A New PID Controller with Lyapunov Stability for Regulation Servo Systems

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Abstract

In this paper, the stability of second order uncertain systems with regulation of PID type controllers is analyzed by using Lyapunov second method for the first time in the time domain. The property of the stability of PIDregulation servo systems is revealed in sense of Lyapunov, i.e., bounded stability due to the disturbances and uncertainties. By means of the results of this stability analysis, the maximum norm bound of the error from the output without variation of the uncertainties and disturbances is determined as a function of the gains of the PID control,which make it enable to analyze the effect resulted from the variations of the disturbances and uncertainties using this norm bound for given PID gains. Using the relationship of the error from the output without variation of the uncertainties and disturbances and the PID gain with maximum bounds of the disturbances and uncertainties, the robust gain design rule is suggested so that the error from the output without the variation of the disturbances and uncertainties can be guaranteed by the prescribed specifications as the advantages of this study. The usefulness of the proposed algorithm is verified through an illustrative example.

Keyword: PID control, regulation control, Lyapunov stability, robust control

I. Introduction

The PID control shown in Fig.1 is the very old, well known, useful, and most popular standard form control algorithm to engineers in almost industrial fields such as power electronics, robotics, aircraft engineering, boilers, instrument equipment, automatic machines, processes among the existing developed control algorithms so far because of fast response, most simple structure, feedback type, zero steady state error, capability of coping with actuator saturation and time delay, stable and excellent performance for slow dynamic plants, good robustness after elaborate tuning, practical proof, and trust from field engineers[1]. The reason of the difficulty of tuning the PID control is the different output from the theoretically expected output designed in the time or frequency domains due to the modeling errors and zeros in closed loop transfer functions and the function of the reference value for closed loop regulation servo systems. Since Ziegler and Nichols proposed the design methods of the PID gains, based on the open loop step response in time domain and relay feedback frequency response in frequency domain in 1942[2], the many design methods has been suggested[1,3,4-17], for example, model based pole

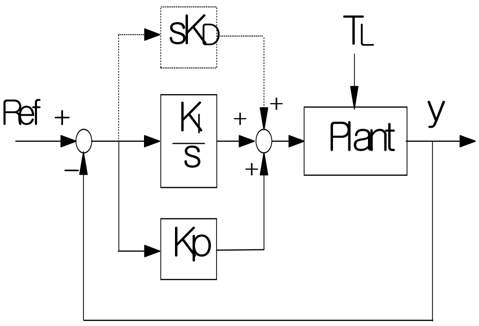

Fig. 1 standard PID controller

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assignment[4-7],optimal method[6], Bang-Bang+PI[8], method for Integral wind-up[9,10], phase and gain margin satisfying PI[11,12], and auto-tuning automation [13,14,18,17] etc. The most studies on the design of PID controller until now are concentrated on the selection or tuning of the suitable and stable PID gains based on the model or test output response in the time or frequency domain in order to satisfy the field requirements. However, the study about the time domain stability analysis on the transient behavior due to disturbance and parameter variations and the robust gain selection is rarely reported except only the fact that the steady state error is zero because of the integral action.

In this paper, the stability of 2ndorder servo regulation systems such as a position control of dynamic plants investigated using the Lyapunov second method for the first time in time domain. The stability feature of the PID regulation servo systems is identified in the sense of Lyapunov under uncertainties and disturbance. The bound of the stable region of PID controllers is obtained with respect to the uncertainty, disturbance and PID gains. And the robust design rules to guarantee the specifications on the error from the nominal output is suggested as the advantages of this study. A MATLAB simulation of a position regulation servo control of a brushless direct drive motor by the PID algorithm with the suggested gains is given to show the usefulness of the proposed design rules which are not unique but useful.

II. Stability Analysis Using Lyapunov Second Method

2.1 Plant and PID control

A. Plant Description

In the position control of dynamic plants such as motors, plants can be modeled as a second order system

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = -a_1(t)X_1 - a_2(t)X_2 + b(t)U - F(t) \quad (1)$$

where X_1 is the position state variable of the control object as an output, X_2 is the speed state variable, U is the PID control input to be designed, $F(t)$ is the disturbance including the load variations, and $a_1(t)$, $a_2(t)$, and $b(t)$ are the uncertain system parameters expressed as

$$a_1(t) = a_1^0 + \Delta a_1(t)$$
$$a_2(t) = a_2^0 + \Delta a_2(t)$$
$$b(t) = b^0 - \Delta b(t) \quad (2)$$

where a_1^0, a_2^0, and b^0 are the nominal parameters obtained from the modeling process. The modeling errors, $\Delta a_1(t)$, $\Delta a_2(t)$, $\Delta b(t)$, and $F(t)$ are assumed to be bounded by the known bounds determined in the modeling process and are defined as

$$\Delta a_{1M} = \max\{|\Delta a_1(t)|\}$$
$$\Delta a_{2M} = \max\{|\Delta a_2(t)|\}$$
$$\Delta b_M = \max\{|\Delta bt)|\}$$
$$F_M = \max\{|F(t)|\} \quad (3)$$

and without any loss of generality, $b(t)$ is assumed to be positive and its minimum and maximum bounds are represented as

$$0 < b_m < b(t) < b_M \quad (4)$$

where

$$b_m = \min\{b(t)\}, \qquad b_M = \max\{b(t)\} \quad (5)$$

B. PID control

For regulating the o utput of the plants (1) to the reference X_R, the typical standard type of the PID control becomes

$$U = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \dot{e}(t) \quad (6)$$

where the error $e(t)$ and its derivative $\dot{e}(t)$ are defined respectively as

$$e(t) = X_R - X_1$$
$$\dot{e}(t) = -\dot{X}_1 = -X_2 \quad (7)$$

and X_R means the constant desired reference value for the position output. If the PID control is working with the stable gains, the steady state value of the integral in the PID control can be obtained as

$$I_S = \int_0^{t_s} X_R - X_1 d\tau = \frac{a_1(t_s)X_R + F(t_s)}{b(t_s)K_I} \tag{8}$$

where t_s implies the tine in steady state. This value will be used in next stability analysis. By PID control, the closed loop servo regulation system becomes

$$\dot{X}_1 = X_2$$
$$\dot{X}_2 = -(a_2^0 + b^0 K_D)X_2 - (a_1^0 + b^0 K_p)X_1 - b^0 K_I \int_0^t X_1 d\tau + b^0 K_P X_R + b^0 K_I X_R t - D(t) \tag{9}$$

where $D(t)$ is the lumped disturbance as

$$D(t) = \Delta a_1 X_1 + \Delta a_2 X_2 + F(t) + \Delta b U \tag{10}$$

The output in form of the transfer function with the reference and lumped disturbance can be obtained as

$$X_1(s) = \frac{b^0(K_P s + K_I)}{\Lambda(s)} X_R(s) - \frac{1}{\Lambda(s)} D(s) \tag{11}$$

where $X_R(s)$ and $D(s)$ are each Laplace transform

$$X_R(s) = \frac{X_R}{s} \tag{12}$$

and $\Lambda(s)$ is the characteristic equation as

$$\Lambda(s) = s^3 + (a_2^0 + b^0 K_D)s^2 + (a_1^0 + b^0 K_p)s + b^0 K_I \tag{13}$$

As can be seen, the closed loop system becomes 3rd order with one zero at $s_z = -K_P/K_I$. Generally, the PID regulation servo system is designed by using the transfer function (11) with possibly large zero or pre-filter for canceling the zero and desired three roots of (13) with the three degree of freedom, K_P, K_I, and K_D. However, since the lumped disturbances clearly influence on the output of the servo system from (11) which results in the difficulty of the controller design, many engineers notice the robustness problems to guarantee the designed performance for all the lumped disturbances. In this paper, this robustness problems can be easily solved by means of the analysis about the stability of the PID regulation control servo system with Lyapunov second method in time domain for deriving the robust gain design rule.

2.2 Analysis of Lyapunov Stability and Robust Gain Design Rule

A. Analysis of Lyapunov Stability

To analyze the stability of the PID regulation servo system, first of all, a Lyapunov candidate function is taken as in this paper

$$V = \frac{1}{2} X^T \cdot X, \qquad X^T = [e_0 \quad e \quad \dot{e}] \tag{14}$$

where e_0 is defined as an error of the integral to the steady state valueof the integral, i..e.:

$$e_0 = I_s - \int_0^t e(\tau) d\tau \tag{15}$$

Defferentiating (14) with respect to time and rearanging it with (1), (6), and (7) leads

$$\begin{aligned} \dot{V} &= e_0 \cdot \dot{e}_0 + e \cdot \dot{e} + \dot{e} \cdot \ddot{e} \\ &= -e_0 \cdot e + e \cdot \dot{e} + \dot{e} \cdot \left[-a_1^0 e - a_2^0 \dot{e} - b^0 U \right] + (a_1^0 X_R + D)\dot{e} \\ &= -e_0 e - (a_1^0 - 1 + b^0 K_P) e\dot{e} - a_2^0 \dot{e}^2 \\ &\quad -- b^0 \dot{e} (K_P e + K_I \int_0^t e d\tau + K_D \dot{e}) + (a_1^0 X_R + D)\dot{e} \\ &= -e_0 e - (a_1^0 - 1 + b^0 K_P) e\dot{e} - (a_2^0 + b^0 K_D)\dot{e}^2 \\ &\quad + b^0 K_I e_0 \dot{e} - b^0 K_I I_s \dot{e} + (a_1^0 X_R + D)\dot{e} \\ &= -X^T Q_i X + D', \qquad i = 1,\ 2,\ \text{and}\ \ 3 \cdots \end{aligned} \tag{16}$$

where D' is defined as

$$\begin{aligned} D' &= \left\{ a_1^0 - a(t_s) \frac{b^0}{b(t_s)} \right\} X_R \dot{e} + \Delta a_1 X_1 \dot{e} + \Delta a_2 X_2 \dot{e} \\ &\quad + \left\{ F(t) - F(t_s) \frac{b^0}{b(t_s)} \right\} \dot{e} + \Delta b K_P e\dot{e} + \Delta b K_I \int_0^t e d\tau \dot{e} + \Delta b K_D \dot{e}^2 \end{aligned} \tag{17}$$

and the positive definite matrices Q_i should be non singular. unfortunately the matrices Q_i are not unique for example, Q_i, $i = 1,\ 2,$ and 3 are

$$Q_1=\begin{bmatrix} 0 & 2 & -b^0K_I/2 \\ -1 & 0 & (a_1^0-1+b^0K_P)/2 \\ -b^0K_I/2 & (a_1^0-1+b^0K_P)/2 & (a_2^0+b^0K_D) \end{bmatrix}$$

$$Q_2=\begin{bmatrix} 0 & 1/2 & -b^0K_I \\ 1/2 & 0 & (a_1^0-1+b^0K_P)/2 \\ b^0K_I & (a_1^0-1+b^0K_P)/2 & (a_2^0+b^0K_D) \end{bmatrix}$$

$$Q_1=\begin{bmatrix} 0 & 2 & -2b^0K_I \\ -1 & 0 & 2(a_1^0-1+b^0K_P) \\ b^0K_I & -(a_1^0-1+b^0K_P) & (a_2^0+b^0K_D) \end{bmatrix} \quad (18)$$

moreover, many other Q_i may exist. The choice is

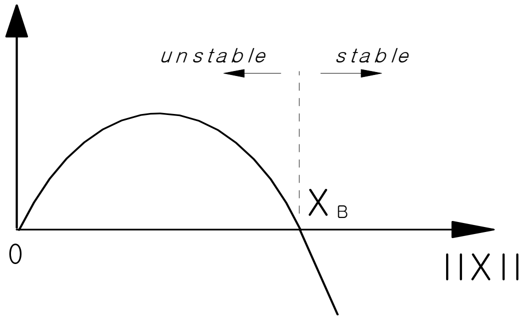


Fig. 2 Stable region in sense of Lyapunov

given to designers. Finally, the following equation can be obtained

$$\dot{V}<0 \quad \text{for} \quad \|X\|>X_B \quad (19)$$

where X_B is a stable bound for PID regulation servo system as shown in Fig. 2.

$$X_B=(\|D'\|/\|Q_i\|)^{1/2} \quad (20)$$

Therefore the PID control exhibits the bounded stability in the sense of Lyapunov for the regulation servo system with respect to the uncertainties and disturbances. The stable bound of the state means the maximum error from the nominal output due to changes of disturbances and uncetainties. Hence after estimating the stable bound using the bounds of the uncertainties and disturbances, (3) and (4), the error from the nominal output can be estimated as functions of the gains K_P, K_I, and K_D, further more, it is possible to derive the rule to determine the gains of PID control so that the maximum error form the nominal output is guaranteed by a finite desired value.

B.RobustGainDesignRule

From (3), (4), (17) and (20), the estimated stable bound becomes

$$\widehat{X_B}=(\|D'\|/\|Q_i\|)^{1/2} \quad (21)$$

$$D'=\left|\left\{a_1^0-a(t_s)\frac{b^0}{b_m}\right\}\right|\|X_R\||\dot{e}|+\Delta a_{1M}|X_1||\dot{e}|+\Delta a_{2M}|X_2||\dot{e}|$$
$$+\left|\left\{F(t)-F(t_s)\frac{b^0}{b_m}\right\}\right||\dot{e}|+\Delta b_M K_P|e\dot{e}|$$
$$+\Delta b_M K_I\left|\int_0^t e\,d\tau\right||\dot{e}|+\Delta b_M K_D\dot{e}^2 \quad (22)$$

in (22), X_R, X_1, X_2, e, $\dot{e}$, and $\int_0^t e\,d\tau$ are physically bounded in the stable regulation systems, for example max. $|e|=X_R$. Let e_a be the specification of the allowed maximum error from the nominal output. The gains of the PID control will be designed in the two steps, i.e. stable design and robust design in order to satisfy the specification on the maximum error from the nominal output in the presence of the uncertainties and disturbance i.e. $e_a>\widehat{X_B}$

B.1StableDesignRule

For the nominal system without any uncertaintiesand disturbances, the PID control must operate with stability. The gains of PID control should be designed for Q_i to be positive real, that is all the eigenvalue of Q_i are positive. The characteristic euqations of Q_i become

$$|\lambda-Q_1|=\lambda^3-(a_2^0+b^0K_D)\lambda^2 \quad (23)$$
$$-\left\{(a_1^0-1+b^0k_P)^2/4+(b^0K_I)^2/4-2\right\}\lambda$$
$$+b^0K_I(a_1^0-1+b^0K_P)/4-2(a_2^0+b^0K_D)=0$$

$$|\lambda-Q_1|=\lambda^3-(a_2^0+b^0K_D)\lambda^2$$
$$-1/4\left\{(a_1^0-1+b^0k_P)^2-8(b^0K_I)^2+1\right\}\lambda$$
$$+3/4(b^0K_I)(a_1^0-1+b^0K_P)+1/4(a_2^0+b^0K_D)=0 \quad (24)$$

$$|\lambda-Q_1|=\lambda^3-(a_2^0+b^0K_D)\lambda^2 \quad (25)$$
$$+2\left\{(a_1^0-1+b^0k_P)^2+(b^0K_I)^2+1\right\}\lambda$$
$$-2(b^0K_I)(a_1^0-1+b^0K_P)-2(a_2^0+b^0K_D)=0$$

From (23), (24), and (25), the each condition for the stability canbe derived for the positive definite matrices of Q_i as

$$\therefore \begin{cases} K_D > -(a_2^0/b^0) \\ -(a_1^0-1+b^0K_P)^2 > (b^0K_I)^2 - 8 \qquad \text{for } Q_1 \\ (b^0K_I)(a_1^0-1+b^0K_P) < 8(a_2^0+b^0K_D) \end{cases} \tag{26}$$

$$\therefore \begin{cases} K_D > -(a_2^0/b^0) \\ 8(b^0K_I)^2 > (a_1^0-1+b^0K_P)^2 + 1 \qquad \text{for } Q_2 \\ 3(b^0K_I)(a_1^0-1+b^0K_P) < -(a_2^0+b^0K_D) \end{cases} \tag{27}$$

$$\therefore \begin{cases} K_D > -(a_2^0/b^0) \\ (a_1^0-1+b^0K_P)^2 > -(b^0K_I)^2 - 1 \qquad \text{for } Q_3 \\ (b^0K_I)(a_1^0-1+b^0K_P) > -(a_2^0+b^0K_D) \end{cases} \tag{28}$$

If one of equ. (26), (27), and (28) is satisfied, the niminal system under PID control can be stable. However, it is difficult to satisfy the conditions of (26) and (27), that of (28) describes the best solution for the stability. Thus, using the condition of (28), the gains of the PID control will be used in view of the stability as a minimum requirement of general control systems.

B.2RobustDesignRule

The robust design rule will be discussed through the two cases, i.e, with only disturbances and with uncertainties and disturbances.

i)Withuncertaintiesanddisturbances

The following relationship of the error specification and the estimated stable bound should be satisfied because the maximum error from the nominal output isresulted from the overshoot due to the damping condition of the gains and uncertainties and disturbance itself

$$K_P > \Big[-(a_1^0-1)e_{a+\Delta}a_{1M}(|X_R|+|X_1|) + \Delta a_{2M} + F_M + \Delta b_M K_I \Big|\int_0^t e d\tau\Big| + \Delta b_M K_D|\dot{e}|\Big] / \left[(b^0-\Delta b_M)e_a\right]$$

$$e_{a > \max\{os_\Delta(\zeta)\} + \max\{\hat{X}_B\}} \tag{29}$$

where $os_\Delta(\zeta)$ means the maximum overshoot according to the damping condition of the uncertain system with the gains, K_P and K_I due to the variations of the uncertainties and disturbances.

ii)Withonlydisturbances

$$K_P > \left\{F_M/e_a - a_1^0 + 1\right\}/b^0$$

$$e_a > os_n(\zeta) + (F_M \cdot |\dot{e}|/\|Q_i\|)^{1/2} \geqq os(\zeta) + \left(\left|\left\{F(t) - F(t_s)\frac{b^0}{b_m}\right\}\right\| \dot{e}|/\|Q_i\|\right)^{1/2} \tag{30}$$

where $os_n(\zeta)$ means the overshoot according to the damping condition of the nominal system with the gainsK_P, K_I, and K_D due to the variations of the disturbances, if critical and over damping conditions, then $os(\zeta)$. Therefore, the PID gain to satisfy the specification on the error from the output without variations of the uncertainties and disturbances can be determined using the stable design and robust design rule. There may be an iterative design in order to satisfy both design rules. Then this design method to determine the gain of the PID control can guarantee the maximum error from the output without the variation of the for all the uncertainties and disturbances. In addition to, it can be applicable to analyze the induced error due to changes of disturbance and uncertainties for the previously chosen gains.

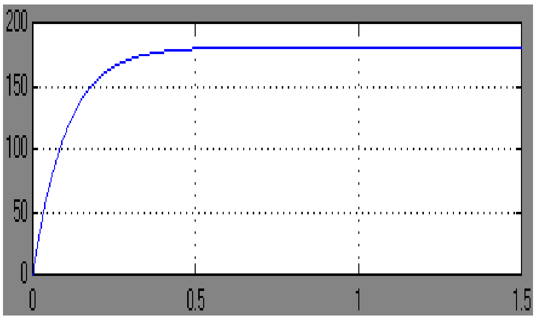
III.SimulationStudies

To show the usefulness of the suggested gain design rules, the simulation on the position control of a brushless direct drive servo motor as shown in Table 1 will be carried out under only load disturbances. Using the parameters in Table 1, a nominal model of the motor can be obtained as

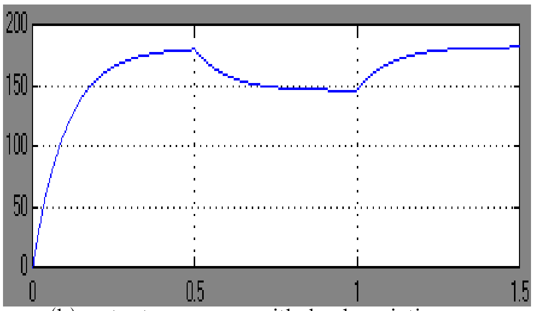
$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = -54.25 \cdot X_2 + 12446. \cdot U \tag{31}$$

A reference command is given as 180^0typically. Full load didturbance is applied from 0.5 [sec] to 1.0[sec]. Under this condition, for the two cases of the error from the nominal output, i.e, i) 20[%] of command($e_a = 36^0$) and ii) 1[%]of command



(a) nominal output response without load variations



(b) output response with load variations

Fig. 3 Simulation results for case I) 20[%] error ($e_a = 36^0$)

Table 1 Characteristics of a motor
표 1 전동기의 특성

Item	Value	Unit
Rated Power	120	[Watt]
Rated Torque	11.0	[Nm]
Rated Speed	123	[rpm]
Rated Voltage	70.0	[Volt]
Rotor Inertia	0.00156	[Kgm^2]
Current constant	3.038	[Nm/A]
Number of Pole	16	

($e_a = 1.8^0$), the PID gains are designed by the stable design rule, (28) and the robust design rule, (30) equation for matrix Q_3 as the representative and the no overshoot condition as an inherent rule

1) case 1)20[%] of command($e_a = 36^0$)

.condition .gain selection .pole./zero analysis

$$\begin{cases} K_P > 1.99 \\ K_I > 0.0 \\ K_D > 0.0044 \end{cases} \rightarrow \begin{cases} K_P = 2.00 \\ K_I = 0.1 \\ K_D = 0.2 \end{cases} \rightarrow \begin{cases} s_z = -0.5 \\ s_{p1} = -0.1 \\ s_{p2} = -9.8 \\ s_{p3} = -2533.6 \end{cases}$$

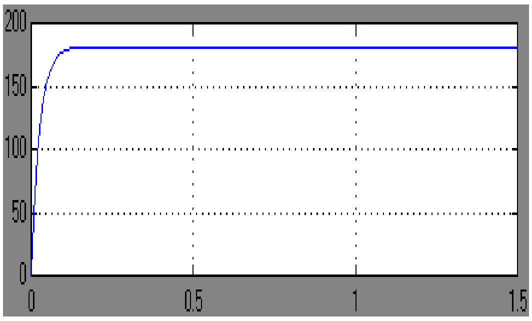
(32)

1) case ii)1[%] of command($e_a = 1.8^0$)

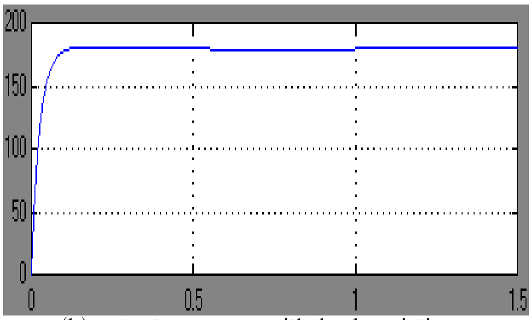
.condition .gain selection .pole./zero analysis

$$\begin{cases} K_P > 39,79 \\ K_I > 0.0 \\ K_D > 0.0044 \end{cases} \rightarrow \begin{cases} K_P = 40. \\ K_I = 10 \\ K_D = 1 \end{cases} \rightarrow \begin{cases} s_z = -0.25 \\ s_{p1} = -0.252 \\ s_{p2} = -39.7 \\ s_{p3} = -12460. \end{cases} \quad (33)$$

where s_{π}, $i = 1$, 2, and3 are the poles of the closed loop transfer function, (10), one of them is relatively



(a) nominal output response without load variations



(b) output response with load variations

Fig. 4 Simulation results for case ii) 1[%] error ($e_a = 1.8^0$)

close to the zero . As a results of the computer simulations on the position control of the motor by the designed PID, Fig. 3 and 4 show the no overshoot output responses of the two cases without the load variations in (a) and with the load variations in (b).In Fig.3, 35.1^0 (19.5%) error from the nominal output at 1[sec] and -35.04^0 (19.47[%}) error from the output without load variations after the first disturbance at 0.5[sec] at 1.5[sec] appear.

In Fig. 4, 1.73^0 (0.96[%]) error from the nominal output at 0.6[sec] and -1.7^0 (0.94[%}) error from the output without load variations after the first variation at 0.5[sec] at 1.1[sec] can be found. These results show satisfaction of the given specification on the error as designed. If the output is designed with overshoot, the overshoot due to the variations of the disturbance, $os_n(\zeta)$ that can be found with the nominal plant and maximum value of the load disturbance is considered in the design of the controller. As can be seen from now, the forcus of the this paper is concentrated on the analysis of the effect of the disturbance variations and guaranteeing the error specifications from the output without the vairations, not on the shape of the output that is . Generally, the larger gain, the smaller error due to the same disturbances. The technique in this paper can provide the accurate values of the gains how large gains should be selected.

IV. Conclusions

In this paper, the stability of second order servo systems regulated by PID type controllers is analyzed by using Lyapunov second method for the first time in the time domain. The stability property of PID regulation servo systems is discovered, that is the bounded stability in sense of Lyapunov. By means of the results of this stability analysis, the maximum bound of the error from the output without variations of the disturbances and uncertainties is determined as a function of the gains of the PID control, which can be applied to the effect analysis for the output response due to the variations of the disturbances and uncertainties. And using the relationship of the PID gain and maximum bound of the disturbances and uncertainties, the rules for selection of the PID gain are suggested so that the error from the output without the variations of the disturbances and uncertainties can be guaranteed by the prescribed bound, named by the stable and robust design rules. Although those rules are not unique and analytic, it is accurate and useful to find the gain solution how large values are sufficient to satisfy the given error specifications. The usefulness of the proposed algorithm is verified through an illustrative example withthe MATLAB simulations of a position regulation servo control of a brushless direct drive motor by the PID algorithm with the suggested gains. The techniques in the paper can give rise to the capability of analysis of the effect of variations of the disturbance to theoutput response, i.e, calculation of the error from the output without variations and possibility of gain design to satisfy the specification on the error given by users.

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