# Real-time Implementation of Robust Set-point Weighted PID Controller for Magnetic Levitation System

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*Abstract***:** In this paper, a novel Set Point Weighted Proportional Integral Derivative (SPWPID) controller has been proposed for the Magnetic levitation (Maglev) system in Simulink and real time. The recently evolved Teaching Learning Based Optimization (TLBO) has been used to identify the suitable controller parameter values by optimizing the objective function. The performance of the SPWPID controller is compared with that of the PID controller, designed using TLBO. Moreover, the performance of the SPWPID controller has also been compared with the performance of the 1-DOF and 2-DOF PID controller designed for the same Maglev plant [15]. The result of the comparison shows that the SPWPID controller outperforms both the 1-DOF and 2-DOF PID controllers in terms of overshoot and settling time. The robustness analysis has also been incorporated to demonstrate the robust behavior of the plant with the SPWPID controller.

*Keywords*: Maglev, Set-Point Weighted PID, PID, TLBO.

## 1. Introduction

Maglev is an example of an inherently nonlinear and unstable system. Because of these properties, it becomes difficult to design a controller which will efficiently control this system. The application of Maglev can be found in different fields of research which include high-speed transportation systems [1], photolithography devices for semiconductor manufacturing [2], seismic attenuators for gravitational wave antennas [3], self-bearing blood pumps [4] for use in artificial hearts etc. Because of such vast applications, it becomes extremely important to develop a proper control strategy for the Maglev system. The literature review shows that the design of the controller utilizes different control techniques such as sliding mode control, $H_\infty$ control, TID and I-TD control, fractional order control etc. In addition, the use of the evolutionary algorithm, fuzzy logic and neural network can also be found in the literature [5-11].

Because of its simple structure and easy implementation, the PID controller has always been a favorite choice for the control engineers and has been applied in several fields of research [12-14]. To provide an overall good performance, different techniques are chosen but a controller is rarely found where it has got the potential to provide a good response in all respects.

This paper provides a novel approach, where an SPWPID controller is designed to efficiently control the Maglev system. The recently evolved Teaching Learning Based Optimization (TLBO) has been used to identify the suitable controller parameter values by optimizing the objective function. The performance of the SPWPID controller is compared with that of the PID controller designed using TLBO. Moreover, the performance of the SPWPID controller has also been compared with the performance of the 1-DOF and 2-DOF PID controller designed for the same Maglev plant [15]. The result of the comparison shows that the SPWPID controller outperforms both the 1-DOF and 2-DOF PID controllers in terms of overshoot and settling time.

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The robustness analysis has also been performed to demonstrate the robust behavior of the plant with the SPWPID controller.

This paper is organized into six sections. In section 1, the introduction of the paper is provided. Section 2 gives the schematic diagram and transfer function of the Maglev system. The design of the PID and SPWPID controller using TLBO for Maglev system is provided in section 3. Section 4 deals with the simulation diagram, response of the system with the PID and SPWPID controllers. In section 5, the robustness analysis for the SPWPID controller with Maglev system has been provided. The concluding part and future scope of research is highlighted in section 6.

## 2. Maglev System

The schematic diagram of the Maglev system [15] considered for this study is provided in Figure 1. In this paper, the Maglev system (Model no. 33-210) from Feedback Instruments has been considered. When current flows through the coil, it gets magnetized and it attracts the ball in the upward direction. At the same time, the gravitational force of the earth pulls it in the downward direction. There is an infrared sensor present in the Maglev set up which monitors the position of the ball continuously.

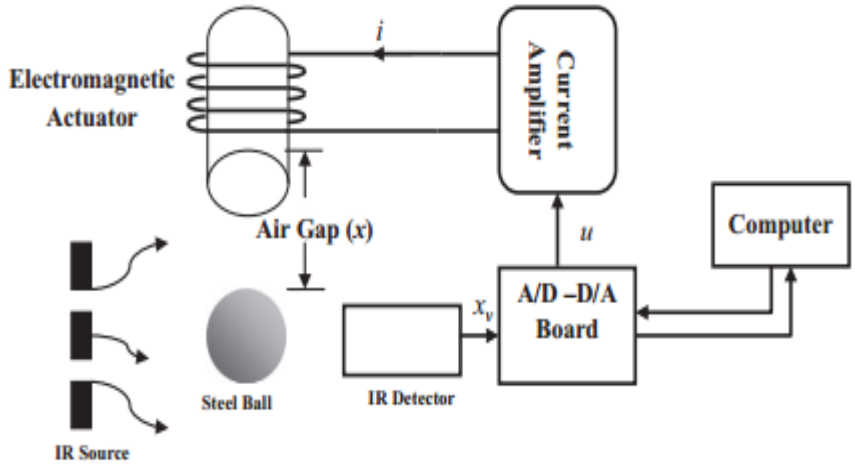



Figure 1. Schematic diagram of Maglev system

The mechanical and electrical unit along with the connection-interface panel that assembles into a complete control system setup is provided in Figure 2.

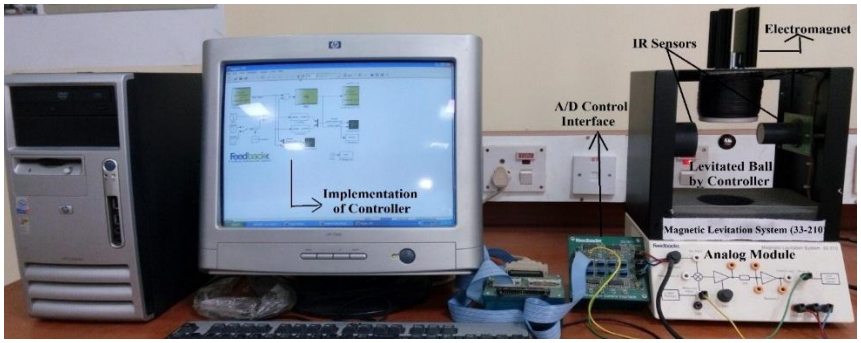



Figure 2. Maglev control system

The simplest nonlinear model [16] in terms of ball position $x$ and electromagnetic coil current $i$ is given by

$$m\ddot{x} = mg - k\frac{i^2}{x^2} \quad (1)$$

where, $m$ is the mass of the ball, $g$ is the gravitational constant and $k$ depends on the coil parameters.

In order to linearize the nonlinear Maglev plant, the calculation of the equilibrium point is mandatory. The equilibrium point of the current and position is calculated by equating $\ddot{x} = 0$ and found to be as 0.8A and 0.009 m (-1.5 V, when expressed in volts) respectively.

Table 1. The system parameters of the Maglev system [15]

| Parameter | Notation | Value |
|---|---|---|
| **Mass of the steel ball** | $m$ | 0.02 kg |
| **Acceleration due to gravity** | $g$ | 9.81 m/s$^2$ |
| **Equilibrium value of current** | $i_0$ | 0.8 A |
| **Equilibrium value of position** | $x_0$ | 0.009 m |
| **Control voltage to coil current gain** | $k_1$ | 1.05 A/V |
| **Sensor gain, offset** | $k_2$, $\eta$ | 143.48 V/m, -2.8 V |
| **Control voltage input level** | $u$ | $\pm$ 5 V |
| **Sensor output voltage level** | $x_v$ | + 1.25 V to -3.75V |

The nonlinear system (1) can be linearized to

$$\Delta\ddot{x} = -\left(\frac{\partial f(i,x)}{di}|_{i_0,x_0}\,\Delta i + \frac{\partial f(i,x)}{dx}|_{i_0,x_0}\,\Delta x\right) \quad (2)$$

Where, $\Delta x$ and $\Delta i$ is the small deviation from the equilibrium point $x_0$ and $i_0$ respectively. Evaluating partial derivatives and taking Laplace transform on both side of equation (2), the transfer function can be obtained as

$$\frac{\Delta x}{\Delta i} = \frac{-k_i}{s^2 - k_x} \quad (3)$$

where, $k_i = \frac{2g}{i_0}$ and $k_x = \frac{2g}{x_0}$ [15]

As $x$ and $i$ are proportional to $x_v$ and $u$, the transfer function can be modified to the form $\frac{\Delta x_v}{\Delta u}$ [15] and given by

$$G_p(s) = \frac{\Delta x_v}{\Delta u} = \frac{b}{s^2 - p^2} = \frac{-3518.85}{s^2 - 2180} \quad (4)$$

where, $x_v$ is sensor output and $u$ is the input to current amplifier.

The poles of the Maglev system are located at $\pm 46.69$. Because of the presence of one pole on the right half of the 's' plane, the system becomes highly unstable. To achieve a stable controlled behavior of the system, it becomes extremely important to design a suitable controller.

## 3. Design of Controllers

This section describes the design of PID and SPWPID controller for the Maglev system.

*A. PID Controller Design using TLBO*

*A.1. Dominant Pole calculation*

For this study, the design specifications have been taken as

Maximum overshoot $\leq$ 5% and
Settling time $t_s \leq$ 2 sec and
Phase margin $\geq 60°$

According to the first two specifications, dominant poles obtained by solving the characteristic equation $s^2 + 2\zeta w_n s + w_n^2 = 0$ are: $s_{1,2} = -2 \pm 2.1i$

*A.2. System with PID Controller*

The general structure of PID controller is

$$G_c(s) = K_P + \frac{K_I}{s} + K_D s \quad (5)$$

where, $K_P$ = proportional gain, $K_I$ = integral gain, $K_D$ = derivative gain

Characteristics equation of the system with PID controller for unity feedback is given by

$$1 + G_p(s)G_c(s) = 0 \quad (6)$$

$$i.e \;\; 1 + \left(\frac{b}{s^2 - p^2}\right)\left(K_P + \frac{K_I}{s} + K_D s\right) = 0 \quad (7)$$

$$i.e. \; 1 + \left(\frac{-3518.85}{s^2 - 2180}\right)\left(K_P + \frac{K_I}{s} + K_D s\right) = 0 \quad (8)$$

*A.3. Objective Function Formulation*

Substituting the value of $s_1$ in the above equation and separating real ($R$) and imaginary ($I$) parts, one obtains

$$R = 1 + 1.6138K_P - 0.3853K_I - 3.2146K_D \quad (9)$$

$$I = -0.0062K_P - 0.4015K_I + 3.4014K_D \quad (10)$$

The objective function '$f_{PID}$' considered for obtaining the value of $K_P$, $K_I$ and $K_D$ has the following format

$$f_{PID} = |R|^2 + |I|^2 \quad (11)$$

*A.4. Objective Function Optimization using TLBO*

The TLBO [17] coined by Rao et al. presents a very simplistic approach for solving constrained as well as un-constrained equations. The algorithm is inspired by the gradual increase in the knowledge of the students in the class by the interaction of the teacher and students as well as student to student interaction. The optimization procedure contains two parts.

- Teaching Phase - The teacher is the most knowledgeable person in the class. Therefore, the teacher teaches the students in the class. Every student having different receptive power gets different amounts of knowledge from the same teacher. In this way, the knowledge of the overall class increases.
- Learning Phase – The knowledge of individual students increases by interacting with random students in the class and sharing knowledge with them.

The choice of the TLBO over other optimization techniques in search space reduction is due to its merit of having no algorithmic parameter as in DE, GA or PSO. For finding the PID controller parameter values, the objective function '$f_{PID}$' has been optimized using TLBO.
The objective function considered here has three unknowns, *i.e.* $K_P, K_I$ *and* $k_D$. The range of these parameters taken for writing the MATLAB code has been decided after a number of trial runs and provided in Table 2.

Table 2. Range of controller parameters considered for writing the MATLAB code

| Parameter | $K_P$ | $K_I$ | $K_D$ |
|---|---|---|---|
| Lower range | -5.4 | -10 | -0.15 |
| Upper range | -3.4 | -8 | 0 |

A stepwise implementation of the algorithm for search space reduction in our problem is as follows:

Step 1: Initialize a population of random values for the three design vectors $K_P, K_I \; and \; K_D$ within the above limits. Let the population be *N*.
Step 2: Evaluate the cost of the population *f*.
Step 3: Repeat

- Find the best cost from the population, the design variables corresponding to the best cost becomes the Teacher. Rest of the population becomes students.

$$K^{teacher} = [K_P^{best}, K_I^{best} and \; K_D^{best}] \tag{12}$$

- Learning between Teacher and Students. New generation $[k_P^{new}, k_I^{new} and \; k_D^{new}]$ are generated by the

$$K_{tech}^{new} = [K_P^{new}, K_I^{new} \; and \; K_D^{new}] = \Delta P_K^{old} + rand(K^{teacher} - T^f M) \tag{13}$$

where, $T^f$ is the teaching factor and *M* is the mean result of all students.

- If student is more knowledgeable. Replace new solution with old, otherwise no change is made.

$$K_{tech} = \begin{cases} K_{tech}^{new} & f(K_{tech}^{new}) < f(K_P, K_I, K_D) \\ [K_P, K_I, K_D] & f(K_{tech}^{new}) \geq f(K_P, K_I, K_D) \end{cases} \tag{14}$$

- Learning among randomly selected students. Let two random set of design variable be denoted as vector *i* and *j*.

$$K_{learn,i}^{new} = K_{tech,i} + mod(rand(K_{tech,i} - K_{tech,j})) \tag{15}$$

- If new student is more knowledgeable. Replace new solution with old, otherwise no change is made.

$$K_{learn,i} = \begin{cases} K_{learn,i}^{new} & f(K_{learn,i}^{new}) < f(K_{tech,i}) \\ K_{tech,i} & f(K_{learn,i}^{new}) \geq f(K_{tech}, i) \end{cases} \tag{16}$$
$$For \; i = 1,2 \ldots, N$$

- Memorize best solution

Step 4: Until iteration < maximum iteration.

The objective function '$f_{PID}$' has been optimized using the recently evolved algorithm TLBO for finding the PID controller parameter values with the population and maximum iteration as 50. The objective function considered here has three unknowns *i.e.* $K_P, K_I$ and $K_D$. The values of $K_P$, $K_I$, and $K_D$ have been found after optimizing the objective function within the mentioned range of parameters, and given in Table 3.

Table 3. PID controller parameter values after optimizing the objective function

| Parameter | $K_P$ | $K_I$ | $K_D$ |
|---|---|---|---|
| Value | -3.4 | -8.0000 | -0.1500 |

*B. SPWPID Controller Design*
The steps involved in set-point weighted PID controller design is as follows.

*B.1. System with SPWPID Controller*
An SPWPID controller is similar to a 2 DOF controller. As different signal paths are present for the set-point and process outputs, it has got more flexibility to satisfy the design specifications accurately. The SPWPID controller can be represented as a PID controller with a PD controller present in the inner loop [18]. The control structure of an SPWPID controller with the plant and unity feedback is provided in Figure 3. Because of such a structure, the SPWPID controller is also known as the PID-PD controller.

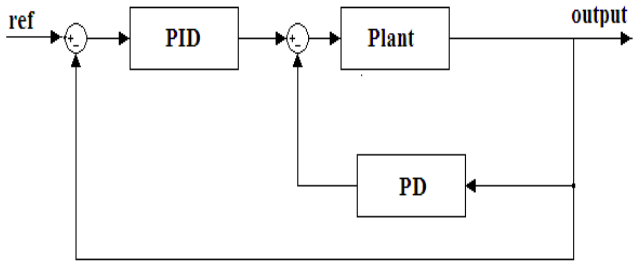



Figure 3. Control Structure of an SPWPID controller

With unity feedback, the characteristics equation of the system with the SPWPID controller is given by

$$1 + G_p(s)\big((G_{PID}(s) + G_{PD}(s)\big) = 0 \quad (17)$$

where, $K_{P1}$, $K_I$ *and* $K_{D1}$ are the proportional, integral and derivative gain of PID controller and $K_{P2}$ and $K_{D2}$ are the proportional and derivative gain of the PD controller. The above equation with the values of controller parameters can be written as

$$1 + \left(\frac{-3518.85}{s^2-2180}\right)\left(\left(K_{P1} + \frac{K_{I1}}{s} + K_{D1}s\right) + (K_{P2} + K_{D2}s)\right) = 0 \quad (18)$$

*B.2. Objective Function Formulation*

Substituting the value of $s_1$ (which has already been calculated in PID controller design section) in the above equation, the real ($R_1$) and imaginary ($I_1$) parts are found to be

$$R_1 = 1 + 1.6138K_{P1} - 0.3853K_{I1} - 3.2146K_{D1} + 1.6138K_{P2} - 3.2146K_{D2} \quad (19)$$

$$I_1 = -0.0062K_{P1} - 0.4015K_{I1} + 3.4014K_{D1} - 0.0062K_{P2} + 3.4014K_{D2} \quad (20)$$

The objective function '$f_{SPWPID}$' considered for obtaining the SPWPID controller parameter values ($K_{P1}$, $K_{I1}$, $K_{D1}$, $K_{P2}$ and $K_{D2}$) has the form same as the objective function considered for finding the PID controller parameter values *i.e.*

$$f_{SPWPID} = |R_1|^2 + |I_1|^2 \quad (21)$$

*B.3. Objective Function Optimization*

The objective function contains five unknowns $K_{P1}$, $K_{I1}$, $K_{D1}$, $K_{P2}$ and $K_{D2}$. But the values obtained in the PID controller design have been replaced in Equation (21), which reduces the number of unknowns from five to two. The objective function is then optimized using the TLBO. The range of these parameters considered for optimizing the objective function has been decided after a number of trial runs, and is provided in Table 4.

Table 4. Range of controller parameters considered for writing the MATLAB code

| Parameter | $K_{P2}$ | $K_{D2}$ |
|---|---|---|
| Lower range | -2 | -0.11 |
| Upper range | -1 | 0 |

After optimizing the objective function within the mentioned range of parameters, the values of $K_{P2}$ and $K_{D2}$ has been found and given in Table 5.

Table 5. SPWPID controller parameter values after optimizing the objective function

| Parameter | $K_{P2}$ | $K_{D2}$ |
|---|---|---|
| Value | -1 | -0.11 |

## 4. Results and Discussion

For this study, a square wave with a mean of -1.55 V has been considered as the input signal in order to operate the Maglev system around the neighborhood of the equilibrium point. The simulation diagram of the Maglev system with the PID and SPWPID controller is shown in Figure 4-5.

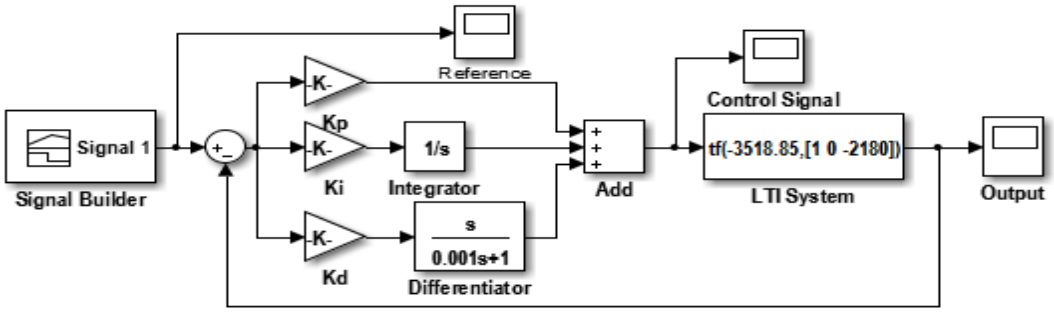



Figure 4. Maglev system with PID controller

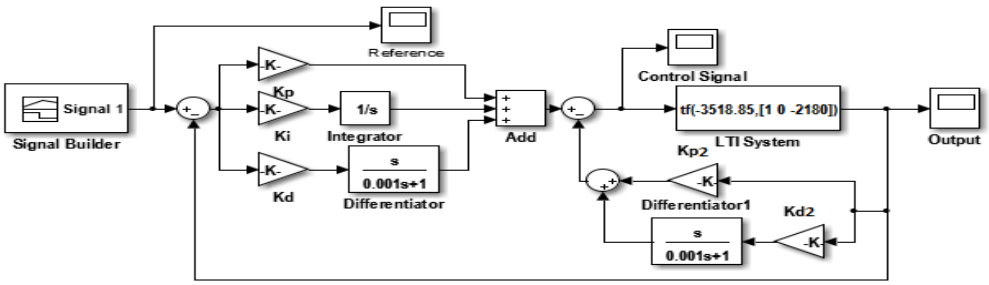



Figure 5. Maglev system with SPWPID controller

The simulation has been carried out for 50 seconds and the response of the simulation with the PID and SPWPID controller in Simulink has been provided in Figure 6.

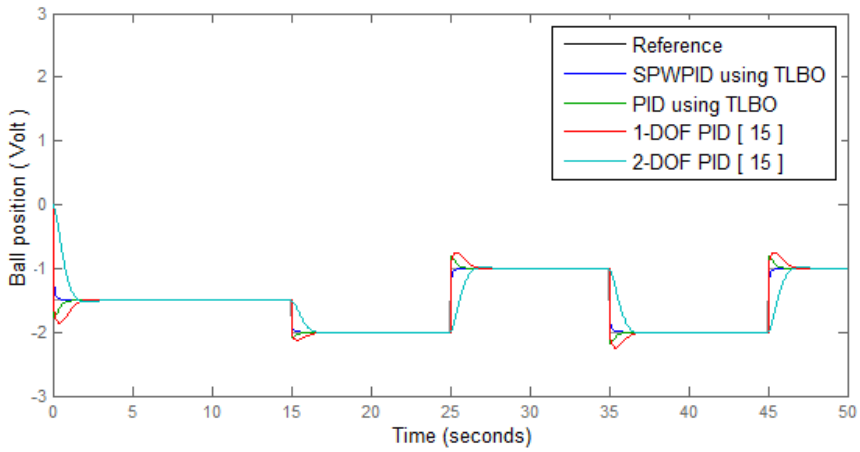



Figure 6. Simulink response of Maglev system with PID and SPWPID controller

For real time simulation the first 10 seconds have been used for compensating the disturbance encountered, due to hand positioning of the ball as well as inherent nonlinearities present in the

system. The response of the real time simulation of the Maglev system with different controllers is provided in Figure 7.

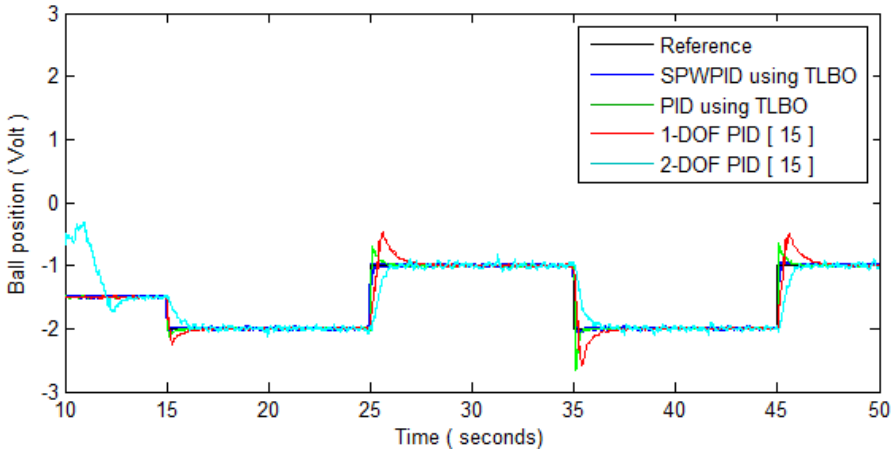



Figure 7. Real-time response of Maglev system with PID and SPWPID controller

The performance of the Maglev system with PID and SPWPID controllers in the simulation environment has been summarized in Table 6. The transient response specifications for 1 and 2 DOF PID controllers have also been determined by using the controller parameters given in [15].

Table 6. Comparison between PID and SPWPID Controller

| Controller | Maximum overshoot (%) | Settling time (sec) | Rise time (sec) |
|---|---|---|---|
| SPWPID using TLBO | Negligible | 0.369 | 0.137 |
| PID using TLBO | 18.3 | 0.811 | 0.00364 |
| 1-DOF PID [15] | 24.7 | 1.67 | 0.00158 |
| 2-DOF PID [15] | 1.51 | 1.50 | 0.988 |

From the data available in Table 7 and analyzing Figures 6 and 7, it has been found that the PID controller designed using TLBO provides better performance as compared to the 1-DOF PID controller as discussed in [15] and it has also been found that the SPWPID controller outperforms both the 1-DOF and 2- DOF PID controllers in term of the overshoot and settling time.

**5. Robustness Analysis**

In the presence of some noise, disturbance and parameter variation, if a system can hold its stability and satisfy some specific conditions, then the system is said to be robust. In this section, the robustness of the system with the SPWPID controller has been provided in terms of gain margin, phase margin and the iso-damping property. The robustness indices are given as:

$$|G_{PID}(jw_{gc}).G_p(jw_{gc})| = 1 \quad (22)$$

$$Arg(G_{PID}(jw_{gc}).G_p(jw_{gc})) = -\pi + \phi_{pm} \quad (23)$$

$$\frac{d(Arg(G_{PID}(jw_{gc}).G_p(jw_{gc})))}{dw} = 0 \quad \text{(Iso-damping property)} \tag{24}$$

where, $G_{PID}(jw_{gc}) = k_P + \frac{k_I}{jw_{gc}} + k_D\, jw_{gc}$, $G_p(jw_{gc})$ Plant transfer function, $w_{gc}$ = Gain crossover frequency, $\phi_{pm}$ = Desired phase margin.

It has been verified that the condition described in equations (22) and (23) is completely satisfied for the SPWPID controller with the Maglev system. The magnitude and phase plot of the open loop transfer function with the Maglev plant is shown in figure 8.

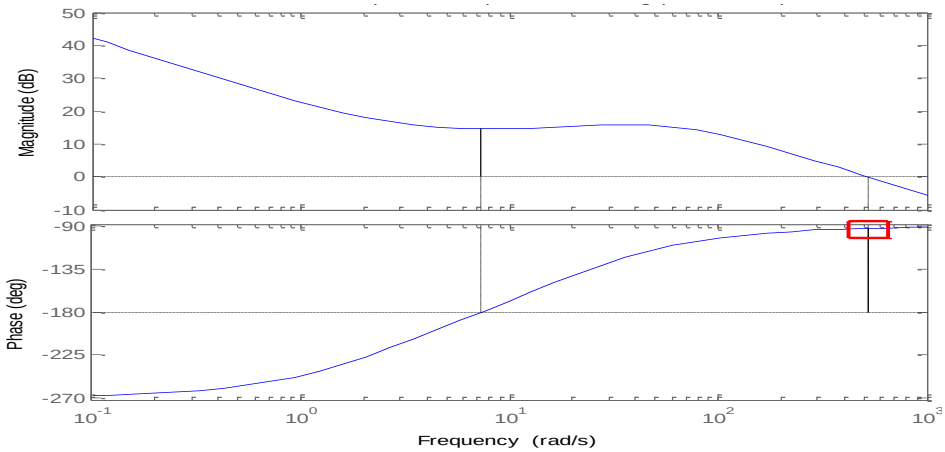
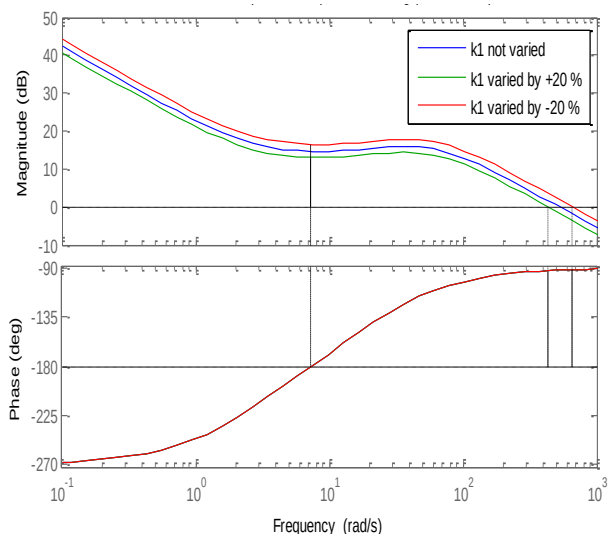



Figure 8. Bode Plot of Maglev system with SPWPID controller showing flatter phase curve (red box) around gain cross over frequency

It can be noted from Figure 8 that the open loop phase has a flatter phase curve denoted by a red box around the gain cross over frequency satisfying the iso-damping property. Further, from the Figures 9-10, it can be observed that as the coil current constant ($k_1$) and the sensor gain constant ($k_2$) vary between -20% and +20%, the open loop phase plot exhibits a flatter phase curve around the gain crossover frequency, ensuring a good loop robustness to model uncertainties. Table 7 shows the gain margin, phase margin, gain cross-over frequency and slope of the phase curve around the gain cross-over frequency (iso-damping condition) for the SPWPID controller with the Maglev plant.



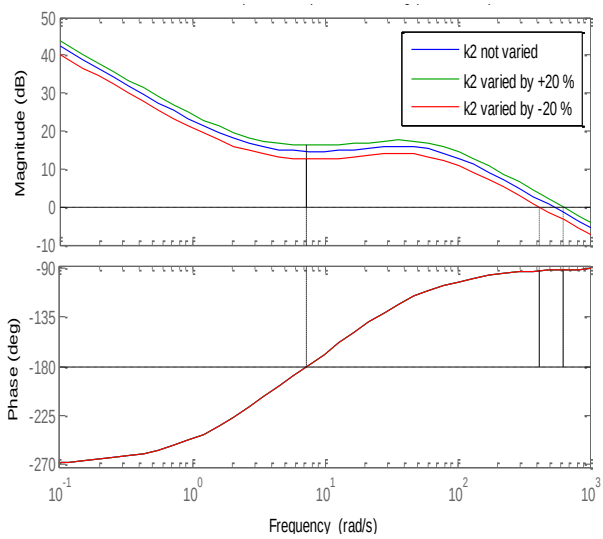



Figure 9 & 10. Bode Plot of Maglev system with SPWPID controller by varying $k_1$ and $k_2$ from -20% to +20%

Table 7. Robustness analysis of the Maglev system with SPWPID controller

| Gain Crossover Frequency ($w_{gc}$) in rad/sec | Gain Margin (db) | Phase Margin (degrees) | Slope of the phase angle around $w_{gc}$ (Iso-damping condition) |
|---|---|---|---|
| 524 | -14.6 | 87.5 | $9.6242*10^{-6} \approx 0$ |

It can be noted from Table 7 that the Gain margin is negative, but as the Phase margin is greater than the Gain margin, the system with the SPWPID controller is closed loop stable. The closed loop stability can also be verified by observing the location of all the closed loop poles. For our study, all the closed loop poles of the Maglev system with the SPWPID controller lie on the left half of the '*s*' plane and guarantee closed loop stability.

## 6. Conclusion

This paper addresses a realistic controller design by introducing a novel SPWPID controller for the Maglev system in simulation and real time. The recently evolved Teaching Learning Based Optimization (TLBO) has been used to identify the suitable controller parameter values by optimizing the objective function. The performance of the SPWPID controller is compared with that of the PID controller designed using TLBO. Moreover, the performance of the SPWPID controller has again been compared with the performance of the 1-DOF and 2-DOF PID controller designed for the same Maglev plant [15]. The result of the comparison shows that SPWPID controller outperforms both the 1-DOF and 2-DOF PID controllers in terms of overshoot and settling time. The robustness analysis has also been performed to demonstrate the robust behavior of the plant with the SPWPID controller. Future research work on this topic may include the design of the fractional order SPWPID controller which is expected to show an improved performance.

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