DESIGN OF GENETIC ALGORITHM TUNED PID CONTROLLER FOR AIR GAP CONTROL OF A MAGNETIC LEVITATION SYSTEM

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ABSTRACT

Magnetic levitation (maglev) systems offer high-speed, low-noise, and environmentally sustainable transportation solutions, but their performance critically depends on precise air gap control. This study presents the design of a Proportional-Integral-Derivative (PID) controller for a maglev train system, optimized using a Genetic Algorithm (GA). The system was modeled and simulated in MATLAB/Simulink, and controller performance was evaluated under reference tracking, disturbance rejection, and load variation scenarios. A comparative analysis was conducted against a conventional Ziegler–Nichols (ZN) tuned PID controller. Results show that the GA-tuned controller achieved a rise time of 0.0224s, settling time of 0.0631s, no overshoot, and steady-state error, outperforming the ZN-tuned controller which exhibited 13.74% overshoot and slower disturbance recovery despite a slightly faster rise time. Furthermore, the GA-tuned controller-maintained robustness under mass variation and rejected step disturbances within 0.023–0.050s, meeting design specifications. The findings demonstrate that GA optimization provides superior air gap regulation and robustness compared to conventional tuning methods, enhancing the reliability of maglev systems.

Keywords: Magnetic levitation, Proportional-Integral-Derivative, Genetic Algorithm, Ziegler–Nichols

1 INTRODUCTION

Magnetic levitation (maglev) is a method by which an object is suspended in the air with no support other than magnetic fields. The fields are used to reverse or counteract the gravitational pull and any other counter accelerations [1]. The magnetic levitation technology has been receiving increasing attention by researchers as its applicability is on the increase. Magnetically levitated systems possess advantages ranging from frictionless, no contamination, long life, high speed, low noise etc., [2]. Maglev technology has been researched and developed since the 1960s, especially in Japan and Germany [3]. Subsequent advancements made in the technology has made it possible to implement the high-speed rail transport system now found in advanced countries like Germany, Japan, France, Italy, China, United Kingdom, United states and so on with speed in excess of 400km/hr. These are undoubtedly the most advanced vehicles currently available in the railway industries [4]. The maglev as one of the promising advanced technologies of the day can be made use of in various fields, including, transportation systems (magnetically levitated train), nuclear engineering (the centrifuge of nuclear reactor), civil engineering (elevator), and so on [4]. Similarly the phenomena of maglev has also been used in aspect of food and water analysis, a versatile technique based on magnetic levitation for characterizing and distinguishing a variety of materials on the basis of their density [5].There are a number of advantages derived from contactless nature of maglev system, some of which includes: absence of wear and tear due to friction, reduced maintenance cost, increased efficiency and environmental friendliness (no emission of greenhouse gases) etc. A study carried out by [3], showed that the maglev train system is about 4 - 8dB quieter than other high-speed systems. Furthermore, with the lingering global energy and environmental pollution control crisis, maglev can be seen to be the future means of transport. In view of the highlighted milestone achievements in the application of maglev system in transportation, which according to [6] demonstrated that the system provides fast, safe, comfortable, and efficient transportation over a wide speed range. Presently this means of transport where it's been utilized, is majorly for intercity passenger movements while the fossil fuel powered heavy-duty trucks still dominates freight transportation. In most major cities of especially developing countries the vehicle fleets are quite old and poorly maintained [7]. The world energy crises and global warning call for a reduction of energy consumption. High speed rail,increasingly viewed as an effective solution to inter-city passenger transportation challenge of the twenty first century [8]. and hence there is need to further look at the possibilities of utilising the technology for freight transport.

2 MATERIALS AND METHODS

Consider a simple magnetic levitated train system shown in Figure 1. The system includes a train boggy, electromagnet, permanent magnet, controlling circuit, driving circuit and displacement sensors. The output controller tries to improve the magnetic force against the gravitational force and external disturbances. This is achieved by controlling the current through the electromagnet to maintain a constant distance between the bogie and rail.

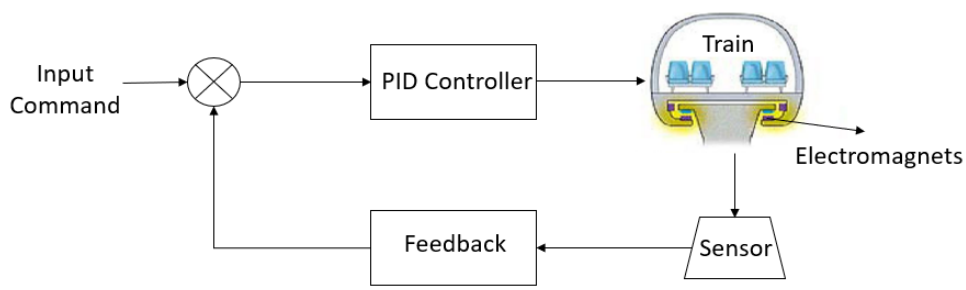


Figure 1. Schematic drawing of the magnetic levitation system.

To derive the model of a maglev train, let us consider the levitation dynamics governing the system based on the following assumptions: The train is treated as a rigid body. Magnetic forces are modelled using electromagnetic principles. Disturbances (like track irregularities) may be considered as external inputs. The train's vertical dynamics depend on displacement$y$, velocity$\dot{y}$, and current$I$. The magnetic force F_m is proportional to I^2 and inversely proportional to y^2. The position and the motion of the train in the magnetic field are dependent on the forces acting on it. These forces are the gravitational force, electromagnetic force and the disturbance force. The dynamic equation of the maglev system is derived as follows [9, 10].

$$m\ddot{y} = F_m - F_g + F_d \tag{1}$$

Where: m: Mass of the train, y: Vertical displacement or airgap between train and track, F_m: Magnetic force, $F_g = mg$: Gravitational force, F_d: Disturbance force. The magnetic force is given by:

$$F_m = k\frac{I^2}{y^2} \quad (2)$$

Substituting (2) into (1) gives:

$$m\ddot{y} = k\frac{I^2}{y^2} - mg + F_d \quad (3)$$

From the current dynamics:

$$L\frac{dI}{dt} + IR = V \quad (4)$$

Rearranging equation. (12) Gives:

$$\dot{I} = -I\frac{R}{L} + \frac{1}{L}V \quad (5)$$

Linearizing around the equilibrium points $y_0,\ \dot{y}_0 = 0,\ I_0\ and\ V_0$.

$$F_m = k\frac{I^2}{y^2} \approx \frac{2kI_0}{y_0^2}\Delta I - \frac{2kI_0^2}{y_0^3}\Delta y \quad (6)$$

Substituting into the equation. (3) Gives:

$$m\Delta\ddot{y} = \frac{2kI_0}{y_0^2}\Delta I - \frac{2kI_0^2}{y_0^3}\Delta y + F_d \quad (7)$$

Also linearizing equation. (5):

$$\Delta\dot{I} = \Delta I\frac{R}{L} + \frac{1}{L}\Delta V \quad (8)$$

Using the state-space representation. We define the state variables and the control input as:

$$x_1 = \Delta y, x_2 = \Delta\dot{y}, x_3 = \Delta I, u = \Delta V$$

The state equations become:

$$\dot{x}_1 = x_2 \quad (9)$$

$$\dot{x}_2 = \frac{1}{m}\left(\frac{2kI_0}{y_0^2}x_3 - \frac{2kI_0^2}{y_0^3}x_1 + F_d\right) \quad (10)$$

$$\dot{x}_3 = -\frac{R}{L}x_3 + \frac{1}{L}u \quad (11)$$

Equations (9) – (11) in state-space form is:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ -\frac{2kI_0^2}{my_0^3} & 0 & \frac{2kI_0}{my_0^2}\\ 0 & 0 & -\frac{R}{L}\end{bmatrix}\begin{bmatrix}x_1\\ \\ x_3\end{bmatrix}\begin{bmatrix}0\\ \frac{1}{m}\\ 0\end{bmatrix}F_d \quad (12)$$

2.1 Stability Analysis of the Maglev System

The stability of the system model in equation (12) can be assessed depending on the location of the poles of the system in the complex plane (s-plane). Another method is to calculate the eigenvalues of the state-space system matrix A. The stability of a system depends on the eigenvalues of the system's state-space matrix in (12): If all eigenvalues have negative real parts (i.e., they are in the left half of the complex plane), the system is stable. If any eigenvalue has a positive real part, the system is unstable. If any eigenvalue has a zero real part but no eigenvalue has a positive real part, the system is marginally stable.

2.2 PID Control for Vertical Displacement of the Maglev Train

One of the critical control objectives in a maglev system is maintaining the vertical displacement of the train, which is crucial for both the safety and performance of the system. The train must be levitated at a constant height above the track to ensure smooth and efficient operation. This height is controlled by adjusting the magnetic forces that counteract the gravitational pull on the train. A PID controller is commonly used for such control systems due to its simplicity, effectiveness, and ease of implementation. The PID controller aims to regulate the vertical displacement of the maglev train by adjusting the levitation forces in response to changes in the train's height. The control law for the PID controller is given by:

$$F_{lev}(t) = K_p . e(t) + K_i \int_0^t e(t)dt + K_d . \frac{d}{dt} e(t) \tag{13}$$

Where: $e(t) = y_{ref}(t) - y(t)$ is the error between the reference vertical displacement $y_{ref}(t)$and the actual displacement $y(t)$. The PID control law acting on the Maglev system is shown in Figure 2.

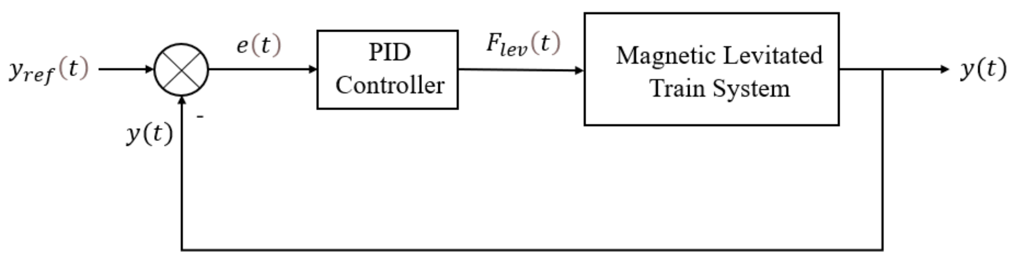


Figure 2. Control of Maglev using PID Controller

2.3 Objective Function for PID Tuning

The performance of the PID controller is evaluated by an objective function that quantifies how well the controller minimizes the displacement error while maintaining the system stability and performance. In this research, the objective function used for tuning PID parameters is based on the Integral of Time by Absolute Error (ITAE). The objective function for PID tuning is defined as:

$$J_{obj} = \int_0^T t|e(t)|dt \tag{14}$$

Where: T is the simulation time, by minimizing the objective function (ITAE), the system reduces both the steady-state error and the transient response. This ensures that the maglev train quickly and accurately reaches the desired height without excessive oscillations or delays. The PID controller must also strike a balance between fast responses (minimizing settling time) and avoiding large overshoots.

2.4 PID Control Tuning using Genetic Algorithm (GA)

To find optimal values for the PID parameters, the objective function is minimized using Genetic Algorithms Optimization. GA is selected in this research because it has the ability to perform a global search for the optimal PID parameters. Conventional optimization methods, such as gradient-based techniques are iterative where the same calculations are repeated in every iteration. In such approaches, initial design is estimated and is improved until optimality conditions are satisfied [11, 12]. However, such techniques are prone to getting stuck in local minima. This limitation is significant when dealing with complex and nonlinear systems like the Maglev control where the objective function may have multiple local optima. The optimization process involves: Generating candidate PID parameters. Simulating the maglev system with the candidate PID controllers. Calculating the objective function for each set of parameters. Selecting the best-performing parameters based on the smallest value of the objective function. This process is illustrated in the flow chart shown in Figure 3.

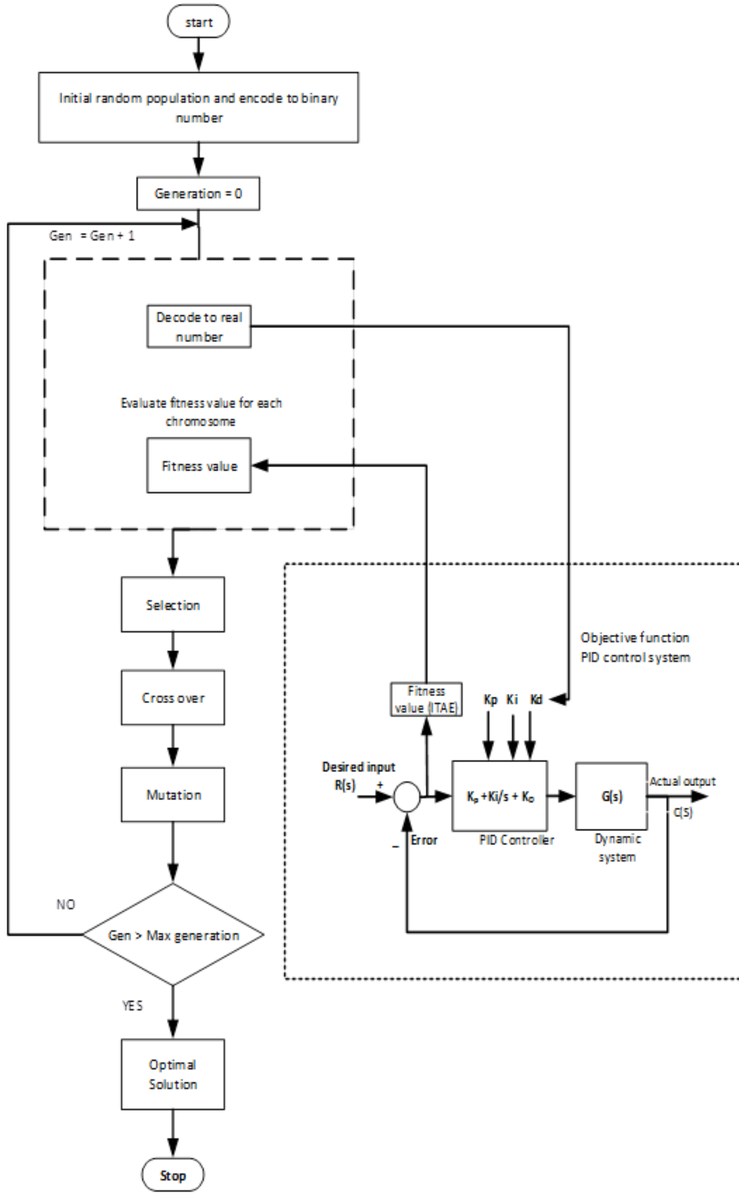


Figure 3. Genetic Algorithm Flowchart for PID parameter Tuning

3 RESULTS AND DISCUSSION

In this section, the results of simulations of the maglev train system under the PID control strategy are presented and discussed. The chapter evaluates the effectiveness of the tuned PID controller using Genetic Algorithms for controlling the vertical displacement of the maglev train. Various performance metrics, such as tracking error, overshoot, settling time, and system stability, are presented. These results are analyses to assess the impact of the PID tuning on the system's behavior. In addition, a comparison between the GA-tuned PID controller and traditional tuning method using Zeigler Nichol’s method is provided to highlight the advantages of using Genetic Algorithms in optimizing the PID parameters.

3.1 Open-Loop Response and Stability Analysis of the Maglev System

For simulating the Maglev system, the parameters given in Table 1 are used. Substituting the parameters into equation (20), the open-loop response of the system to a step input signal and the poles/zeros positions were obtained and the corresponding response is shown in Figure 4.

Table 1: Parameters of the Maglev System [13]

Parameter	Value
Bogie mass ($\boldsymbol{m}$)	$5000kg$
Gravitational force ($\boldsymbol{g}$)	$9.81m/s^2$
Initial vertical displacement ($\boldsymbol{y_0}$)	$0.015m$
Magnetic force constant ($\boldsymbol{k}$)	2.04
Initial current ($\boldsymbol{I_0}$)	$42A$
Inductance of the coil ($\boldsymbol{L}$)	$280nH$
Resistance of the coil ($\boldsymbol{R}$)	$300\text{k}\Omega$

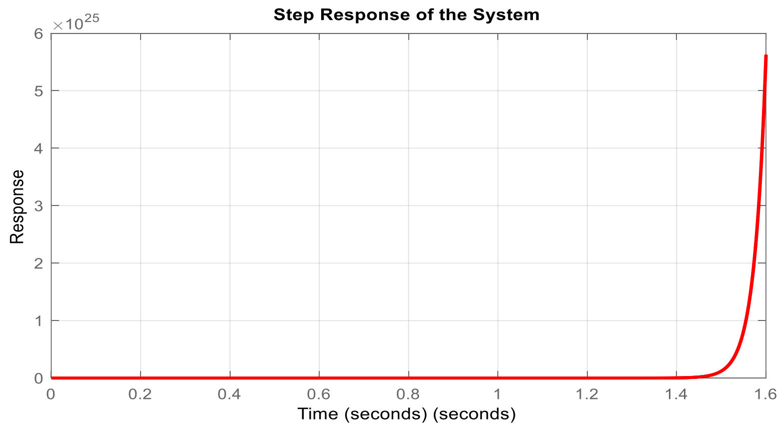


Figure 4. Open-loop step response of the maglev system

The result in Figure 4 clearly shows that the system is unstable as the amplitude of the displacement moves out of control indicating a strong reaction to the step input. The response suggest that the system is over damped or critically damped. Since the system's stability depends on the location of its poles in the complex plane (s-plane). The eigenvalues of the system matrix **A** in equation (20) give the poles of the system as follows: $p_1 = -132.5005$, $p_2 = 38.3530$ and $p_1 = -38.3526$. The system has a positive real part, so it is unstable.

3.2 Closed-Loop Respond with ZN-Tuned PID controller

The complete Simulink model of the maglev system with the controllers included is shown in Figure 5. The closed-loop step response simulation of the system with a PID controller tuned using the Zeigler-Nichol's method was first run in MATLAB and the response is as shown in Figure 6.

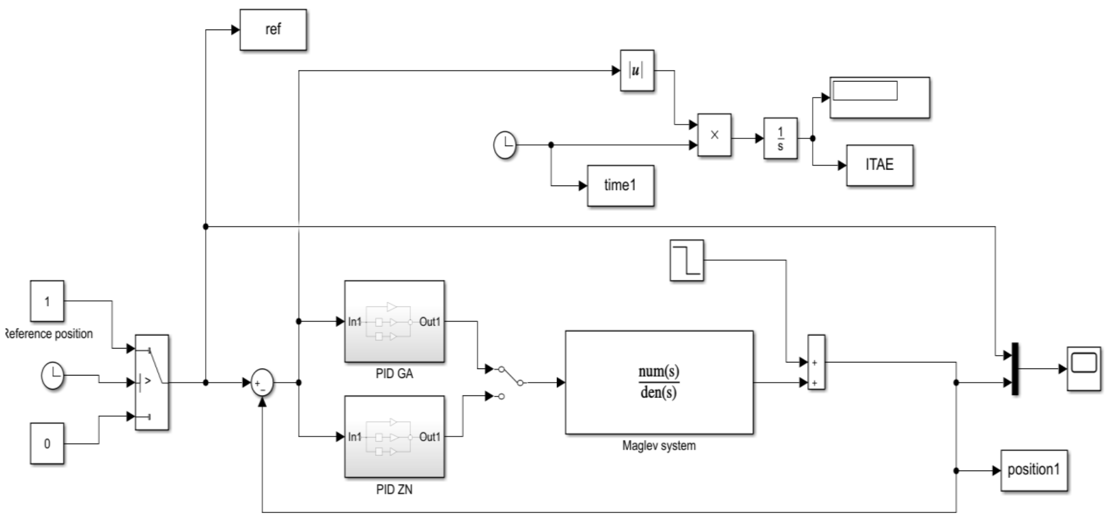


Figure 5. Simulink model of Closed-loop block diagram of the controlled system

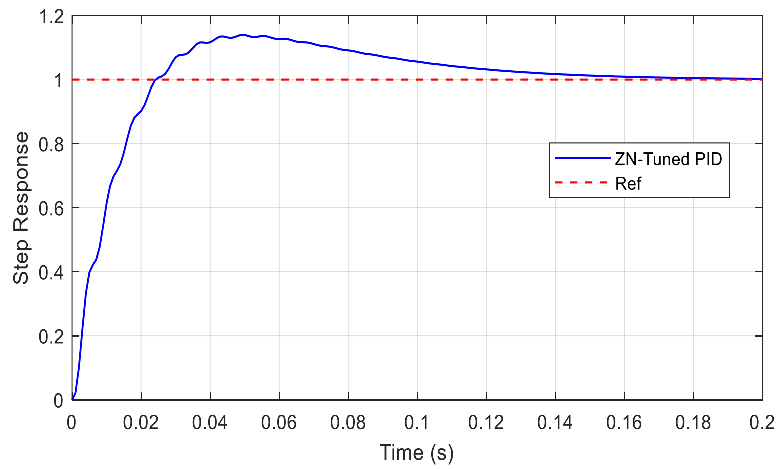


Figure 6. Closed-loop step response of the system with ZN-tuned PID controller

Table 2 summarize the characteristics of the response and also shows the tuned PID parameters, the rise time, settling time as well as the steady state value. The response showed that the system settled in good time, which was within the simulation time of 0.2sec. However, there is an undesirable overshoot of over 12%.

Table 2: PID parameters and the response characteristics without disturbance

PID Parameters			Rise Time (s)	Overshoot	Settling Time (s)	Steady-state Value
K_p	K_i	K_d				
120	2400	1.5	0.000588	1.236	0.1872	1.0

3.3 PID controller tuning with GA

The use of GA to optimize the PID controller gains requires generating an initial population consisting of individuals with better quality [14].which are subsequently used by the optimization algorithm to search for the best solution in the solution space [15].Therefore, the controller gains value produced by the Zeigler-Nichols tuning method shall be adopted as the initial population. This is to ensure convergence of the GA does not take longer period to generate optimal solution. In view of the above the MATLAB codes were run to evaluate the objective function and the PID controller gains in three iterations for each parameter to test the repeatability of the algorithm and the ability to converge at an optimal solution with small or no variation. The results for the average value of each parameter are shown in Figure 7. The GA optimized average controller gains values are: 1479, 11.7688 and 20.8723 for K_p, K_i and K_d respectively.

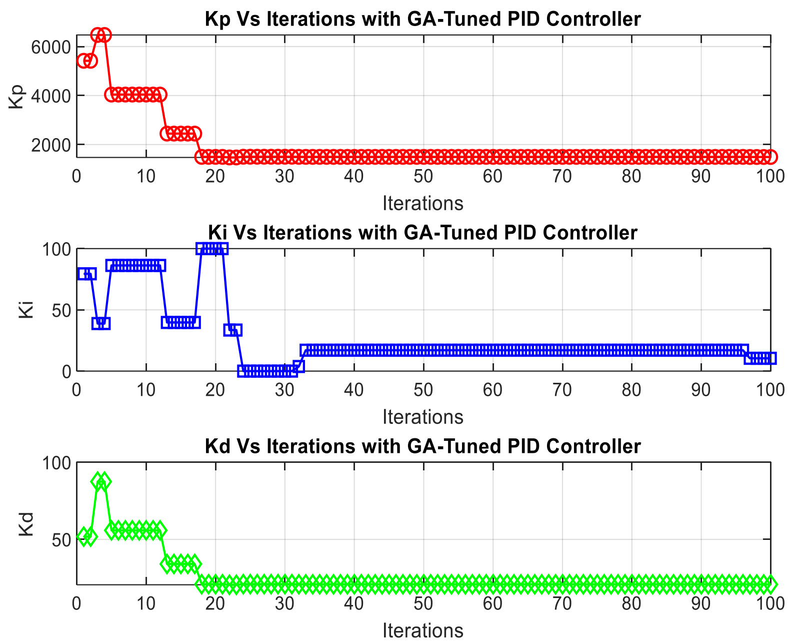


Figure 7. Convergence of PID parameters through generations

The average optimal controller gains values were used in the Simulink model to compare the system response to a step signal for both the Zeigler-Nichols and GA tuned controller and presented in Figure 8.

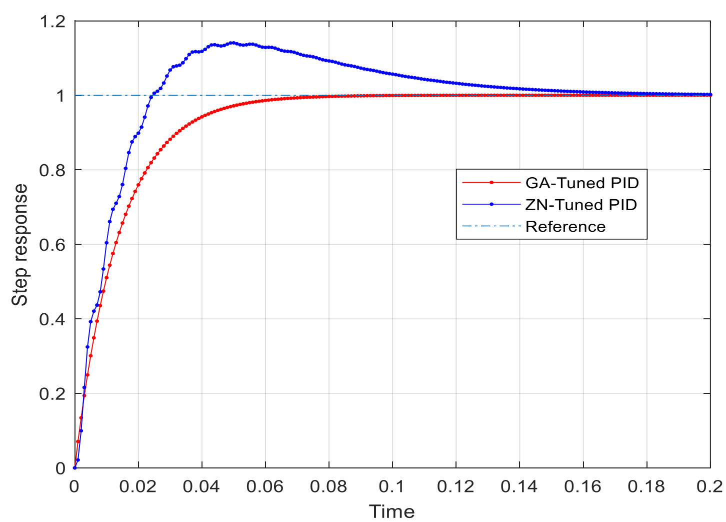


Figure 8. Step response of the system ZN tuned vs. GA tuned PID controller

The system response produced by the GA-tuned PID controller clearly showed that undesired overshoot in the system was removed as compared to the ZN-tuned PID controller. Table 3 shows result of the comparative step response of the system between the ZN-tuned and the GA-tuned PID controller. The results indicated a better response from the GA-tuned controller with zero percent (0%) overshoot and a faster settling time.

Table 3: ZN vs. GA tuned PID parameters and the response characteristics

Characteristics	GA-Tuned PID	ZN-Tuned PID
Rise Time (s)	0.0224	0.0172
Settling Time (s)	0.0631	0.1648
Overshoot (%)	0.0000	13.7400
Peak Amplitude	1.0000	1.1374
Peak Time (s)	0.0810	0.0473
Steady-State Value	1.0000	1.0000

3.4 Comparative controller reference tracking

The ability of the controllers to track and maintain the reference air gap of 0.015m (15mm) was investigated by toggling the step signal from a value of 1 down to 0.015 instead of going back to zero (0). The result in Figure 9 indicated that the GA-tune PID was able successfully track the reference air gap as compared to the ZN-tuned PID controller.

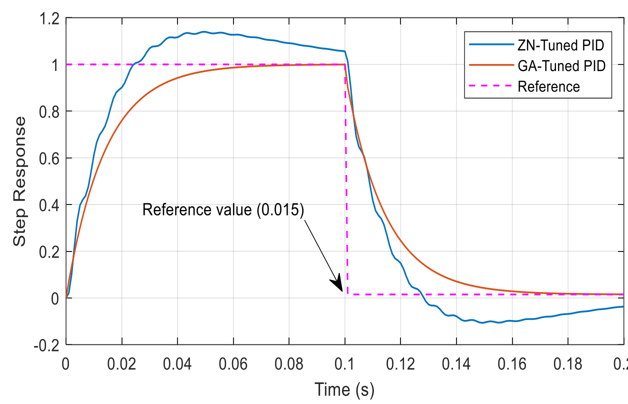
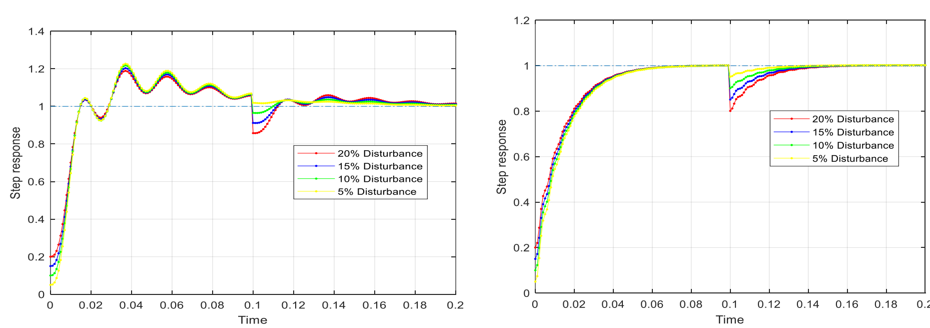


Figure 9. Comparison of GA-Tuned PID vs. ZN-Nichols reference tracking

3.5 System sensitivity to disturbance

To test the system sensitivity to disturbance (aerodynamic drags, track irregularities etc.), a percentage of the step signal (in intervals of 5%) was introduced after 0.1s at the output in the Simulink model for both ZN-tuned and GA-tuned PID controller. See results in Figures 10a and 10b respectively.



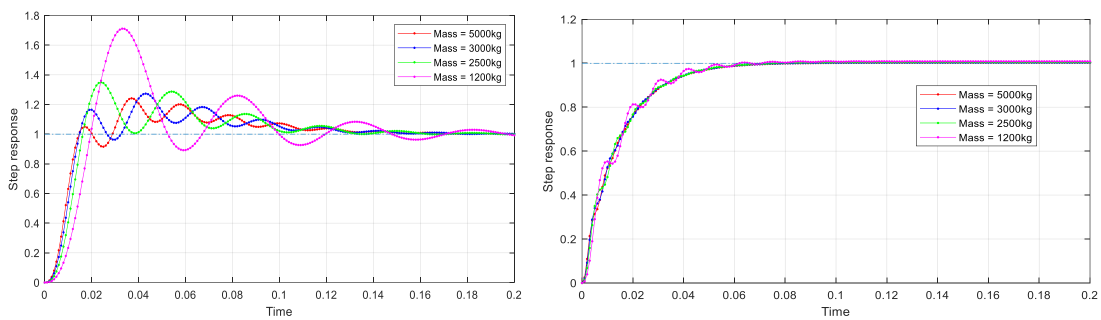
(a) (b)

Figure 10. ZN and GA-Tuned PID controller Disturbance rejection (a) ZN-Tuned PID (b) GA-Tuned PID

The ZN-tuned controller clearly indicated high sensitivity to disturbance from 5% of the step input to 20% of the step input the system could not reach a steady state value throughout the simulation period with overshoots at various intervals. The GA-tune controller on the other hand produced a better response and was able to reach steady state within the simulation time. A closer look at the response curves at maximum of 20% of the step signal further showed the GA-tuned controller still outperformed the ZN-tuned controller. The GA-tuned controller however produced a slightly extended settling time compared to lower value produced by the ZN-tuned controller for the disturbance (e.g. 5%, 10% and 15%).

4.6 Robustness to Changes in Mass ZN-Tuned PID vs. GA Tuned PID

The maglev system analysis is usually considered as a fixed mass in most cases, however in this study the robustness of the PID controller using both the ZN and GA tuning methods were evaluated by varying the levitated load. The minimum and maximum loads considered were 12 tons and 50 tons, which were scaled down by a factor of ten (10); hence the values used in the simulations were in the range of 1200kg to 5000kg. The corresponding system responses to changes in mass are presented in Figure 11a, and Figure 11b. The results clearly showed that the GA-tuned PID controller greatly outperformed the ZN-tuned PID controller irrespective of mass considered within the range of interest.



(a) (b)

Figure 11. Controller Robustness to Change in Mass (a) ZN-Tuned PID (b) GA-Tuned PID

4 CONCLUSIONS

In this paper, genetic algorithm optimized PID controller for the control of air gap for magnetically levitated system was presented. Classical Ziegler-Nichola tuned PID controller and a GA tune PID controller were designed, modelled and simulated using MATLAB/SIMULINK package. These controllers were then evolved to control the air gap of a magnetically levitated system to a desired set point. Various test and analysis including air gap reference tracking, disturbance rejection, and controller robustness to load variation were carried out. The systems' Performance evaluation was carried to access the comparative advantage between ZN- tuned PID and the GA tuned PID controller. The GA-tuned PID controller has a rise time of 0.0224s, settling time of 0.0631s, overshoot of 0.0% and steady state value of 1.0 as against conventional ZN-tuned PID controller which had a rise time of 0.0172s, settling time of 0.1648s, overshoot of 13.74% and steady state value of 1.0 respectively. The GA-tuned controller outperformed the classical ZN-tuned controller in all parameters with the exception rise time. Furthermore, it proved to be capable tracking the reference air gap of the system effectively as compared to the ZN tuned controller. In terms of ability counter external disturbance and return the system response to steady state, the ZN- tuned PID controller could not meet up with desired specification. The GA-tuned PID controller on the other hand was able recover in 0.023s at 5%, 0.032s at 10%, 0.042s at 15% and 0.050s at 20% of step input signal disturbance, which all within the specified simulation. Similarly, performance evaluation of the controllers in respect of variation in mass clearly indicates that GA-tuned controller still plays a better role in maintaining the system response within the desired set point.

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