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Enhanced Proportional Integral Derivative control strategy for Magnetic Ball Levitation System

K.Poomani[1] and S.Sathiyavathi[2]

[1]Assistant Professor, BannariAmman Institute of Technology, Sathyamangalam, Tamilnadu, India.
[2]Assistant Professor, Kongu Engineering College, Perundurai, Tamilnadu, India
[1]poomanik90@gmail.com, [2]sathikec@gmail.com

Abstract

This paper emphasises on the control of a magnetic ball levitation system using an enhanced proportional integral derivative (PID) controller. Though PID controllers produce a controlled output for stable and unstable systems, the performance of the system in terms of overshoot, settling time, Integral Square Error (ISE) and Integral Absolute Error (IAE) are poor. To solve this problem, an enhanced PID controller is designed based on the system open loop transfer function. A compensator in cascade with the PID controller is designed based on bode plot response of the system. The efficacy of the proposed controller is demonstrated via simulation study of a magnetic ball levitation system. The results are compared with the classical PID controller. The proposed controller eliminates the overshoot and reduces ISE and IAE, thus provides smoother system responses.

Keywords*: PID controller, Compensator, Enhanced PID controller, Magnetic Ball Levitation System*

1. Introduction

The controller plays an important role in the improvement of production quality and accuracy, thus reduces the production costs [8]. Intelligent controllers have remarkable success in research for more than two decades. However, PID controllers have widespread acceptance for variety of processes in industries [1, 17]. More than 97% of the regulatory controllers utilize the PID algorithm [13]. The main reason for their versatility is their relatively simple structure and good cost/benefit ratio [4, 12]. The performance of the controller is much dependent on tuning of the PID parameters [15]. Though, application of tuning rule proposed by several authors for stable and unstable processes produce controlled output, the performance of the controller shows deterioration in the quality of the system performance. Separate techniques have been developed for systems which are stable, unstable and integrating in open loop to improve the performance of the closed loop systems with PID controller [9]. The main drawback of these methods is the tedious analytical design which prevents the operators from use in real time applications.

The objective of this paper is to develop a new control strategy capable of producing better performance without modifying the available industrial PID controller. This motivates to introduce an enhanced PID control strategy to achieve satisfactory performance of the system. The proposed controller is applicable for stable, unstable and integrating systems. From the comprehensive summary of the PID tuning methods [3], it is concluded that the number of tuning rules for stable process are much more as compared to unstable process. So this paper is also of an interest for an unstable system.

An example for an unstable system, to prove the effectiveness of the proposed control strategy is magnetic ball levitation system. Magnetic levitation is used in wide range of

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applications such as maglev train, magnetic bearings, wind tunnel, vibration isolation and conveyor systems, *etc*. The reason for increasing popularity is that there is no mechanical contact, friction and noise, component wear, vibration, maintenance cost, *etc*. in which high precision positioning is achieved [18]. The feedback control of the magnetically suspended ball has received a great deal of attention from number of controller design approaches. In 2003, Marjan Golob et al proposed fuzzy logic based PID control to achieve better performance with high speed control [11]. In 2010, R. Morales et al used generalized proportional integral controller to enhance the robustness on the closed-loop system [14]. In 2011, Rong-Jong Wai et al designed a real time PID control methodology via particle swarm optimization (PSO) to achieve stability [16]. Following, Chih-Min Lin et al proposed the method PSO technology to optimize the adaptive PID controller learning rates [5]. However, a major drawback with these approaches is the use of complex analytical procedures. The proposed controller minimizes the burden of computation. To illustrate the effectiveness of the proposed control strategy, simulations are performed in MATLAB which proves the successful design methodology in engineering application.

This paper is organized as follows. Section 2 shows the dynamics of magnetic ball levitation system. In Section 3, the conventional PID controller is solved by classical methods. Section 4 shows the development of enhanced PID controller. The simulation results of conventional PID and proposed controller for the position control of magnetic ball levitation system are presented in section 5 and conclusions are given in the final section.

2. System Description

The schematic of magnetic ball levitation system is shown in Figure 1. It consists of an electromagnet screwed to the support block. The current (i) passing through the electromagnet produces a magnetic force (F) which levitates the steel ball in air. The light sources and the photo sensors are used to determine the actual displacement of the ball. The actual position is compared with the desired position. Based on the error signal (e), the controller generates the necessary control voltage signal (c), which is fed to the current driver circuit. The driver circuit regulates the current through the electromagnetic coil, thus producing the necessary attractive force to achieve the desired position of the steel ball.

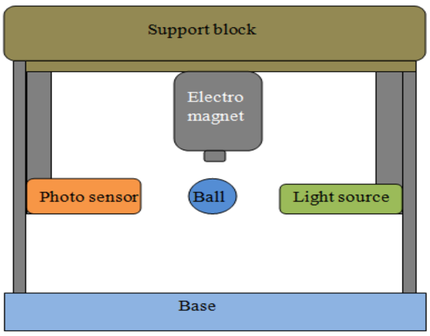

Figure 1. Schematic of Magnetic Ball Suspension System

3. Dynamics of Magnetic Ball Levitation System

The magnetic force produced by the electromagnet is opposite to gravity and it maintains the suspended steel ball in a levitated position as shown in Figure 2. The magnetic force depends on the electromagnet current and the air gap between the steel ball and the electromagnet.

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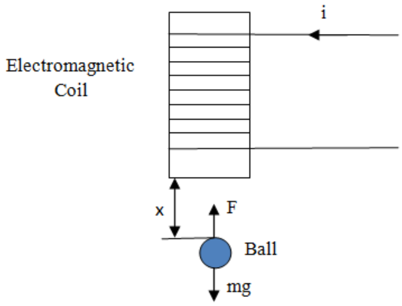

Figure 2. Schematic Illustration of an Electromagnetic Ball Levitation System

The motion of the steel ball in the magnetic field is expressed as [2]

$$m\ddot{x} = mg - c\frac{i^2}{x^2} \tag{1}$$

Where m is the mass of the suspended steel ball, *x* is the air gap between the steel ball and the electromagnet, g is the acceleration due to gravity, c is the magnetic constant and i is the current flowing through the electromagnet coil.

The magnetic force $c\frac{i^2}{x^2}$ is a nonlinear function of current and the air gap. The linearization of the magnetic force near the set point (x_0, i_0) is given in equation as

$$c\frac{i^2}{x^2} = c\frac{i_0^2}{x_0^2} - c\left(\frac{2i_0^2}{x_0^3}\right)x + c\left(\frac{2i_0}{x_0^2}\right)i \tag{2}$$

At equilibrium condition $m\ddot{x} = 0$ gives

$$mg = c\frac{i_0^2}{x_0^2} \tag{3}$$

Substituting equation (2) into equation (1) yields

$$m\ddot{x} = mg - c\frac{i_0^2}{x_0^2} + c\left(\frac{2i_0^2}{x_0^3}\right)x - c\left(\frac{2i_0}{x_0^2}\right)i \tag{4}$$

Evaluating equation (4) using equation (3) gives

$$m\ddot{x} = c\left(\frac{2i_0^2}{x_0^3}\right)x - c\left(\frac{2i_0}{x_0^2}\right)i \tag{5}$$

Taking Laplace transform of equation (5), mathematical calculation gives

$$ms^2X(s) = c\left(\frac{2i_0^2}{x_0^3}\right)X(s) - c\left(\frac{2i_0}{x_0^2}\right)I(s) \tag{6}$$

where X and I denote the steady state quantities. Rewriting equation (6), the transfer function of the magnetic ball levitation system is

$$\frac{X(s)}{I(s)} = \frac{-c\left(\frac{2i_0}{x_0^2}\right)}{ms^2 - c\left(\frac{2i_0^2}{x_0^3}\right)} \tag{7}$$

Table 1 summarizes the variables and parameters used in this problem [10]. Here the equilibrium position of the iron ball is 0.95 – 1.25 cm.

Table 1. Parameters of Magnetic Ball Levitation System

Parameters	Description	Value
m	Mass of the ball (kg)	0.533
x_0	Nominal air gap (cm)	0.95
i_0	Equilibrium current (A)	1.28
g	Gravitational acceleration (m/s^2)	9.8
c	Magnetic constant (Nm^2/A^2)	$37.75*10^{-5}$

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Hence, the transfer function of the nominal plant based on the parameters in Table 1 leads to,

$$G_p(s) = \frac{X(s)}{I(s)} = \frac{-2.009}{s^2 - 2.7068} \quad (8)$$

The above transfer function shows that the magnetic ball levitation system is unstable.

4. Conventional PID Controller

In the PID control structure shown in Figure 3, $G_p(s)$ is the plant and $G_c(s)$ is the PID controller. y is actual output of the system and y_d is the desired output.

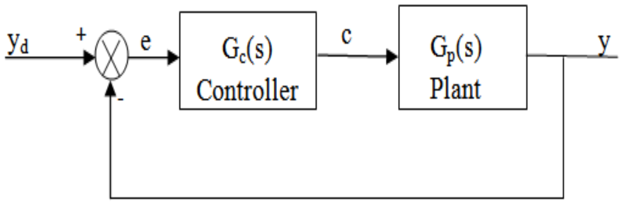

Figure 3. Conventional PID Controller

From the system transfer function given in equation (8), the parameters of the PID controller such as proportional gain (K_p), integral gain (K_i) and derivative gain (K_d) are computed based on the tuning method devised by Huang and Chen [7], Ho and Xu [19], Rostein and Lewin [6] and Morales and Sira-Ramirez [14] and are tabulated in Table 2.

Table 2. PID Controller Parameters for Magnetic Ball Levitation System

Tuning Methods	K_p	K_i	K_d
Huang and Chen (1999)	-6.0892	-17.4045	-3.690
Ho and Xu (1998)	-10.017	-16.5311	-6.0708
Rostein and Lewin (1991)	-23.591	-22.9304	-5.8755
Morales and Sira-Ramirez (2010)	-5.170	-2.0388	-2.3892

5. Enhanced PID Controller

The newly devised PID plus compensator called as enhanced PID is shown in Figure 4.

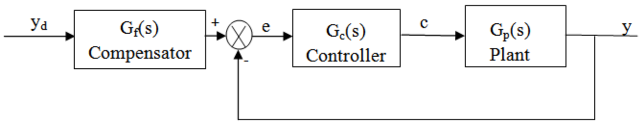

Figure 4. Enhanced PID Controller

The compensator is defined by a model

$$G_f(s) = \frac{\omega_c}{s+\omega_c} \quad (9)$$

$G_f(s)$ is a first order low pass filter to attenuate the effect of model uncertainty which usually increases with the frequency. The filter parameter 'ω_c' is computed based on the Frequency Response Function, where '$j\omega$' is substituted for 's' in $G_p(s)$ and 'ω' is frequency in rad/sec. Finally, the cutoff frequency ω_c is obtained as 0.367 rad/sec from the bode plot of the system.

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The compensator $G_f(s)$ with PID controller improves the performance of the system by eliminating the overshoot and reducing the errors. The parameters K_p, K_i and K_d are chosen from the tuning rules suggested by the authors in Table 2.

6. Results and Discussion

The performance of the conventional PID controller is significantly improved by adding a simple compensator with the proper design methodology. To illustrate its superiority, enhanced PID controller is compared with conventional PID controllers. The performance and robustness of the control system are evaluated based on the performance measures such as overshoot, settling time, ISE and IAE.

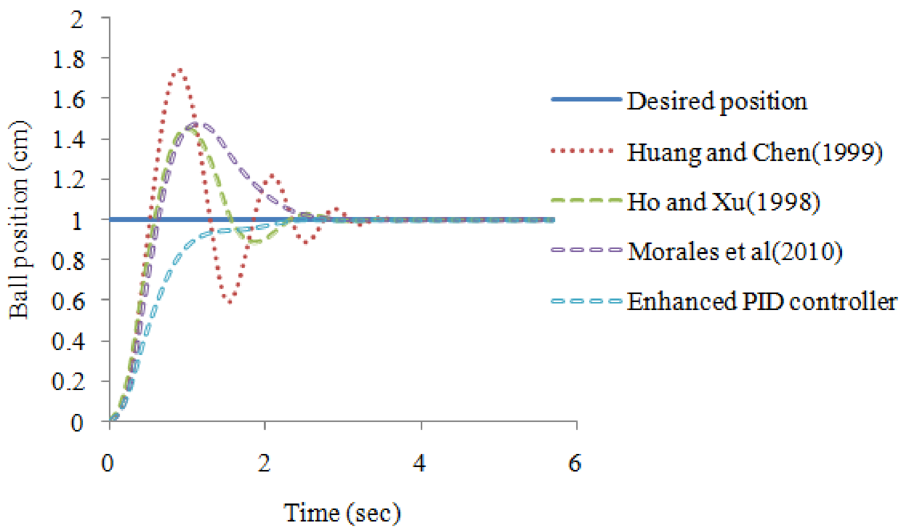

Figure 5. Set Point Tracking Response

A step change of 1.1cm is introduced in the set point. Figure 5 compares the set point responses obtained from the conventional PID controllers and the proposed enhanced PID controller. The proposed controller shows no overshoot. The closed loop performance indices listed in Table 3 confirms the superior response of the proposed controller for the same set point.

Table 3. Performance Analysis of Controllers

Tuning Methods	Performance measures			
	Overshoot (%)	***Settling time (sec)***	***ISE***	***IAE***
Huang and Chen (1999)	73	3.42	9.7	16.6
Ho and Xu (1998)	39	2.52	7.78	12.12
Rostein and Lewin (1991)	47.27	3.3	0.2248	0.5204
Morales and Sira-Ramirez (2010)	43	2.64	8.44	15.01
Enhanced PID controller	0	2.2	7.11	10.83

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To confirm the robust performance of the proposed controller, $\pm$ 5% and $\pm$ 10% tracking response at the operating point of 1.025 cm and 1.175 cm are recorded in figures 6 and 7 respectively. The simulation results demonstrate the superior robust performance of the proposed controller.

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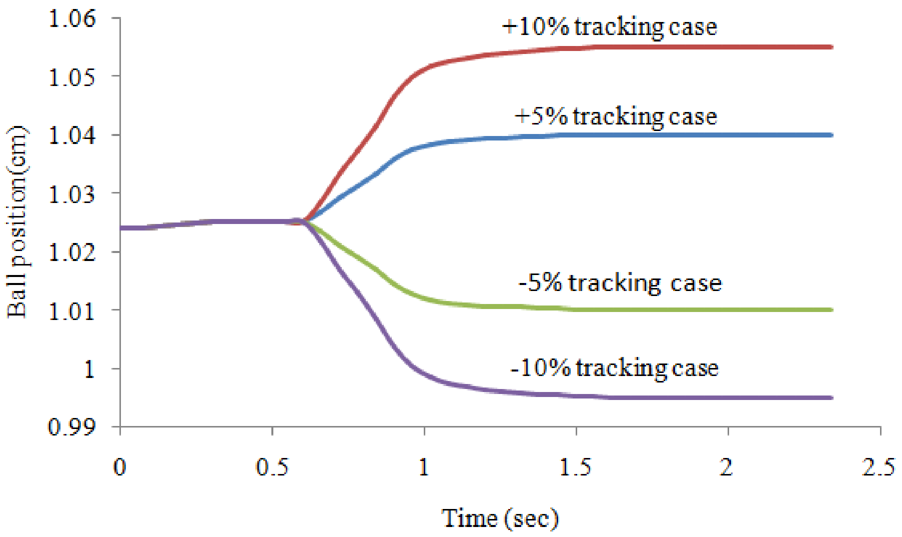

Figure 6.Tracking case for Enhanced PID Controller at the Operating Point of 1.025 cm

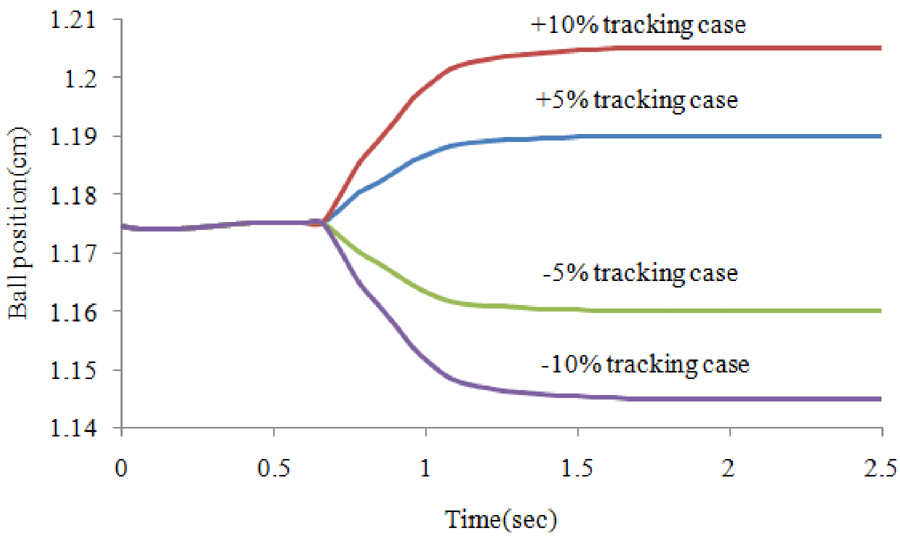

Figure 7. Tracking case of Enhanced PID Controller at the Operating Point of 1.175 cm

7. Conclusion

In this paper, an enhanced PID controller is developed based on the process model. The magnetic ball levitation system is considered in the simulation study in order to demonstrate the superiority of the proposed method. A closed loop response of magnetic levitation system tuned by the proposed method is compared with the existing. The results show that both set point tracking and robust performance of the PID controller can be enhanced by adding a compensator with proper design methodology. The results show

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that the performance of enhanced PID controller is superior to the conventional PID controller.

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