_l^{upper}(t)$ is the upper limit and $W_l^{lower}(t)$ is the lower limit for the adaptive window.

The step response of the Adaptable PD-plus BB is illustrated in Fig. 4. As the outputs reach near the set point at $\hat{t}$, $\Delta y(t)$ of the predictive output($y_p(t+\Delta t)$) will markedly increase. Thus both $W_l^{upper}(t)$ and $W_l^{lower}(t)$ are shifted down below the set point, while maintaining the difference between $W_l^{upper}(t)$ and $W_l^{lower}(t)$ at a constant $2W_l$. Due to the adaptive window, the BB action will be taken at the next control step. Although the adaptive window can be realized with a Neural Network predictive model, the GBPM is an alternative.

Advantages of the GBPM include capability of real-time control, simplicity, and improved regulation properties. However, this scheme may not be applied to non-minimum phase system. We should research for such plants.

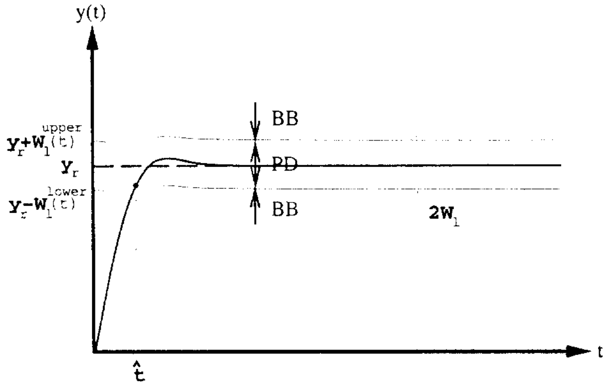


Fig. 4. Step response with adaptive window limit value.

V. Experimental Result

The GBPM based PD-plus BB control scheme is realized in the position control of a DC servo-motor system. The transfer function of the DC servo-motor system is as follows.

$$G(s) = \frac{\Theta(s)}{V_a(s)} = \frac{K_m}{s[(R_a+L_a s)(J_m s+B_m)+K_b K_m]}$$

where $v_a(t) = L^{-1}\{V_a(s)\}$ is the applied motor input voltage and $\theta(t) = L^{-1}\{\Theta(s)\}$is the angle of motor shaft.

Table 1. DC servo-motor spec.

R_a	4.85Ω
L_a	$20mH$
K_b	$0.31 Vsec$
t_m	$8.4msec$
K_m	$0.5kgf \cdot cm/A$
J_m	$0.00065kgf \cdot cm \cdot \mathrm{sec}^2$
B_m	$0\ kgf \cdot cm \cdot \mathrm{sec}$

By replacing the parameters with the values in table I and letting $Y(s) = \Theta(s)$, $U(s) = V_a(s)$ it can be rewritten as follows.

$$G(s) = \frac{Y(s)}{U(s)} = \frac{0.5}{s(13\times10^{-6}s^2+3.15\times10^{-3}s+0.155)}$$

The overall block diagram for position control of a DC servo-motor system is presented in Fig. 5.

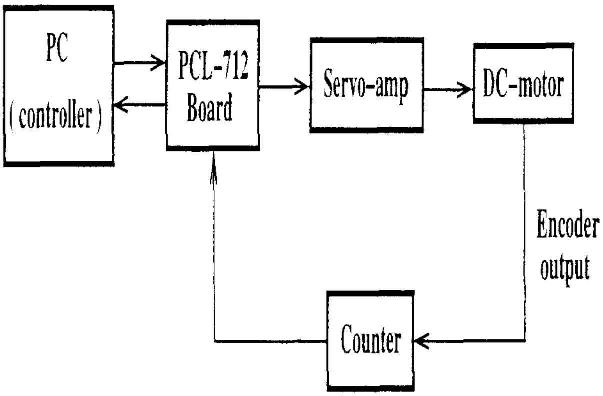


Fig. 5. Experiment setup for a DC servo-motor position control system.

Fig. 6 compares three position trajectories controlled by a PD, a PD-plus BB, and an adaptable PD-plus BB for the same conditions.

The PD output shows small overshoot but large rise time; the PD-plus BB output shows small rise time but large overshoot. The output for the proposed adaptive PD-plus BB shows small rise time as well as small overshoot. Note that the regulation properties of the proposed method is improved by combining merits from the first two methods.

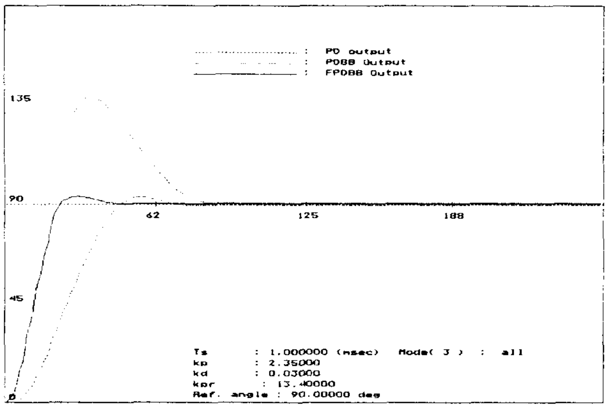
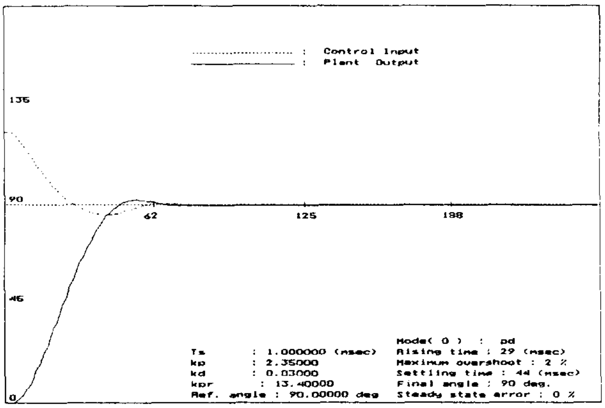


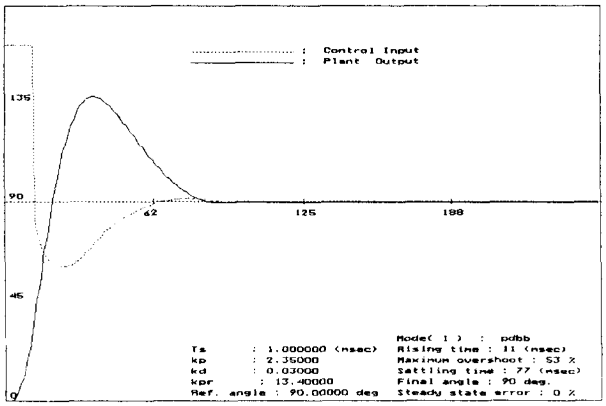
Fig. 6. Comparison of controlled outputs measured.

Fig. 7 (a), (b), and (c) show the plant outputs and control inputs of PD-action, PD-plus BB action, and adaptive PD-plus BB action. The trajectories of window limit of the Fig. 7 (b) and (c) are not shown. Fig. 7 (b) has only one BB action, thus resulting in large overshoot.

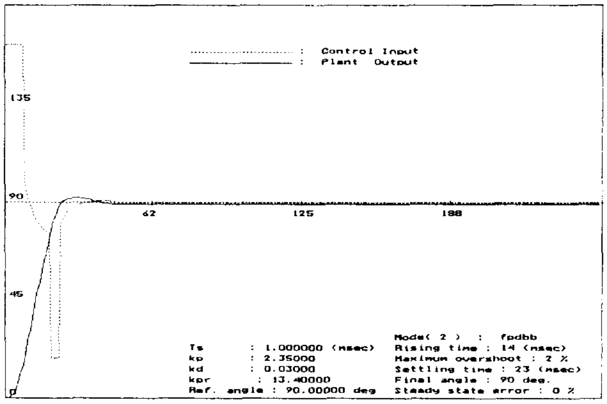
Fig. 7 (c) has two BB actions. The maximum allowable control signal of the first BB action is positive ($+u_m$) and that of the second BB action is negative($-u_m$). Thus the second BB action drags down the large overshoot.



(a)



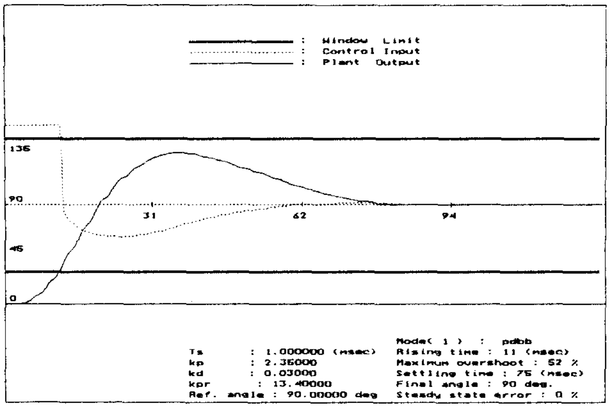
(b)



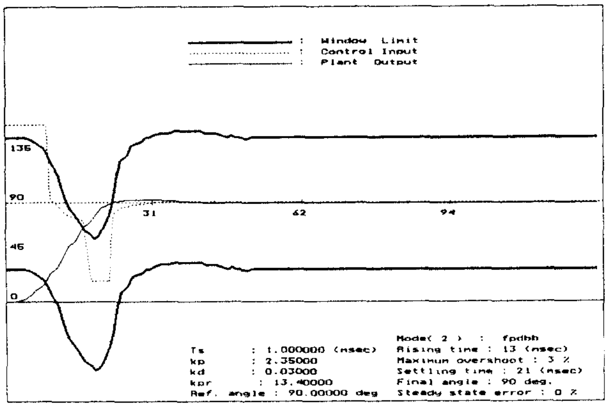
(c)

Fig. 7. Control inputs and measured outputs (a) PD-acton (b) PD-plus BB action (c) Adaptable PD-plus BB acton.

Fig. 8 (a) shows a fixed window limit for the PD-plus BB action, and Fig. 8 (b) shows the variable window limit for the adaptive PD-plus BB action.



(a)



(b)

Fig. 8. Measured output for PD-plus BB action (a) Fixed window limit (b) Adaptive window limit.

Note that the PD-action is employed only when an error between the reference angle and the present plant output angle is smaller than the fixed window limit. If the error exceeds the window limit, then the controller will generate the maximum allowable control input.

From the results, the PD-plus BB control based on the GBPM changes the window limit so that the regulation properties can be improved.

Fig. 8 compares the use of a fixed window with the use of a adaptive window in PD-plus BB control. Note that PD-plus BB control with the adaptive window shows the smaller rise time, the less overshoot, and the shorter settling time. This result is summarized in Table II (the measured values are slightly changed according to each experiment).

Table 2. Experimental Result of Three Methods.

	PD	PD-plus BB	Adaptable PD-plus BB
Rising time	29 msec	11 msec	13 msec
Maximum overshoot	2 %	52 %	3 %
Settling time	44 msec	75 msec	21 msec

The value of k_{pr} is determined experimentally by means of the trial and error method. At the optimal value of k_{pr}, the overshoot will be almost zero. Thus the use of the GBPM improves regulation properties in spite of the trade-off relationship between rise time and overshoot. That is, overshoot and setting time can be greatly reduced with small increase of rise time.

VI. Concluding Remarks

Regulation properties of a PD-plus BB control with a fixed window have been improved by employing an adaptive window based on GBPM method. GBPM has been employed to predict such a window limit. Improvement of regulation properties is validated through an experiment of DC servo-motor position control. The proposed GBPM algorithm has advantages over a Neural Network predictive model in computation time without much sacrificing accuracy. The method proposed in this paper can generally be applicable to a wide variety of servo controls, especially to the case where the rise time requirement is conflicted with the overshoot requirement.

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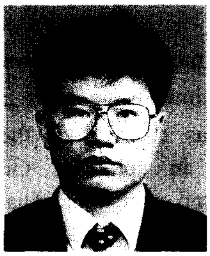

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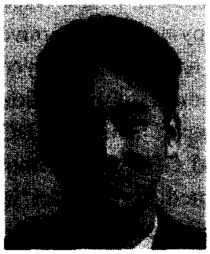

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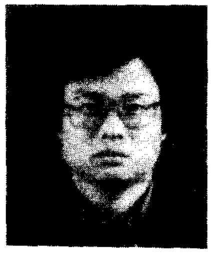

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