Comparison of Ziegler-Nichols and Cohen Coon tuning method for magnetic levitation control system

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Abstract. Magnetic levitation is an example of a nonlinear system that is naturally unstable. In the control system field, it can be also used to check the effectiveness of control methods. Unlike other researches overcoming by analytical method, this research investigates the solution of the nonlinearity of the magnetic field by placing two effect hall sensors on the top and bottom of magnetic coils. After decreasing the effect of nonlinearity, two PID control tuning methods, Ziegler Nichols (ZN) and Cohen Coon (CC), are compared to obtain an appropriate control structure and its initial parameters. The experimental result shows that the best control structure of ZN method is PID whereas its initial parameters, K_p, T_i, and T_d, are 15.33, 0.036 and 0.009, respectively. The rise-time and settling time of the response are 0.54s and 0.59s. The appropriate control structure is PI control whereas K_p and T_i are 30.05 and 0.012 from CC method. The rise-time and settling time resulted are 0.8s and 0.67s. The ZN method with PID control structure has a better response with smaller rise-time and settling time than PI control from CC Method. This research is benefit for solving a problem dealing with magnetic levitation control.

1. Introduction

Magnetic levitation system has an important role in the industry, especially in the railway transportation industry. This technology becomes popular due to minimum fraction, minimizing mechanical strain and high speed [1-3]. Magnetic levitation is using a magnetic force to achieve stable levitation. Due to the positioning object by electromagnetic, this technology has non-contact without environmental hazards and pollution.

However, magnetic levitation is an unstable and nonlinear system so it is difficult to be implemented and controlled. Therefore, magnetic levitation is also an interesting issue to confirm the performance of control. Several control methods have been presented to develop the control system of magnetic levitation. In [4] proposed adaptive fuzzy backstepping control to estimate unknown, partially known, or uncertain input nonlinear function of magnetic levitation system. They verified their proposed method by simulation and laboratory experiment. In [5] the authors combined the linear Hall-effect sensors to measure the magnetic flux which is used to determine the position of a magnetic guided robot (MGR). The accuracy of the method was 0.4 mm rms in both the-x and y-direction over $8{\times}8mm^2$ working area.

In another research [6], PID control based on the frequency domain approach is used to control the laboratory magnetic levitation system. The result shows that the controller can achieve the desired performance. Lead compensation is used to controlled magnetic levitation in [7]. These methods can approach a good performance of control. However, magnetic levitation is difficult to be implemented due to its inherently unstable system. All the magnetic levitation system mentioned previously are designed with one position sensor.

Commonly, control of magnetic levitation is focused on maintaining stability and load capacity. Magnetic levitation system is also can be implemented in a laboratory scale to experiment [6-7]. The fixed electromagnetic force is very sensitive, and there is noise that creates acceleration forces on the steel ball, causing the ball to move into the unbalanced region [8]. Therefore, how to design the laboratory magnetic levitation that can overcome the instability of the magnetic force still challenging. This motivates the researcher to develop another design of magnetic levitation.

This paper is aimed to investigate the mechanical approach to overcome the nonlinearity behaviour of magnetic levitation, instead of a mathematical approach. Two sensors will be attached to the top of the coils (to measure the produced magnetic field by coils) and on the bottom (to measure the magnetic field produced by coils and levitated object), therefore the system will know the object position based on the difference between both sensors. After mitigating the nonlinearity behaviour, two PID control design methods (Ziegler-Nichols & Cohen-Coon) will be introduced to find initial PID parameters and their appropriate control structure (P, PI, PD, PID). Based on the response parameters (delay time, rise time, settling time, overshoot, and error steady-state), the best structure and initial control parameters will be finally derived and compared.

2. Magnetic levitation system

Magnetic levitation is a method of suspended an object vertically without any support other than a magnetic field. It is formulated using Newton's first and second laws. A neodymium magnet is used to be an elevated object. Levitation an object is caused by a magnetic force against the natural force of gravity.

The magnetic field is generated by the current flow through the coil of wire. The dynamic system involves electromagnetic with control of current flow to adjusting electromagnet's energy. The amount of current flow through the coils is adjusting by the parameter of the control system. The linear hall effect is used to be a position control to provide any information about the object's levitation position.

To achieve the desired position of levitation, a dynamic system must have to be controlled with a proper controller due to the inherent unstable of magnetic levitation. The proposed experimentally magnetic levitation system is developed as shown in Figure 1.

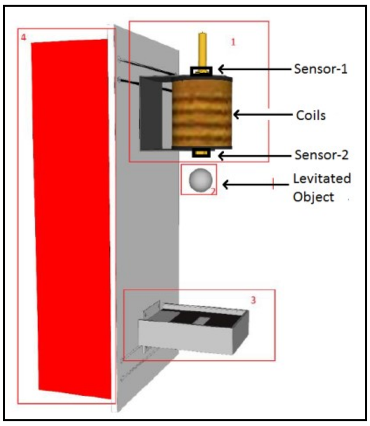

Figure 1. Design illustration of magnetic levitation.

In this research, the magnetic levitation consists of an electromagnet, an object made from neodymium magnet, box to hold the falling object, and the cover box. The electromagnets are consisting of 2400 of coils with 6 cm in diameter. The box is constructed by acrylic. The magnetic levitation system is made in the form of a module so that it can be matched with the power supply, signal condition, reference, and PID controller modules that exist in the laboratory.

To overcome the nonlinearity of the magnetic force, the magnetic levitation is designed using two position sensors. The position sensors are linear hall effect placed on the top and bottom of the electromagnet coils. Therefore, the object position is determined vertically. The object is a permanent neodymium magnet with 20.86 gr, covered with a ping-pong ball.

3. Control system design

3.1. Block diagram system

The Structure of the magnetic levitation control system is shown in Figure 2. This system is suspended as a neodymium magnet as an object based on the desired position. The structure control is used as a closed-loop system, consist of set point, controller, signal conditioning, actuator, plant magnetic levitation, and 2 Hall effect sensors. The position of an object is detected by linear hall effect sensors. The control system is adjusted to the current flow through the magnetic field for applying magnetic force to achieve stable levitation and desired position. Using two hall effect sensors, the relative position of the object (magnet neodymium) can be deduced. The feedback of this system is position signal which is sensed by hall effect sensors. The hall effect sensor is used to measure the magnitude of the magnetic field. In this research, the magnitude of the magnetic field is converted to voltage through the signal conditioning circuit and this signal to be input for the controller.

In this research, a PID controller is used to control the position of an object. The parameter controls are obtained by Ziegler-Nichols type-1 and Cohen Coon methods. The S-shaped curve response of the magnetic levitation system is identified to determine the dead time and time constant of the system.

The position of the object can be adjusted using the set-point module. This position signal is compared with the actual position detected by hall effect sensors. The error position signal is an input for the PID controller. The control action from the controller is amplified before generated the plant. The responses are monitored using Matlab/Simulink.

3.2. PID controller design using Ziegler-Nichols type 1 method

The S-shaped curve can be characterized by two constants, delay time (L) and time constant (T). The delay time and time constant are determined by drawing a tangent line at the inflection point of the S-shaped curve and determining the intersection of the tangent line with the time axis and line $y(t)$ = K, as shown in Figure 3 [9]. The general form of PID formulation as in below [9]:

$$u(t) = K_p(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt} \tag{1}$$

where $u(t)$ denoted control signal, K_p is proportional gain, T_i is integral time, T_d is derivative time and $e(t)$ is the difference between the setpoint and actual signal.
The control parameters for tuning that suggested by Ziegler-Nichols type 1 (ZN-1) are K_p, T_i, and T_d according to the formula shown in Table 1.

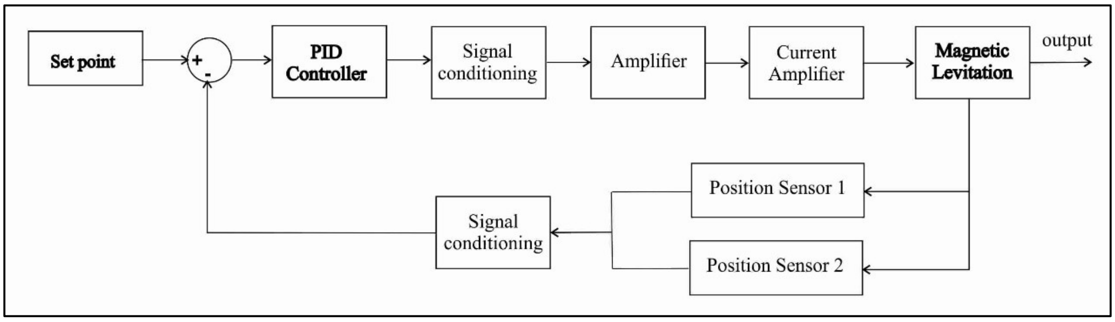

Figure 2. Block diagram system.

Table 1. Ziegler-Nichols type-1 tuning rule.

Type of controller	K_p	T_i	T_d
P	T/L	∞	0
PI	$0.9T/L$	$L/0.3$	0
PID	$1.2\ T/L$	$2L$	$0.5L$

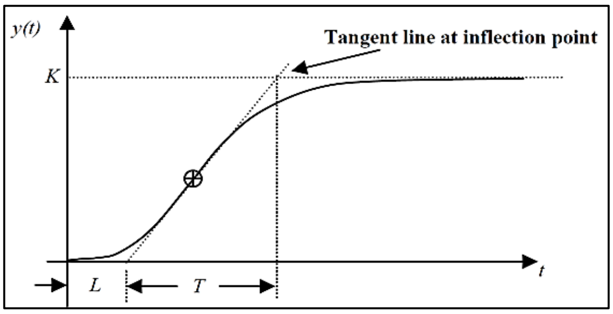

Figure 3. reaction curve with Ziegler-Nichols parameters.

Although ZN-1 is designed based on the open-loop response, for the specific system such as position sensor driven by DC motor and magnetic levitation, the plant is set to a closed loop with gain = 1, otherwise, the response will be unstable. To obtained dead time (T) and time constant (L) of the magnetic levitation, the setpoint is given 3.9 volts to the closed-loop with gain = 1. The response with the step signal as the set point of the system is shown in Figure 4. The values of dead time (L) and time constant (T) as follows,

$$L = 0.018$$
$$T = 0.23 \tag{2}$$

substitute L and T values to the Ziegler-Nichols rules to obtained PID parameters as follows,

- Proportional Gain (P)

$$K_p = \frac{T}{L} = \frac{0.23}{0.018} = 12.7778 \tag{3}$$

- Proportional and Integral Gain (PI)

$$K_p = 0.9\frac{T}{L} = 0.9\frac{0.207}{0.018} = 11.5 \tag{4}$$

$$T_i = \frac{L}{0.3} = \frac{0.018}{0.3} = 0.06 \tag{5}$$

$$K_i = \frac{K_p}{T_i} = \frac{11.5}{0.06} = 191.667 \tag{6}$$

- Proportional, Integral and Derivative (PID)

$$K_p = 1.2\frac{T}{L} = 1.2\frac{0.276}{0.018} = 15.33 \quad (7)$$

$$T_i = 2L = 2\times 0.018 = 0.036 \quad (8)$$

$$K_i = \frac{K_p}{T_i} = \frac{15.33}{0.036} = 425.926 \quad (9)$$

$$T_d = 0.5L = 0.5\times 0.018 = 0.009 \quad (10)$$

So, the derivative gain is determined as follow,

$$K_d = K_p T_d = 0.138 \quad (11)$$

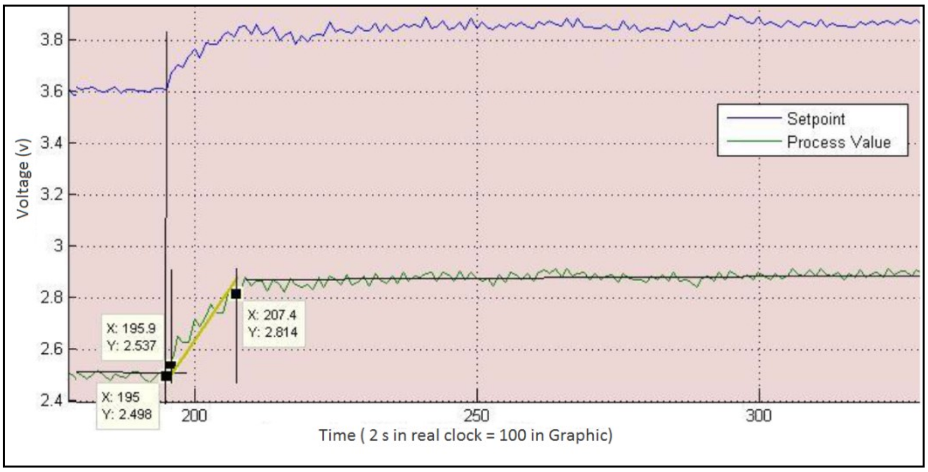

Figure 4. S-shape curve of the response.

3.3. PID controller design using Cohen Coon method

There are several methods to determine values to use for the proportional, integral and derivative of the PID parameters controller. One of these methods is the Cohen Coon tuning method.

The system's response is modelled to a step change as a first-order response plus dead time, using the Cohen-Coon method (Figure 5). From this response, three parameters: K, τ_m, and τ_d are founded. K is the output steady state divided by the input step change, τ_m is the effective time constant of the first-order response, and τ_d is the dead time.

$$\tau_m = \frac{3}{2}(t_2 - t_1) \quad (12)$$

$$\tau_d = t_2 - \tau_m \quad (13)$$

The table of Cohen Coon rules is shown in Table 2. In the Cohen Coon rules the dead time is less than two times the length of the time constant [10]. These relations were developed empirically to provide a closed-loop response with ¼ decay ratio.

Table 2. Cohen Coon tuning formula [10].

Type of Controller	K_c	T_i	T_d
P	$\frac{\tau_m}{Kt_d}(1+\frac{t_d}{3\tau_m})$	-	-
PI	$\frac{\tau_m}{Kt_d}(0.9+\frac{t_d}{12\tau_m})$	$t_d\left(\frac{30+3t_d/\tau_m}{9+20t_d/\tau_m}\right)$	-
PD	$\frac{\tau_m}{Kt_d}(1.25+\frac{t_d}{6\tau_m})$	-	$t_d\left(\frac{6-2t_d/\tau_m}{22+3t_d/\tau_m}\right)$
PID	$\frac{\tau_m}{Kt_d}(1+\frac{t_d}{3\tau_m})$	$t_d\left(\frac{32+6t_d/\tau_m}{13+8t_d/\tau_m}\right)$	$t_d\left(\frac{4}{11+2t_d/\tau_m}\right)$

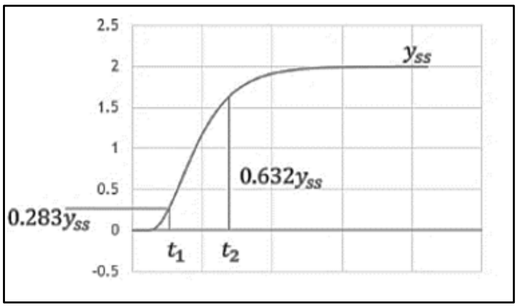

Figure 5. Process reaction curve.

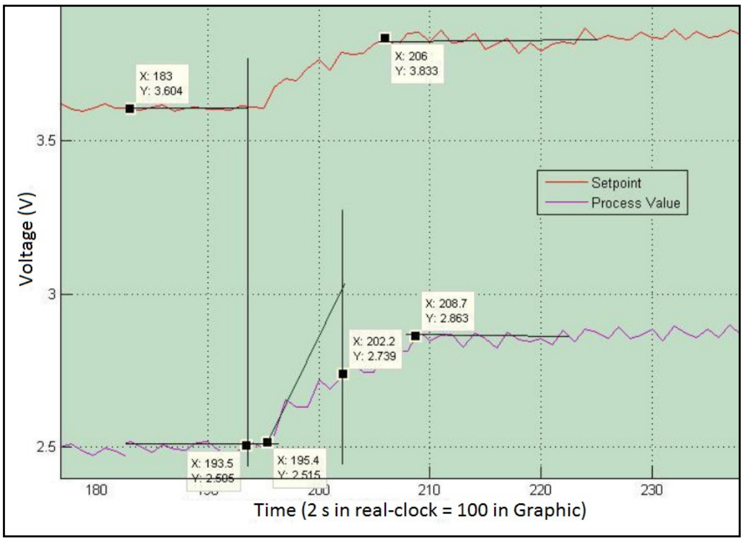

Figure 6. The response of magnetic levitation with 3.8 volts of set point.

The open-loop response of the system which is transient response induced by a step change signal is obtained can be seen in Figure 6. Three parameters: K, τ_m, and τ_d are obtained as follows:

$$K = \frac{2.866 - 2.507}{3.856 - 3.617} = 1.502 \quad (14)$$

$$\tau_d = 0.004 \quad (15)$$

$$\tau_m = 0.202 \quad (16)$$

To obtained P, PI and PID parameters, substitute K, τ_m, and τ_d values to the Cohen Coon rules (table 2). The parameter controllers that have been obtained are summarized in Table 3.

Table 3. PID controller parameters based on the Cohen Coon method.

Type of Controller	K_c	T_i	K_i	T_d	K_d
P	34.53	-	-	-	-
PI	30.05	0.0127	2366.14	-	-
PD	41.38	-	-	0.0011	0.044
PID	18.43	0.01	1861.1	0.0014	25.79

4. Results and discussion

All control parameters derived by either Ziegler-Nichols or Cohen-Coon are subsequently applied to the magnetic levitation plant as depicted in Figure 7. The response is plotted by using the Simulink scope for the analysis purposes. In the control system application, both design methods are aimed to give initial PID control parameters giving the engineer an initial point to refine the response based on rules stated in Table 4.

Table 4. The rule for tuning parameters.

Parameter	Rise Time	Overshoot	Settling Time	Error Steady-state
K_p	Decrease	Increase	Minor Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Minor Change	Decrease	Decrease	Minor Change

In the first method, ZN-1, the response of several control structures are depicted in Figure 8-10. To analyse the quality of the responses, they are measured based on a time delay (T_d), rise-time (T_r), settling time (T_s), %overshoot (%OS), and steady error (e_{ss}). From Table 4, control structure P and PID can maintain the response with no overshoot and error-state. From the closer look of T_r and T_s, PID has a faster time to deliver the object in its steady position. Therefore, the structure of PID from ZN-1 is chosen as the initial point to control the magnetic levitation plant. Detail of the response can be found in Table 5.

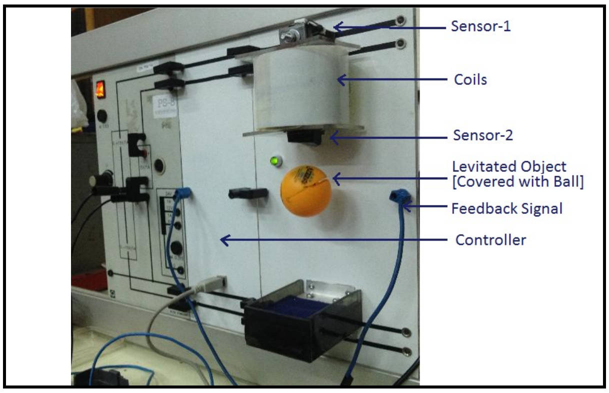

Figure 7. Experimental setup of magnetic levitation system.

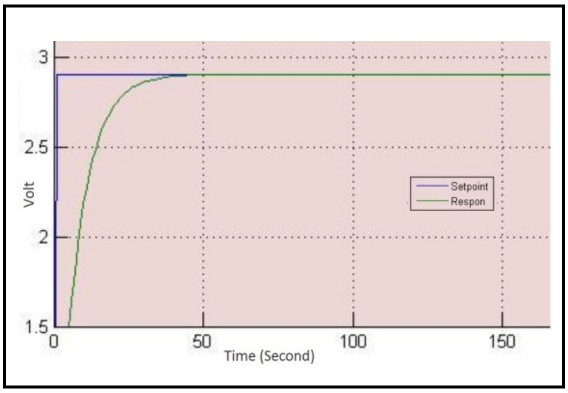

Figure 8. Response of magnetic levitation using Ziegler-Nichols P Controller.

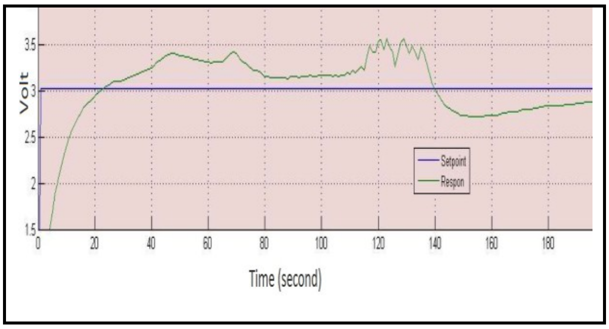

Figure 9. Response of magnetic levitation using Ziegler-Nichols PI Controller.

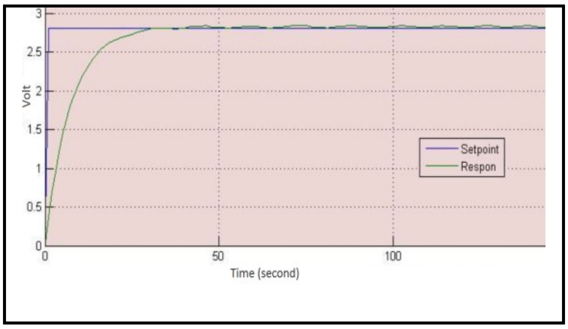

Figure 10. Response of magnetic levitation using Ziegler-Nichols PID Controller.

Table 5. Comparison of various parameters for Ziegler-Nichols.

	P	PI	PID
Time delay (T_d)	0.094 s	0.074 s	0 s
Rise Time (T_r)	0.89 s	0.32 s	0.59 s
Settling Time (T_s)	0.71 s	3.564 s	0.54 s
Overshoot (OS)	0 %	38.17 %	0 %
steady-state error (e_{ss})	0 %	11.5 %	0 %

In the second method, the Cohen-Coon method, it gives several control structures (P, PI, PD, PID) as depicted in Figure 11 and 14, respectively. On the same hand, the responses are also measured based on a time delay (T_d), rise-time (T_r), settling time (T_s), %overshoot (%OS), and steady error (e_{ss}). Unlike the first method, where PI structure gives bad response for all response parameters, in this method, PI has smaller settling time (0.67 s compared to PID (0.74s), PD (0.73s), P (1.12 s)). Together with PD, it has also smaller rise-time (0.8 s compared to P (1.19 s) and PID (0.84)), no time delay, overshoot, and steady-state error. So that, the structure of PI from Cohen-Coon is chosen as the initial point to control the magnetic levitation plant. Detail of the response parameters can be found in Table 6.

The subsequent discussion is to compare PID of ZN method and PI of CC method as shown in Table 7. It can be seen that PID has a smaller rise-time (0.59 s compared to 0.8S of PI from CC method). On the same hand, PID has also smaller settling time with 0.54 s compared to 0.67 s.

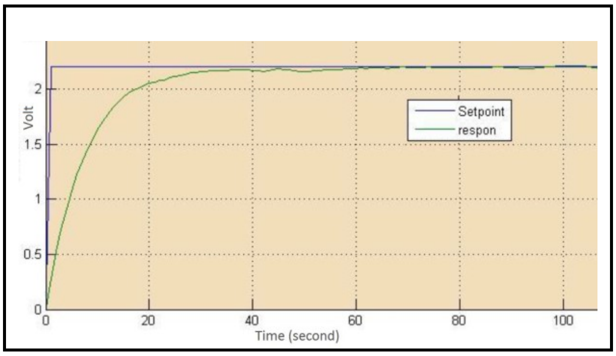

Figure 11. Response of magnetic levitation using Cohen Coon Proportional Controller.

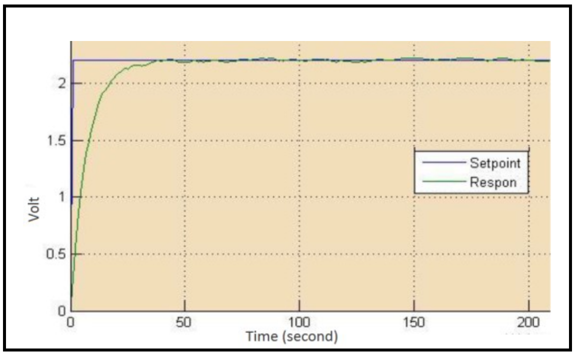

Figure 12. Response of magnetic levitation using Cohen Coon PI Controller.

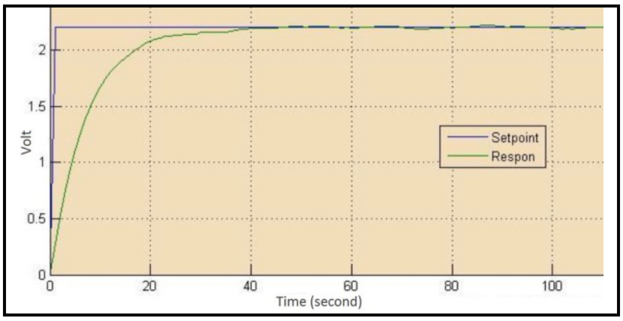

Figure 13. Response of magnetic levitation using Cohen Coon PD Controller.

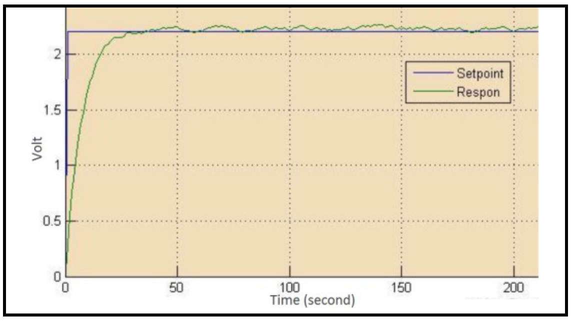

Figure 14. Response of magnetic levitation using Cohen Coon PID Controller.

Table 6. Comparison of various parameters for Cohen Coon methods.

	P	PI	PD	PID
Time delay (T_d)	0 s	0 s	0 s	0 s
Rise Time (T_r)	1.199 s	0.8 s	0.8 s	0.84 s
Settling Time (T_s)	1.12 s	0.67 s	0.73 s	0.74 s
Overshoot (OS)	0 %	0 %	0 %	0 %
steady state error (e_{ss})	0 %	0 %	0 %	1.2 %

Table 7. Comparison of Ziegler-Nichols and Cohen Coon methods.

	Ziegler-Nichols [PID]	Cohen Coon [PI]
Time delay (T_d)	0 s	0 s
Rise Time (T_r)	0.59 s	0.8 s
Settling Time (T_s)	0.54 s	0.67 s
Overshoot (OS)	0 %	0 %
steady-state error (e_{ss})	0 %	0 %

5. Conclusions

In this paper, a mechanical approach, by placing two effect hall sensors on top-bottom of the coils, is successfully applied to minimize the effect of magnetic behavior so that the controller can be easily designed based on the graphical response approach (Ziegler-Nichols and Cohen-Coon methods), instead of mathematical analysis approach. The verification experiment shows that the control structure from Ziegler-Nichols (PID) delivers a good response with no time delay, overshoot and steady-state error. It has also smaller rise-time and settling time than PI control from Cohen-Coon. In the control system application, the structure, control parameters, and the response are the initial point which needs to enhance base on the tuning rule to meet the desired response.

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