Maglev Report

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1. Aim:

To design a controller for maglev system to meet the following specifications:

a) Closed loop system is asymptotically stable.
b) Steady state error with respect to step input (e_{ss}) = 0
c) Settling time (t_s) = 3s
d) % overshoot < 10

2. Summary:

The project's objective is to design a controller for magnetic levitation system using a linearized model. The pre-lab portion included the individual design and assessment of controller to meet the specifications, by assessing it in a basic linear model and linearized model equivalent to the actual physical model. Based on the specifications, it was clear to go ahead with PID controller and various iterations led to an initial controller design with the zero placement in OLHP. The same controller, when applied to the physical system destabilized the system after 10s of step input. After iterations during the experiment, we came up with the final controller design. A pre-compensator was used in all the iterations to compensate for the additional zeroes introduced by the controller gain.

3. Controller Design

3.1 Pre-Lab:

The plant details and specifications of the controller is given in the project description. Our approach to the controller design includes,

- The placement of zeroes in the admissible region,
- Equating zeroes equation to gain equation,
- Selection of master gain from Root Locus,
- Finding controller gains,
- Finetuning the controller.

3.1.1 Pre-Lab calculations:

The plant is given by

$$P(s) = \frac{-3734}{s^2 - 2180}$$

First, Damping Coefficient and Natural Frequency was found from the Transient specifications.

% overshoot (PO) < 10%

$$PO = 100 \cdot e^{\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\right)}$$

which gives $\zeta > 0.59069$

For ease of calculation, we have taken $\zeta = 0.707 \therefore \theta = 45°$ to satisfy the condition of maximum overshoot < 10%,

$$t_s = 3 \text{ seconds} = \frac{3.2}{\zeta \omega_n}$$

which gives $\omega_n = 1.51$ rad/s.

Our team used a PID controller due to following reasons

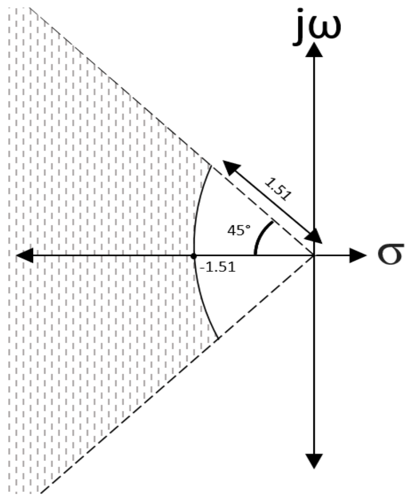
1. Integrator part for achieving 0 Steady State Error w.r.t. step input.
2. Derivative part to stabilize the plant and to induce dissipation to compensate for the missing 's' term.
3. Proportional part to induce dissipation to compensate for the negative free term.

$$\text{PID controller } G_c(s) = \frac{K_P s + K_I + K_D s^2}{s}$$

Following the approach 1 in PID design, the PID controller can be written as

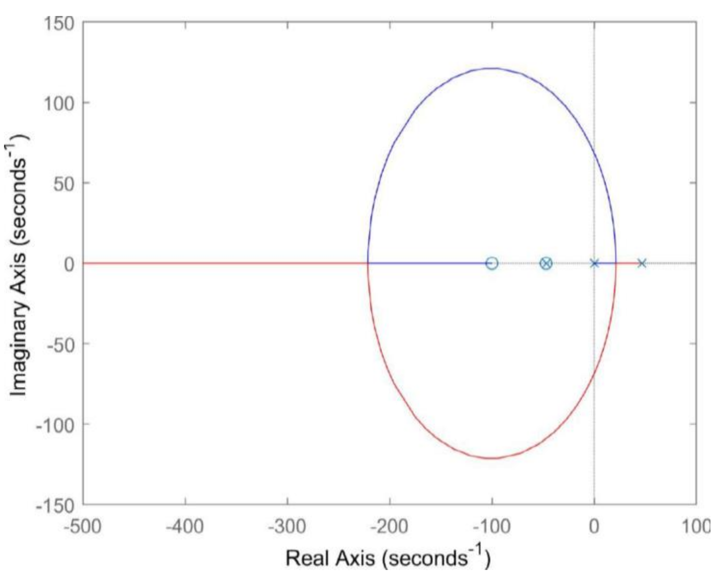
$$\text{PID controller } G_c(s) = K_D \times \left(\frac{\frac{K_P}{K_D} s + \frac{K_I}{K_D} + s^2}{s} \right)$$

Zeros were selected in the admissible region so that any unstable poles will move to the admissible region as we increase the Gain. The admissible region is shown as shaded below:



Initially, the zeroes were taken as - 40±10j. The resultant gains of PID controller is mentioned below:

Kp	Ki	Kd
-3.32084	-70.5678	-0.04151

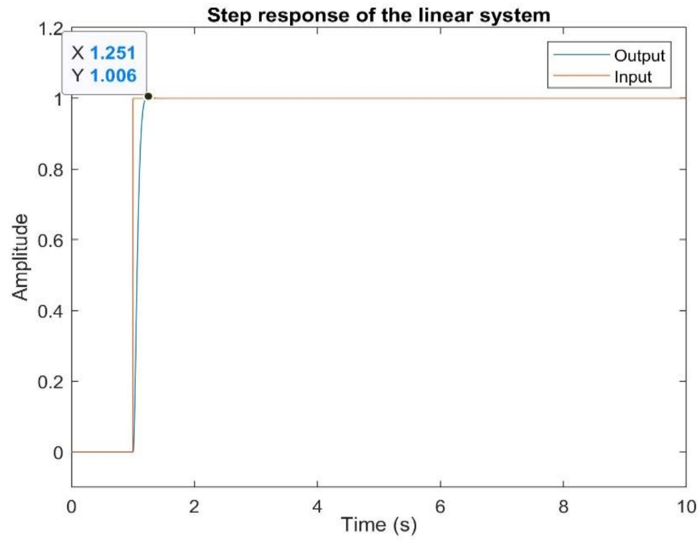


4. Closed-Loop System Performance Analysis

4.1 Simulation studies:

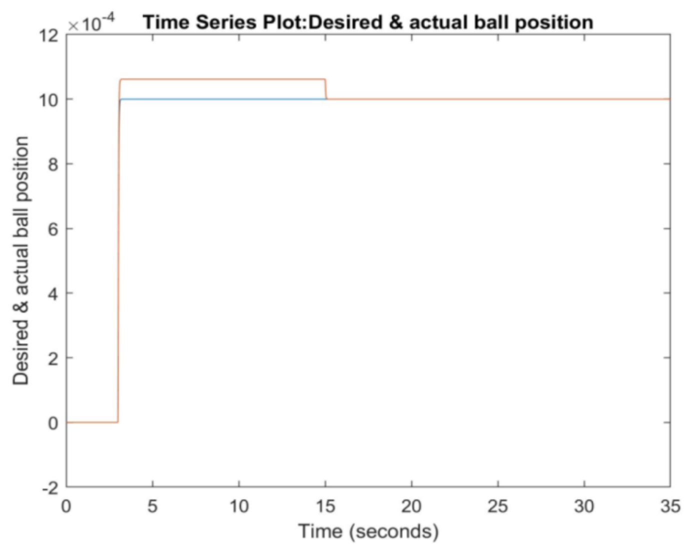
4.1.1 Linear Plant model:

1. There was no Steady State Error.
2. Settling Time was less than 3s.
3. Overshoot was 0.6%.



4.1.2 Non-linear plant model:

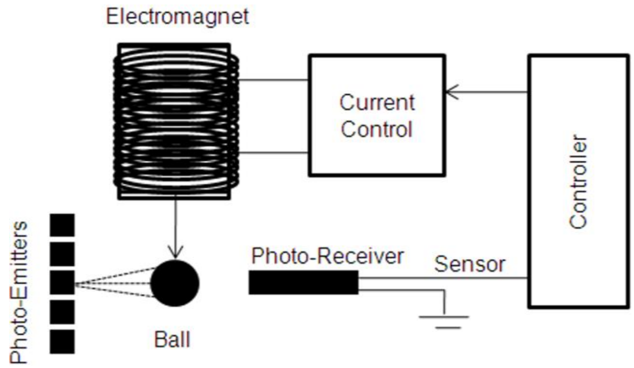
1. There was no Steady State Error
2. Output quickly reached the desired value.
3. Settling time was very less.
4. Overshoot was within the desired specifications.



The initial constant overshoot for 15 seconds is due to the anti-integrator windup property of the lab integrator block. Once the integrator becomes operational after 15 seconds, the system comes to 0 steady state error.
The offset in the output response of non-linear system for the initial 15 seconds, is due to the compensation provided to overcome integral windup. Integral windup is a phenomenon in PID feedback controller where a large change in setpoint (input) makes the integrator to accumulate error during rise, thus causing overshoot.

4.2 Experimental studies:

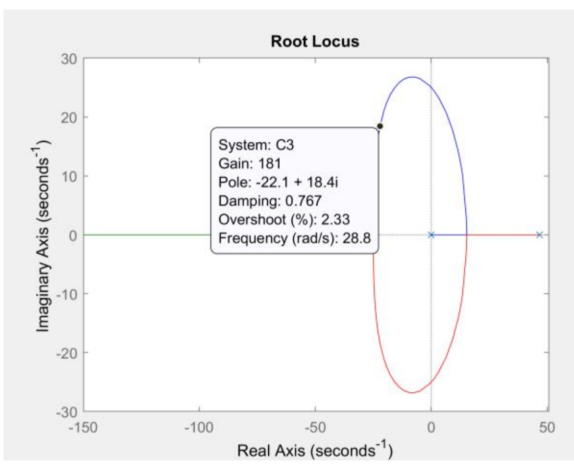
4.2.1 Experimental setup: The MAGLEV setup consists of three primary components – The sensor, the actuator and the controller.
Sensor - The sensor system is an infrared emitter-photodetector pair. A constant voltage is sent to the IR emitter which sends out a beam of infrared light that is detected by the photodetector.
Actuator - It is an electromagnet that enables levitation of the ferrous balls by adjusting the current in the coil wrapped around a steel core.
Controller - It takes the feedback from the sensor to adjust the current in electromagnet to levitate the ball.



4.2.2 Physics of Operation: The photodetector output is directly proportional to the amount of IR light it senses. If there is no object under the coil, the photodetector output will be at its maximum value with the detector fully sensing the light coming from the emitter. When the ball is placed under the coil, the magnetic field draws it towards itself. As this happens, the ball starts to block the IR light sensed by the photodetector. This causes the output of the detector to decrease, current through the coil decreases, the ball falls, the detector begins to sense more light from the emitter and its output increases and the coil begins to pull the ball up again. The controller tunes the switching process so that it appears as though the ball is floating/levitating in mid-air.

5. <u>During lab (Performance of the controller on the actual Maglev hardware)</u>

On the actual Maglev system, our controller designed using the simulations was stable, but became unstable as the time progressed. Hence, we changed our controller in the lab.
Upon application of PID controller, the physical system became stable, but the high integrator gain destabilized the system after 10s of step input. So, we relocated the zeroes in such a way that the master gain decreases thereby decreasing the controller gain values.



5.1 Choice of the pre-compensator: Poles were introduced such that it negates the effect of zeros introduced by the PID Controller and DC gain of the pre-compensator is 1. Using this approach for the Pre-compensator helped us in reducing the Maximum Overshoot.

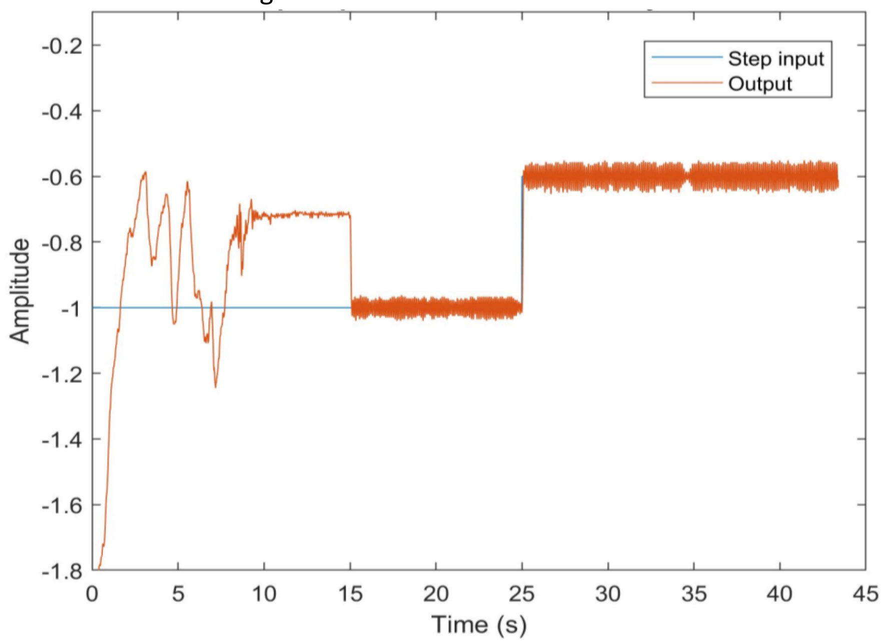
Pre-compensator Transfer Function = $\frac{K_I}{K_D s^2 + K_P s + K_I} = \frac{-30.1768}{-0.048s^2 - 2.41028s - 30.1768}$

Our revised zeroes were - 25±i. The new controller was

Kp	Ki	Kd
-3.32084	-70.5678	-0.04151

5.2 Fine-tuning of the controller:

The controller upon application started to give horizontal oscillations of higher amplitude. Step response of the linearized system with initial controller design:



This necessitated the decrease of K_I gain to reduce the oscillations to admissible level. Final revised K_I value is -25.

The settling time and overshoot of this controller were acceptable, but the system had high frequency vibrations and was not settling down. Hence, we had to modify our controller again.
The finalized controller after fine-tuning was

Kp	Ki	Kd
-2.41028	-30.1768	-0.04821

The results with this controller were satisfactory.

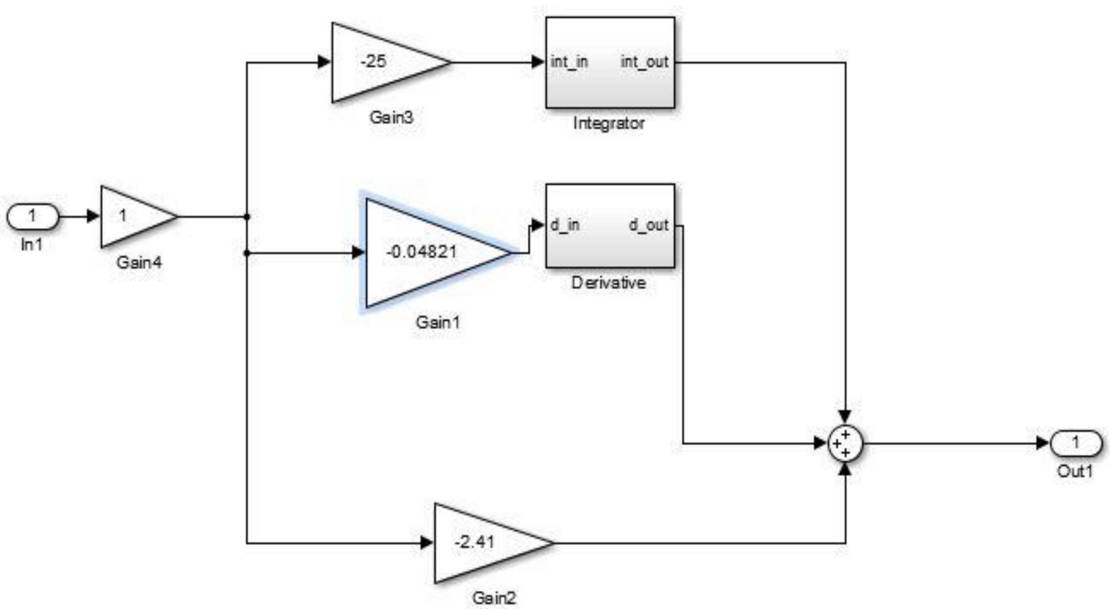


Figure. PID controller block diagram.

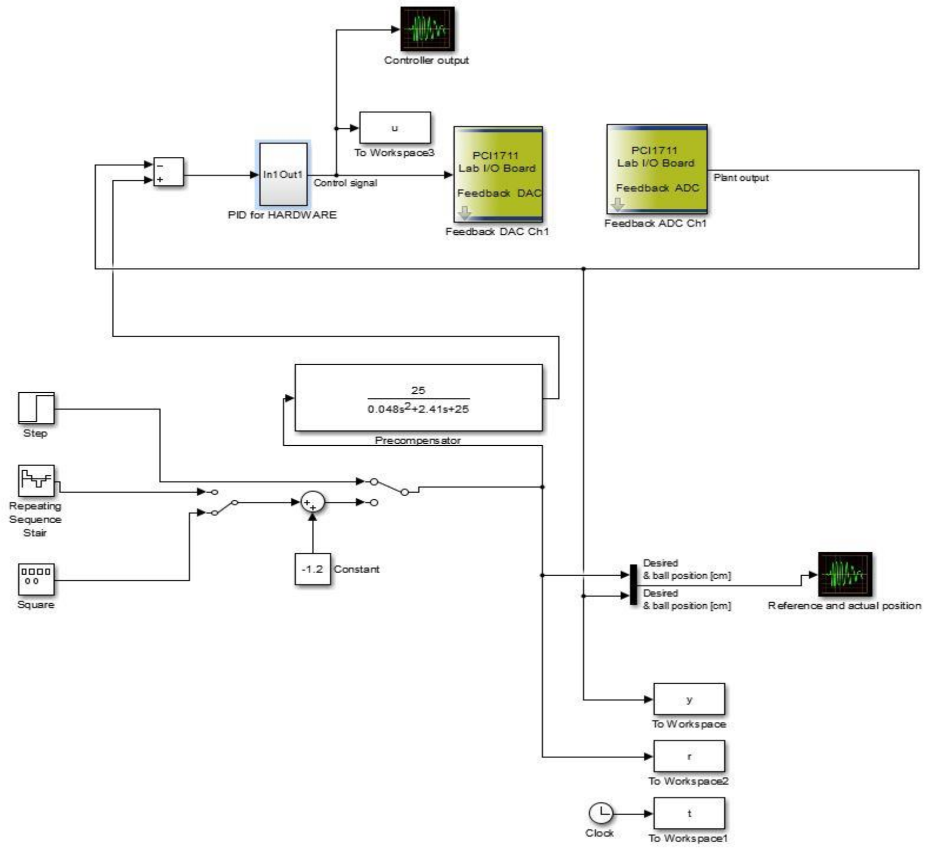
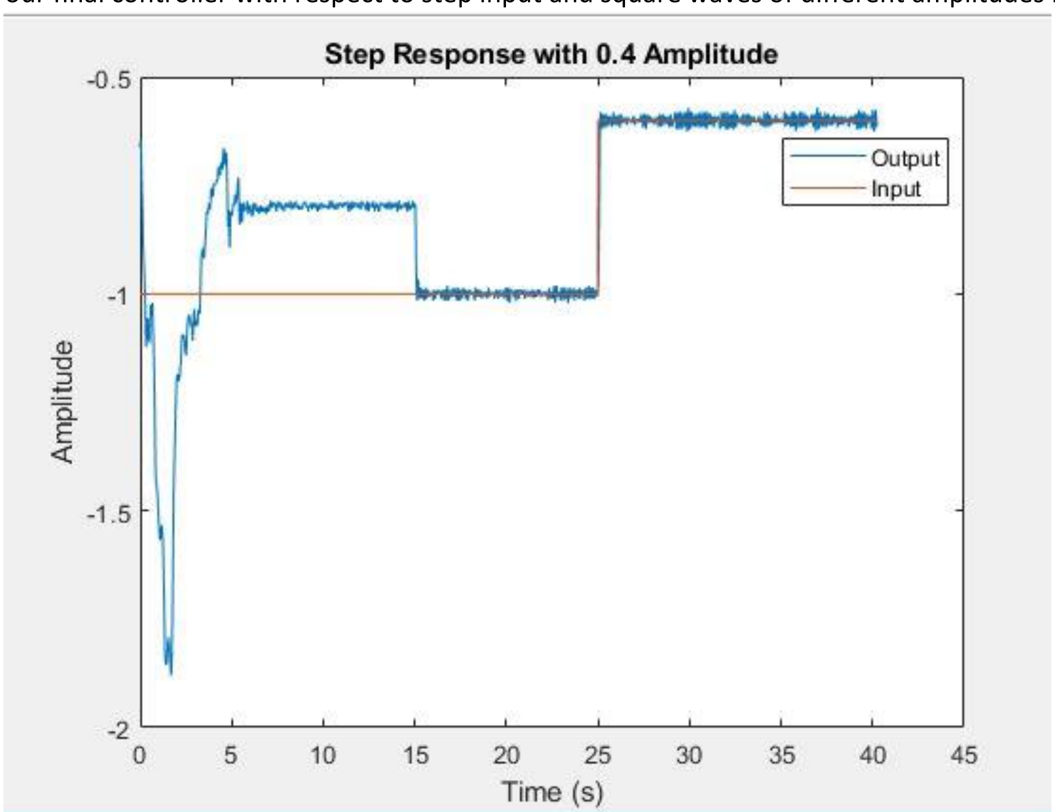


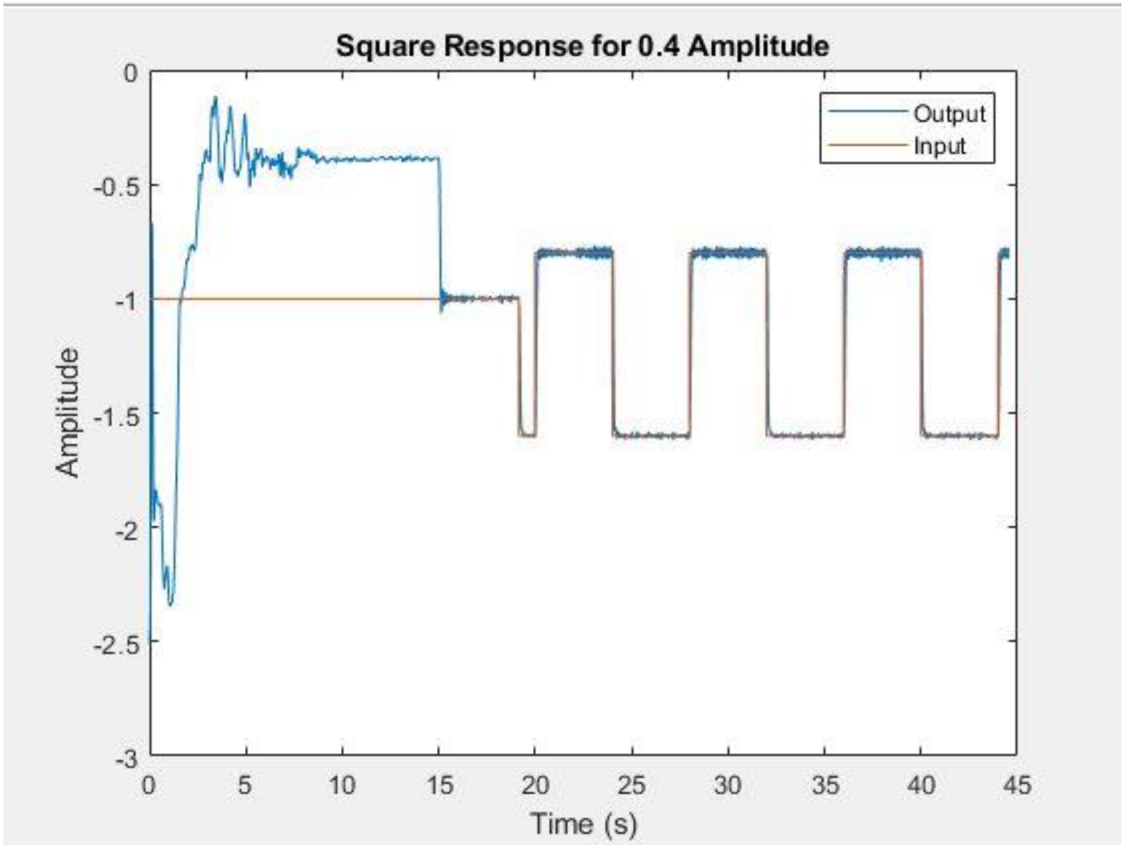
Figure. MATLAB model of the actual physical system.

5.3 Model Response:

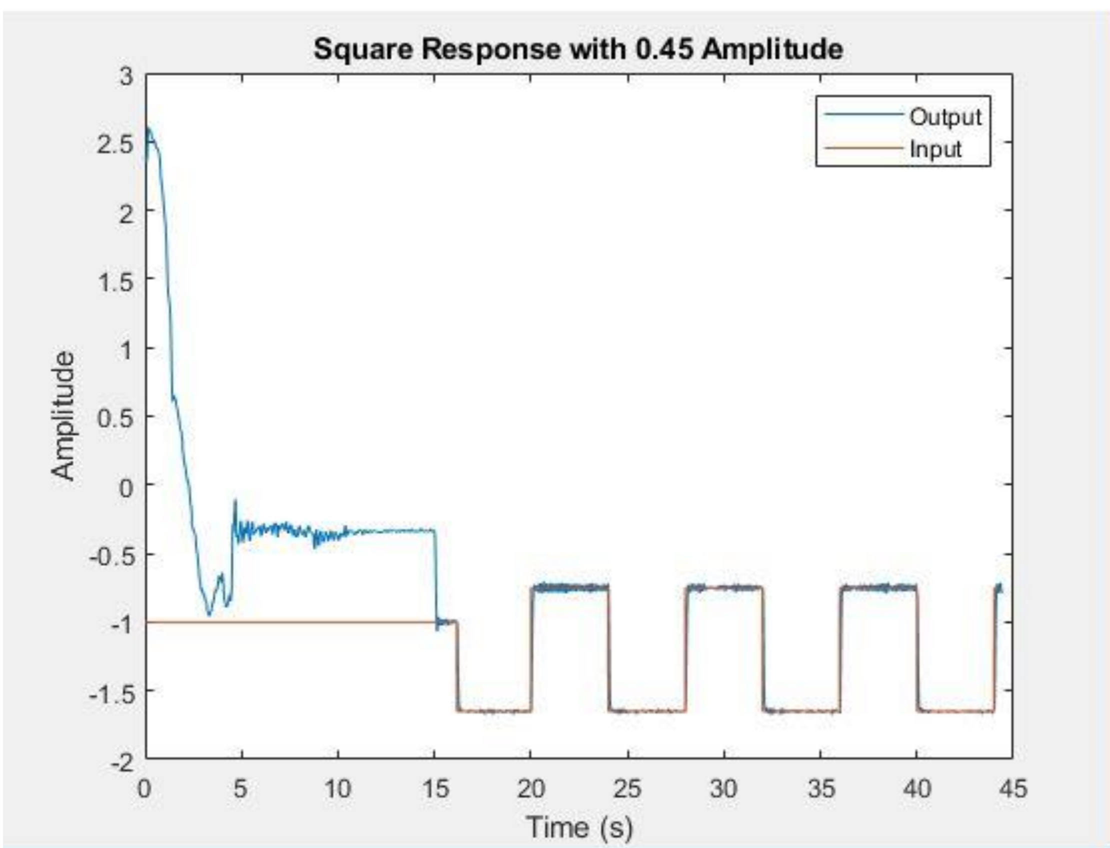
The response of our final controller with respect to step input and square waves of different amplitudes is:



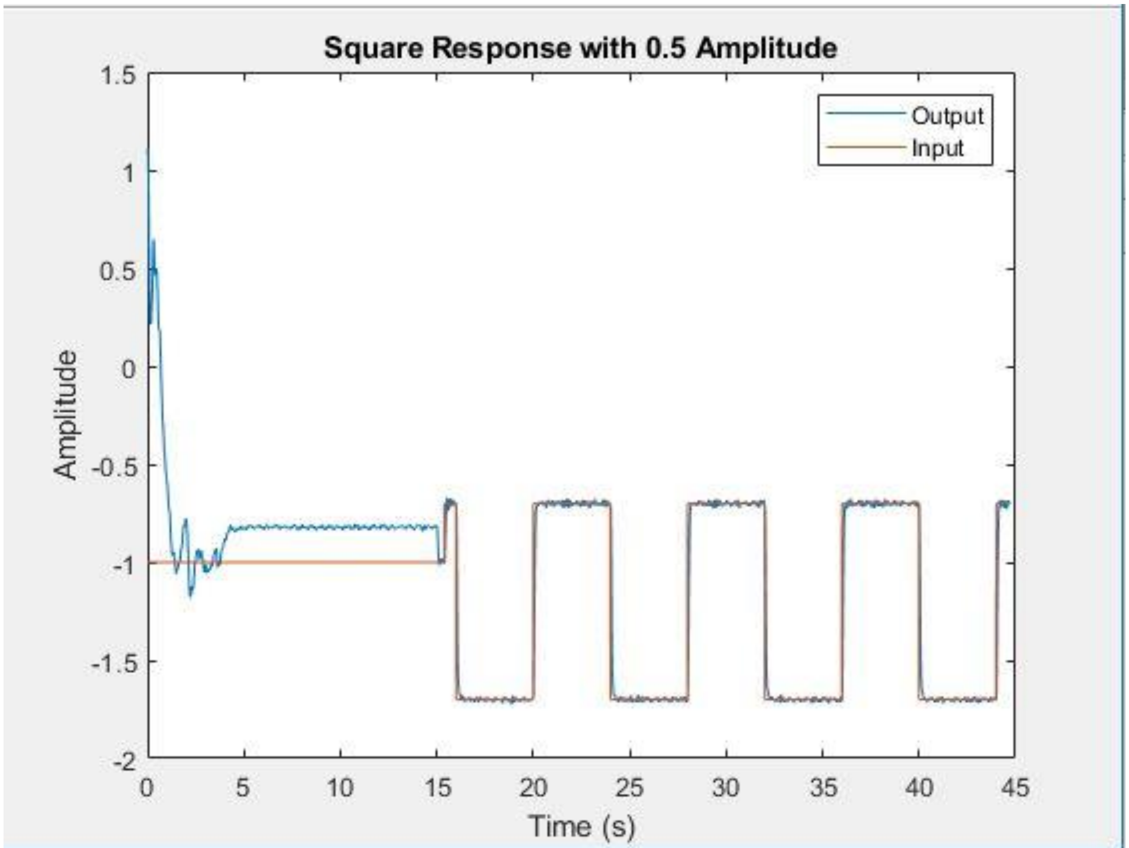
1. Overshoot was 4.725%
2. Settling time was less than 3s.



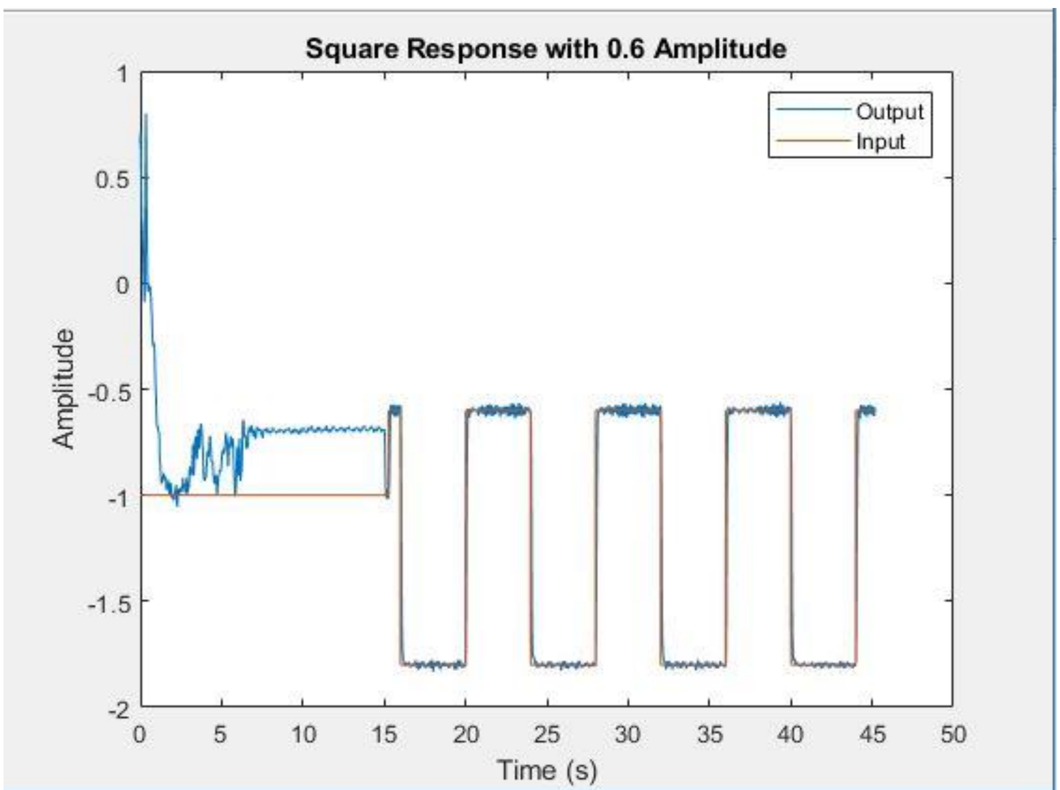
1. Overshoot was 3.475%
2. Settling time was less than 3s.



1. Overshoot was 3.911%
2. Settling time was less than 3s.

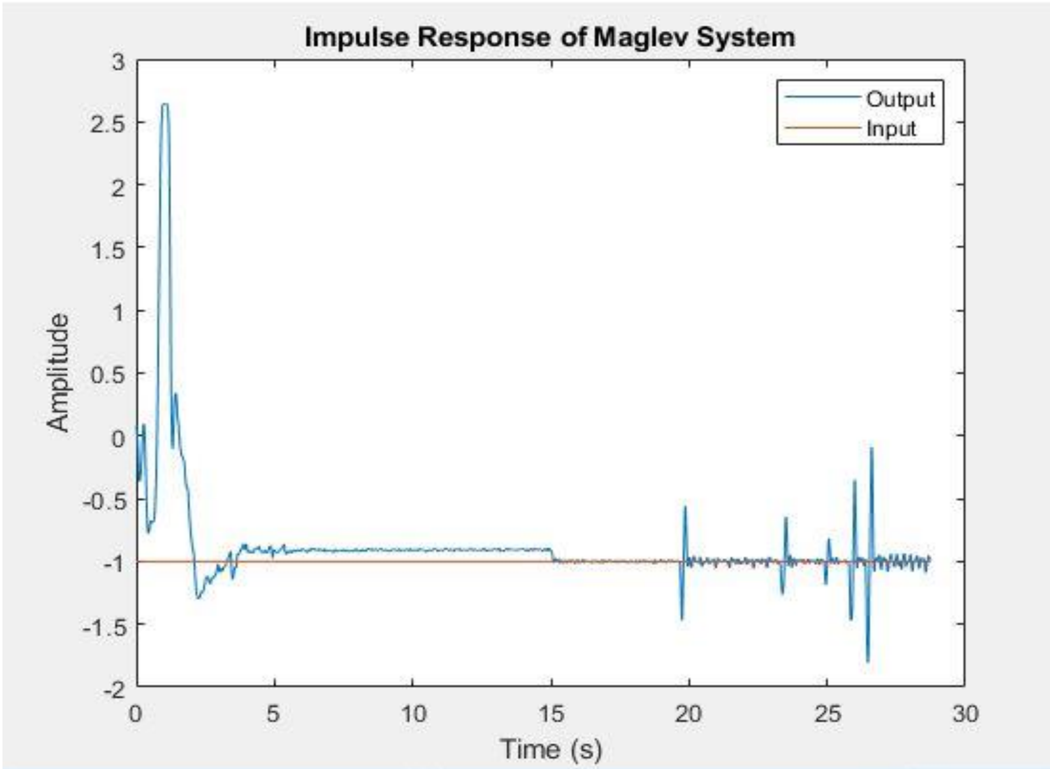


1. There was no Overshoot
2. Settling time was less than 3s.



1. Overshoot was 3%
2. Settling time was less than 3s.

The response of the system to impulse disturbance is the following:



The initial controller which satisfied Non Linear Model for the Pre Lab was Unstable. This was mainly due to the fact that the zeros were placed too far away from the Imaginary Axis causing larger Damping. Hence, we had to change the Controller so that we get the desired results. Intermediate designs of the Controller were Stable enough to keep the ball floating in air, but they had high values of Overshoot and Settling time. The final controller with zeros at -25+/-j and a Gain of 180 helped us in getting the best results as compared to all other Controllers and satisfied all the desired specifications except for the zero steady state error as there were too many oscillations.

6. Conclusions

- Our final controller worked very well for step inputs of 0.4 and square inputs of 0.4, 0.45, 0.5, 0.6. We were able to achieve the target for maximum overshoot and settling time, and were within the satisfactory range of oscillatory vibrations. Disturbance Rejection was also good. The reference tracking during transitions were exceptional.
- The design process led to the expected results, but we needed to tune our controller a little bit. Also, the final system had very small oscillations.
- The most challenging aspect of the lab was tackling the issue that our controller which was working perfectly on the theoretical SIMULINK linear and non-linear models, was not stable on the actual physical prototype.
- Higher values of K for zeros far apart from the Imaginary axis was yielding results for Pre-Lab, but it was not generating desired results for the MagLev System.
- Another challenge we faced was that even after trying several combinations of controllers, we were not able to reduce the steady state vibrations of the ball.
- Hence, we re-designed our controller and tuned the K-values to get the desired results.

7. Appendix

We are a team of 3 members - Karthikbabu R.N., Mayank Josan and Anshul Paunikar. We designed and verified the controller design for the pre-lab separately as it was a part our assignment. After consultation with each other, we came up with 3 best controller designs for the lab. Each of the team member used a different approach for selection of zero. Karthikbabu tried designing a controller for Complex conjugate zeroes far away from the Imaginary axis, Anshul tried for

Complex Conjugate zeros near the Imaginary axis and Mayank tried for zeroes on the Real axis. Complex Conjugate zeros, be it anywhere in the admissible region, were giving the desired results for the Linear model simulation. But in the actual Maglev System, the zeros which were away from the Imaginary axis caused the System to be Unstable. Everyone contributed equally in the lab and after multiple iterations, we decided to go with zeroes near the Imaginary axis as it gave us the desired results. We had created an EXCEL worksheet to quickly calculate the pre-compensator and K-values in case we needed to re-design the controller in the lab, which we did. In the end, we worked together as a team, brainstorming and tuning our controller and achieved the desired result. After the lab, we worked together and completed the lab report.

The Closed Loop System was meeting the desired specification for Overshoot, settling time and Steady State Error and even worked for multiple Impulse Responses.