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& Computer Engineering
Faculty of Engineering & Architectural Science

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Instructor	Professor Zywno

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Assignment/Lab Title:	Control of the Servo Positioning Module

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Due Date:	Apr 6, 2023

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ELE639: Control Systems, Winter 2023

Lab # 3 Report: PID Control of the Servo Module

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<tr><td colspan="3">Total Mark for the Collaborative Part of the Report</td><td>/80</td></tr>
<tr><td>Partner 1 (name):
Safwan Al-Islam</td><td>Partner 2 (name):
Aranan Thevendran</td><td>Partner 3 (name):
Joshua Jayakumar</td><td>Partner 4 (name):
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Executive Summary

In our final Control Systems lab we have been given the task of implementing a PID controller on a physical DC Servo Motor Module with the objective of improving the closed loop response of the system.

A key concept in control systems that will be frequently mentioned in this lab report is the term "nominal range". The nominal range is defined as the area where the system response does not display any non-linear characteristics. The two primary nonlinearities that we must bring attention to are both saturation and deadzone. The saturation nonlinearity begins when the system response becomes "saturated"/limited; its output makes a maximum or a minimum and it cannot respond to any increases/decreases with a change in its input signal. Saturation in this case is when the response of the system achieves a specified amplitude in the block diagram which saturates the control signal. A deadzone on the other hand is the sort of nonlinearity in which the system's response is zero for a specific range (known as the "deadzone"), even if the input is non-zero. When the input signal exceeds this range, however, we go back to seeing linear responses of the system to input signals. By operating the system within the nominal range we aim to by-pass these non-linearities.

In the first portion of this lab, we carried out an in-depth examination of the uncompensated servo module response (Proportional Control) with Kp set to one. We then identify and operate in the nominal range by observing the amplitude of the control signal (seeing if saturation has happened). Operating in the nominal range is crucial because the servo would behave as a linear time invariant system.

In the second portion of this lab, our objective was twofold: ensure system stability and enhance the systems tracking performance in both the transient and steady states. All this while operating in the nominal range, while adhering to the performance specification listed below.

1. Less than 10% Percent Overshoot (PO) in the system closed loop step response;
2. Settling Time (***Tsettle***(±**2**%) - use criterion) less than 0.3 seconds in the system closed loop step response;
3. Rise Time (***Trise***(**10−90**%) - use criterion) less than 0.2 seconds - in the system closed loop step response;
4. Zero Steady State Error (***ess***(***step***)%) in the system closed loop step response;
5. Steady State Error (***ess***(***ramp***)) of the closed loop unit ramp (1 radian/per second, or approx. 57*o* per second) response to within 0.03 radians (approx. 2 degrees) within a time shorter than 0.3 seconds.

For the third portion of the lab experiment we brought our focus to the effect of the nonlinear phenomena we had to deal with; dead-zone, and saturation, and how it impacted the response of the Servo Module. The assessment of three systems in this specific order took place: uncompensated proportional control, compensated proportional integral controller, and compensated proportional integral controller + anti windup. This report comprehensively presents the findings we have obtained from the three distinct sections of this experiment.

Part A Simulated Servo:

PART 1: Uncompensated Simulated Servo Response in Nominal Range

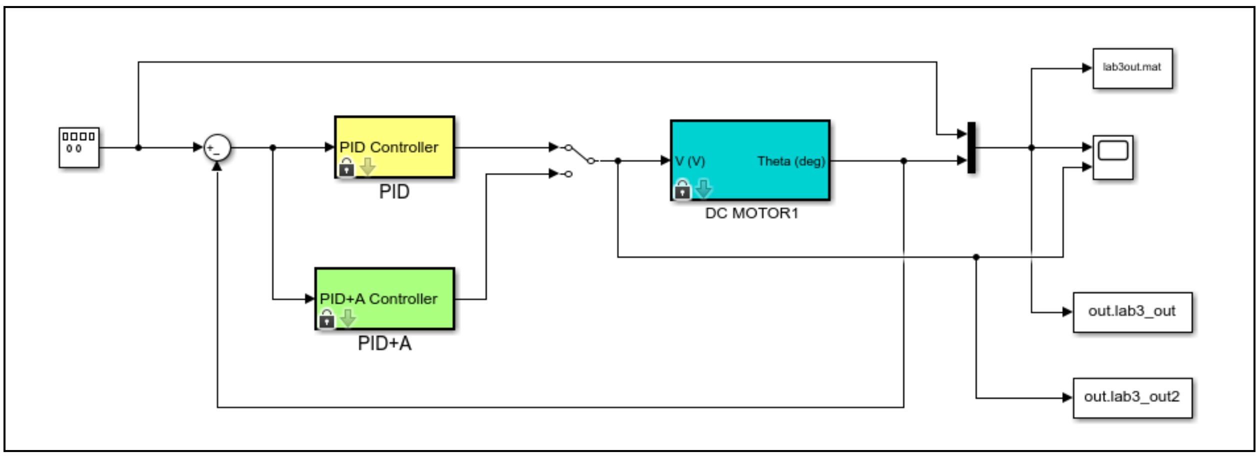

Figure 1. Simulink block diagram of uncompensated servo system.

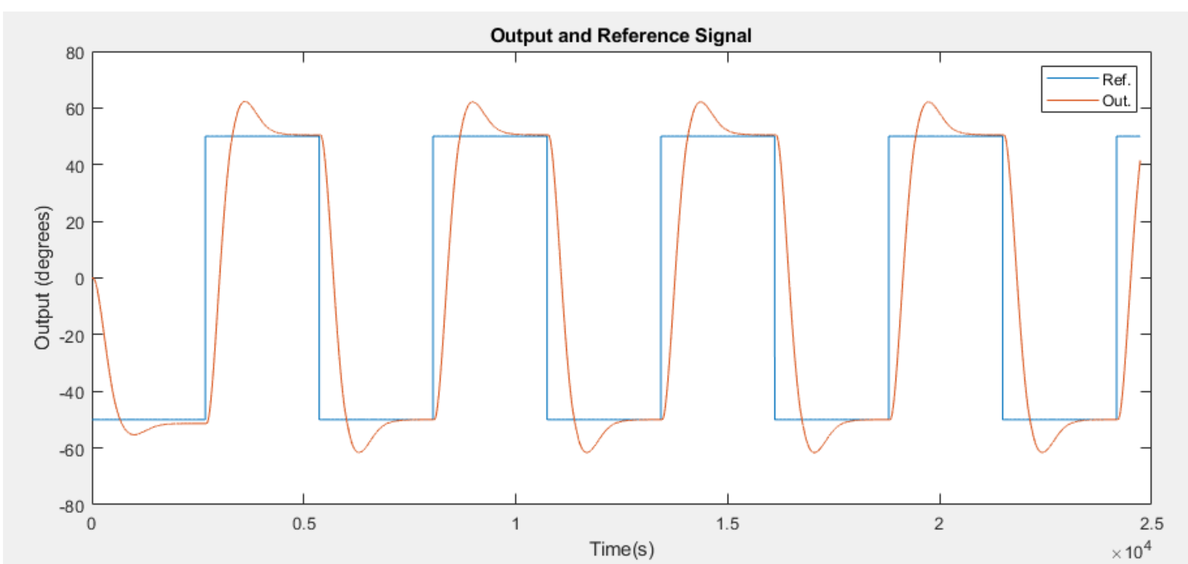

Figure 2. Graph of output and input responses of the block diagram shown in figure 1.

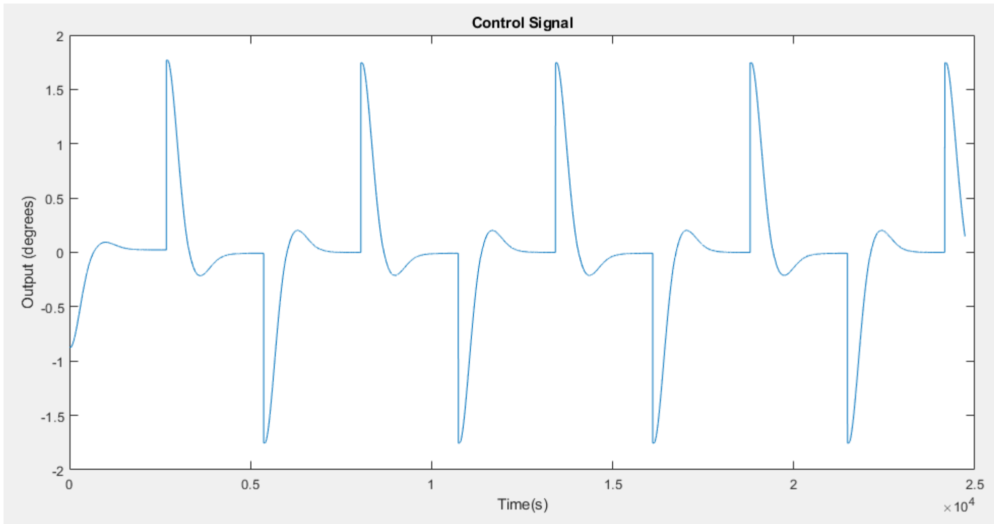

Figure 3. Control Signal

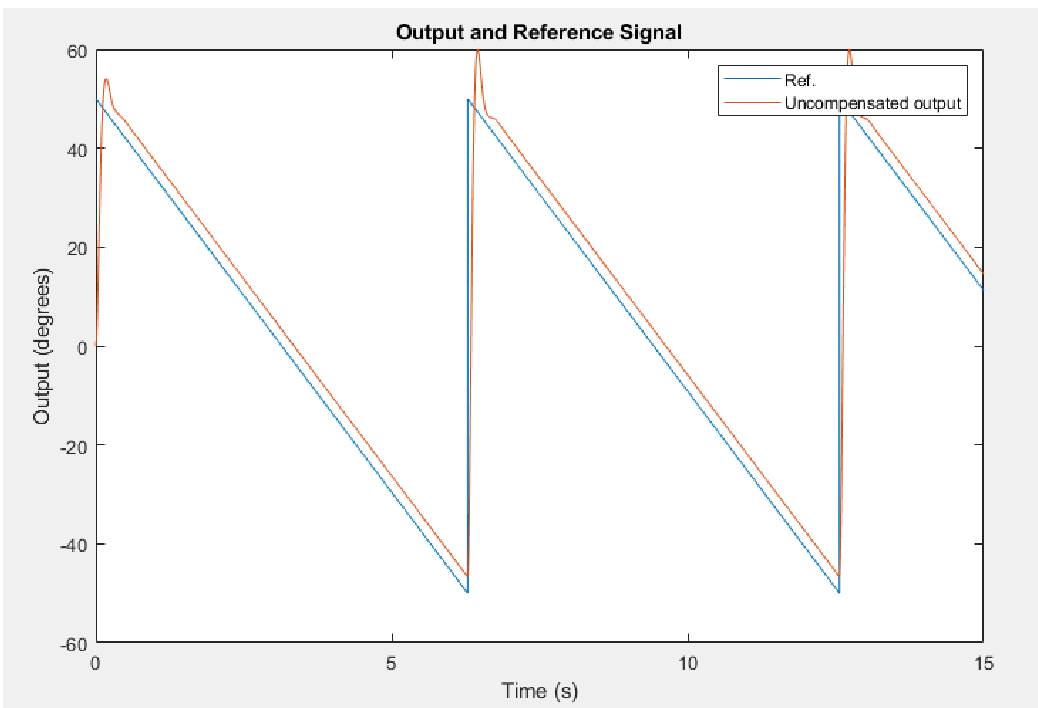

Figure 4. Output and Reference Signal

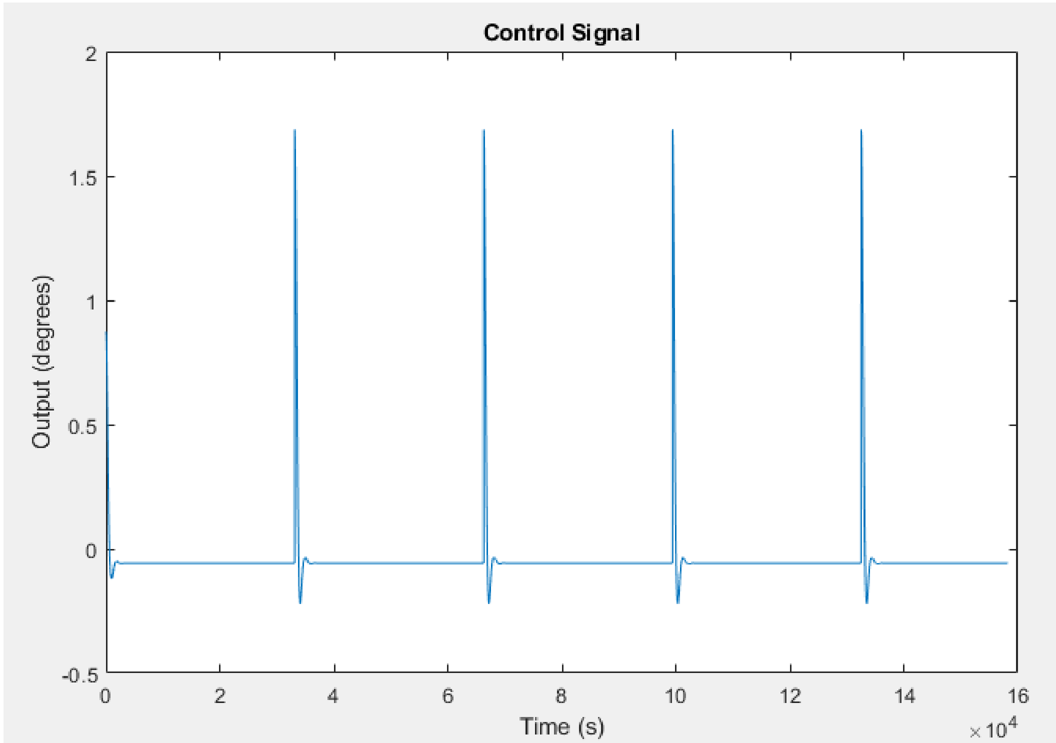

Figure 5. Control Signal

Table 1: Time Response Characteristics for Uncompensated System under Proportional Control (Simulated Servo)

Uncompensated System	Rise-time $tr(0-100\%)$	Percent Overshoot %PO	Settling-time $ts(\pm 2\%)$	Steady state error $ess(step)$	Steady state error $ess(ramp)$
Proportional Controller **K_P = 1**	0.135	22.92	0.349	1.08	3.31

PART 2: Compensated Simulated Servo Response in Nominal Range

2. a) As the proportional gain increases, the steady state error decreases and the settling time and percent overshoot increases.

b) Setting the gain value significantly high or low shows non-linearity in the system. A saturation point is observed for the gain value of Kp= 1.2 , while the effect of dead zone on the system can be seen when maintaining the gain value of Kp= 0.4.

c) We were only able to meet some required specifications using only the P controller.

Table 2: Time Response Characteristics for Compensated System under Proportional Control (Simulated Servo)

Compensated System	**Proportional Gain (*KP*)**	**Rise-time *Trise* (10−90%)**	**Percent Overshoot PO%**	**Settling-time *Tsettle*(±2%)**	**Steady state error *ess*(*step*)**	**Steady state error *ess*(*ramp*)**
Proportional Controller	0.8	0.1	5.37	0.334	4.4	4.07

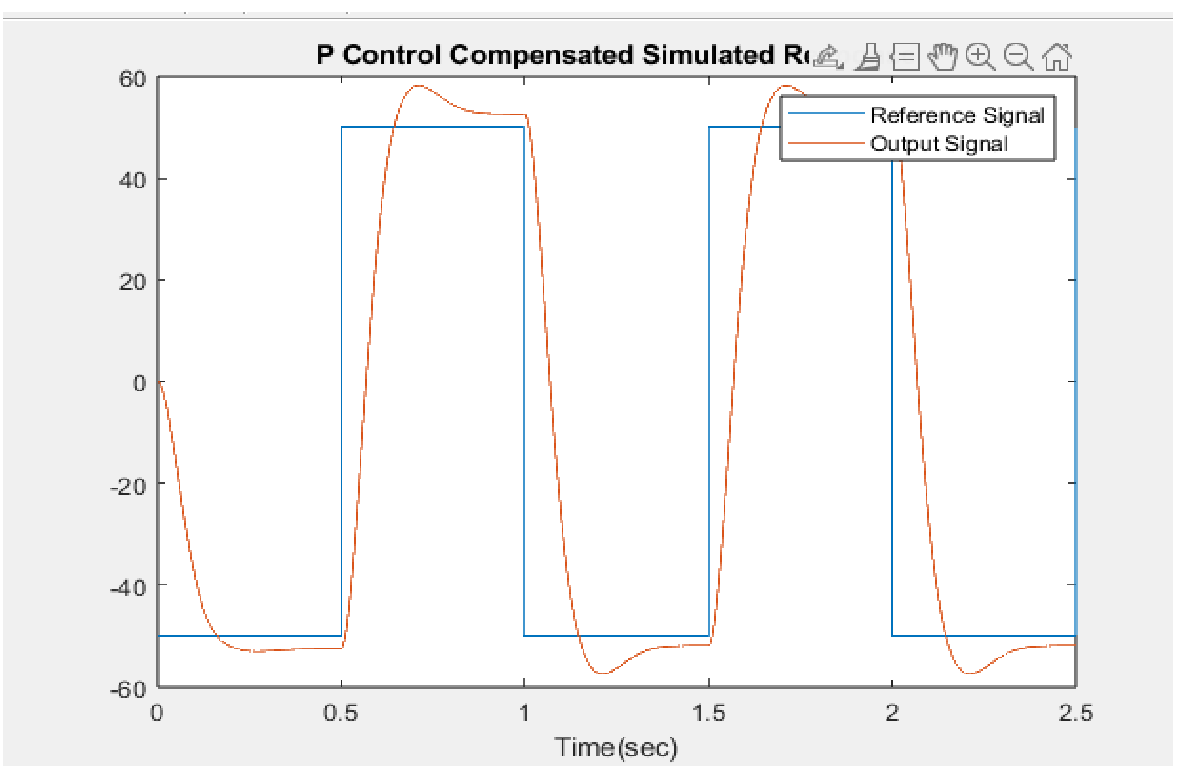

Figure 6. P Control Compensated Simulated Response

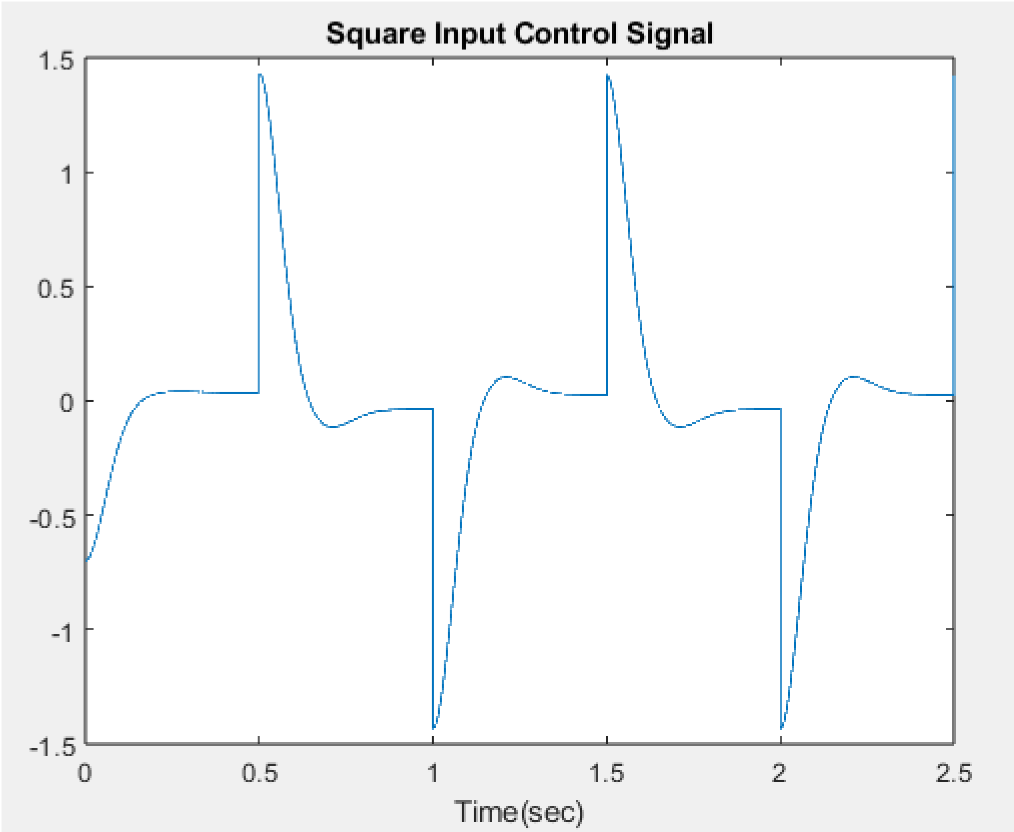

Figure 7. Square Input Control Signal

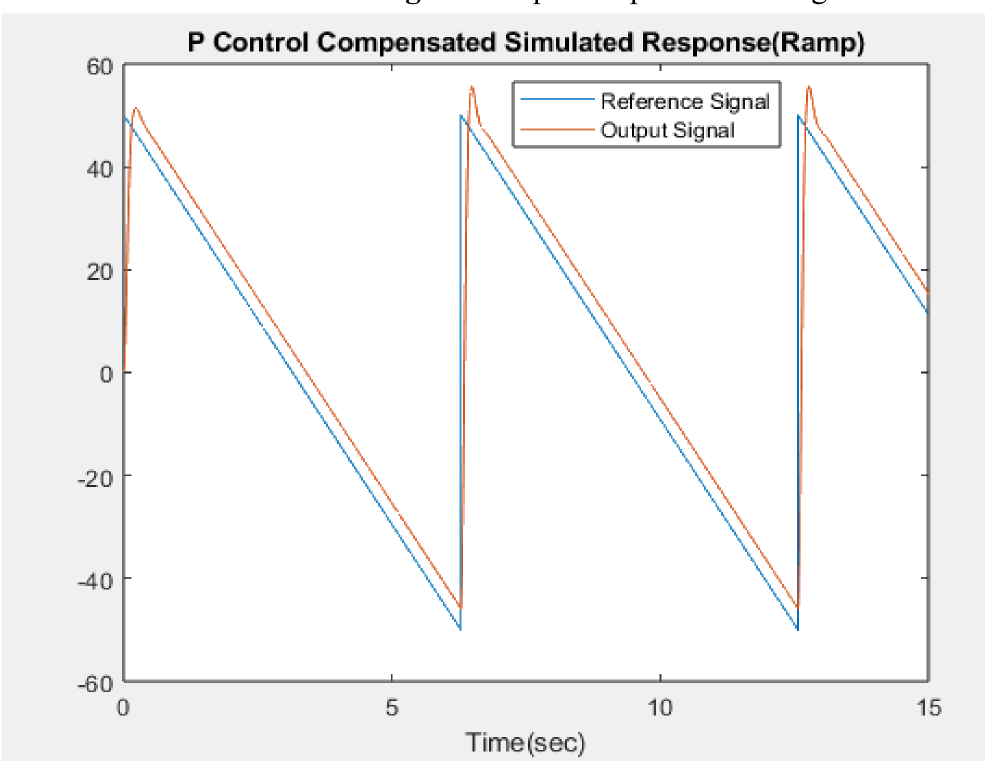

Figure 8. P Control Compensated Simulated Response (Ramp)

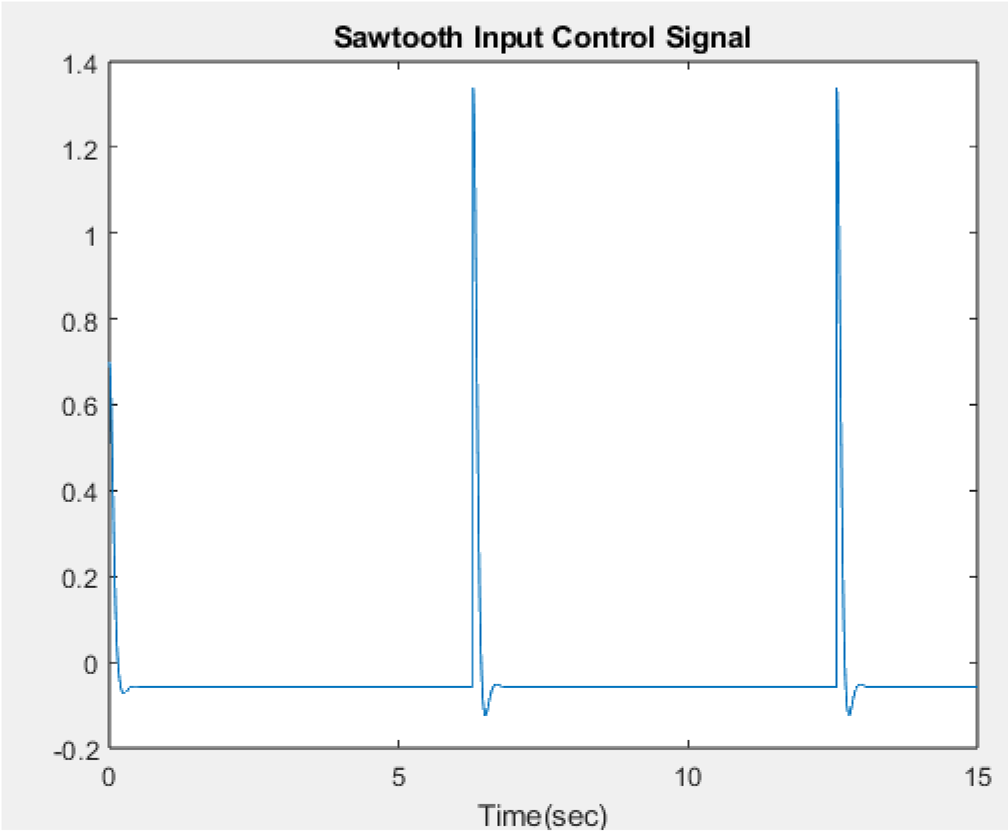

Figure 9. Sawtooth Input Control Signal

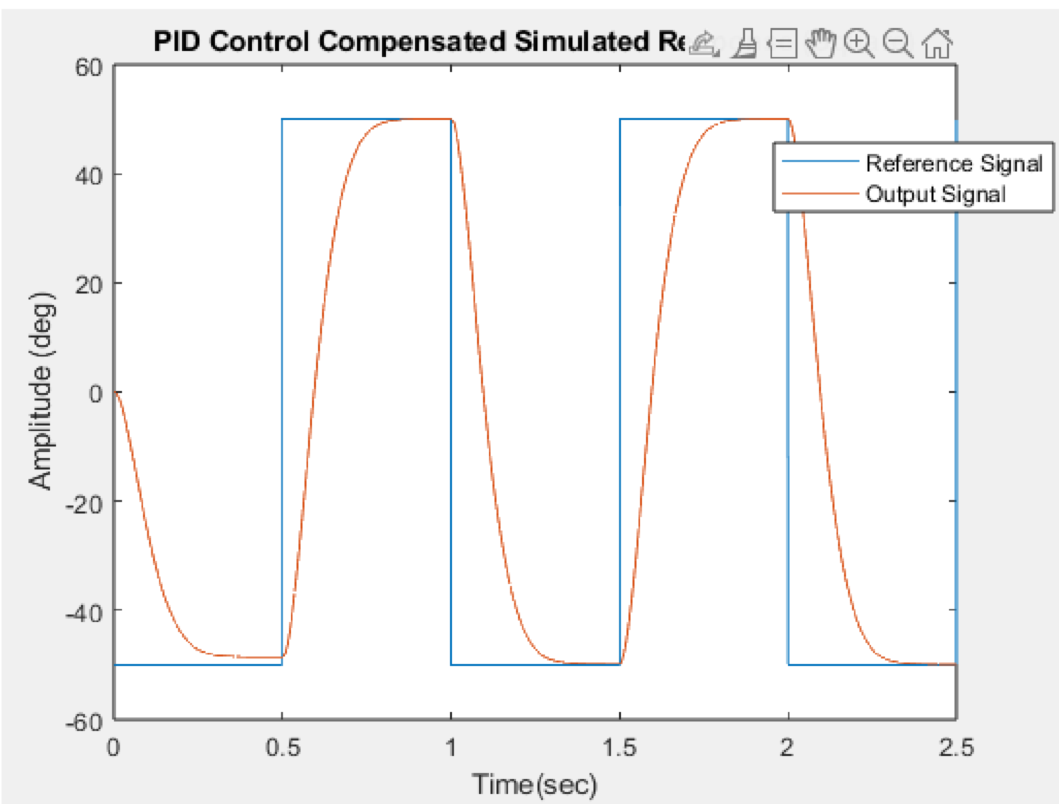

Figure 10. PID Control Compensated Simulated Response

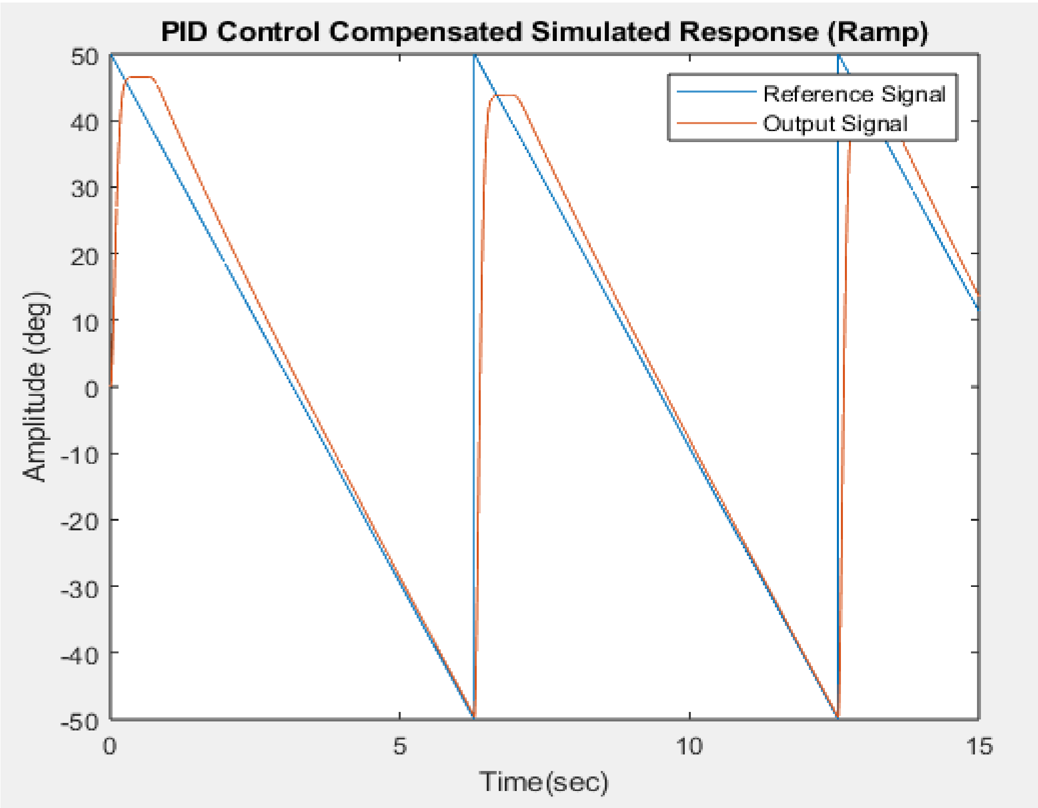

Figure 11. PID Control Compensated Simulated Response

Table 3: Time Response Characteristics for Compensated System PID (Simulated Servo)

Compensated System	**Proportional Gain *KP***	**Derivative Time Constant *τd***	**Integral Time Constant *τi***	**Rise-time *Trise* 10−90%**	**Percent Overshoot PO%**	**Settling-time *Tsettle* (±2%)**	**Steady state error *ess* (*step*)**	**Steady State error *ess* (*ramp*)**
PID Controller	0.5	0.002	2	0.164	0	0.295	0.18	0.04

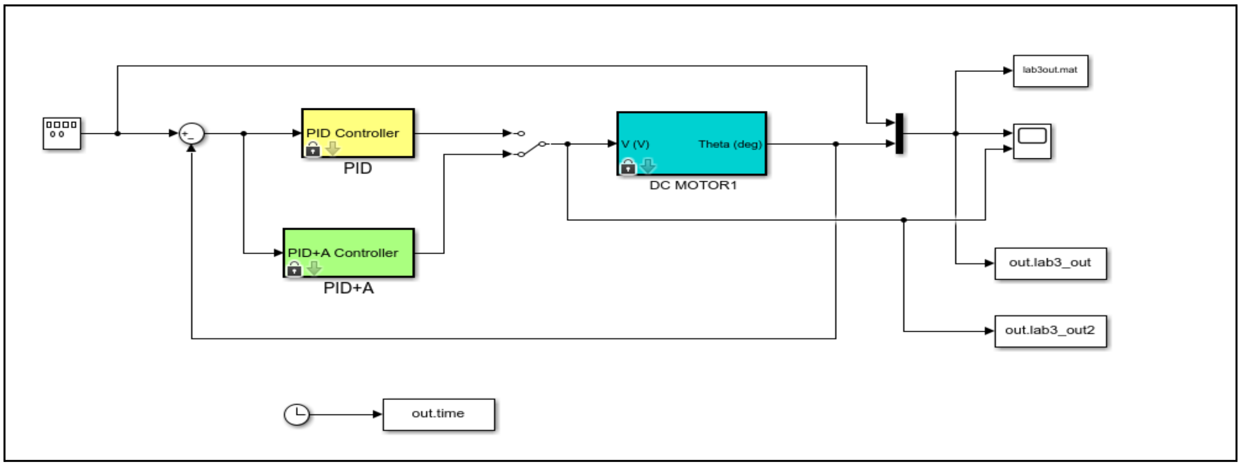

Figure 12. Simulink DIagram for Anti-Windup

Changing the anti-windup doesn't change any of the specs so PID Controller gives the best result out of all three because it meets all of the specs.

Table 5: Time Response Characteristics for Compensated System PID (Simulated Servo)

Compensated System	**Proportional Gain *KP***	**Derivative Time Constant τd**	**Integral Time Constant τi**	**Rise-time *Trise* 10−90%**	**Percent Overshoot PO%**	**Settling-time *Tsettle* (±2%)**	**Steady state error *ess* (*step*)**	**Steady State error *ess* (*ramp*)**
PID Controller	0.5	0.002	2	0.164	0	0.295	0.18	0.04

Part 3: Compensated Simulated Servo Response outside Nominal Range

1.

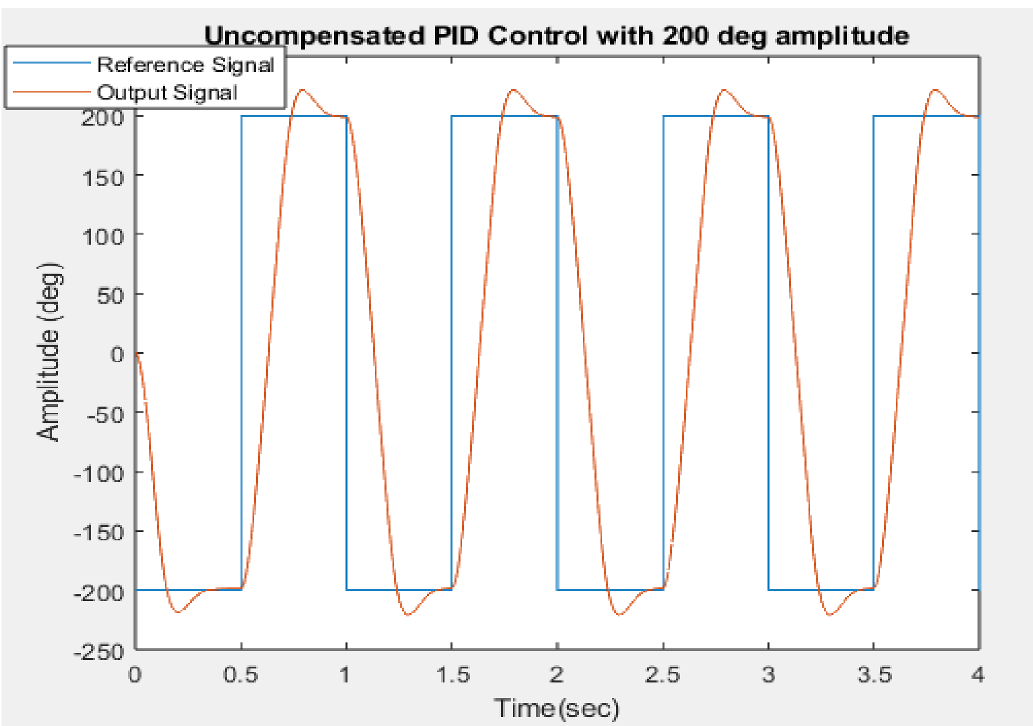

Figure 13. Uncompensated PID Control With 200 Degree Amplitude

3.

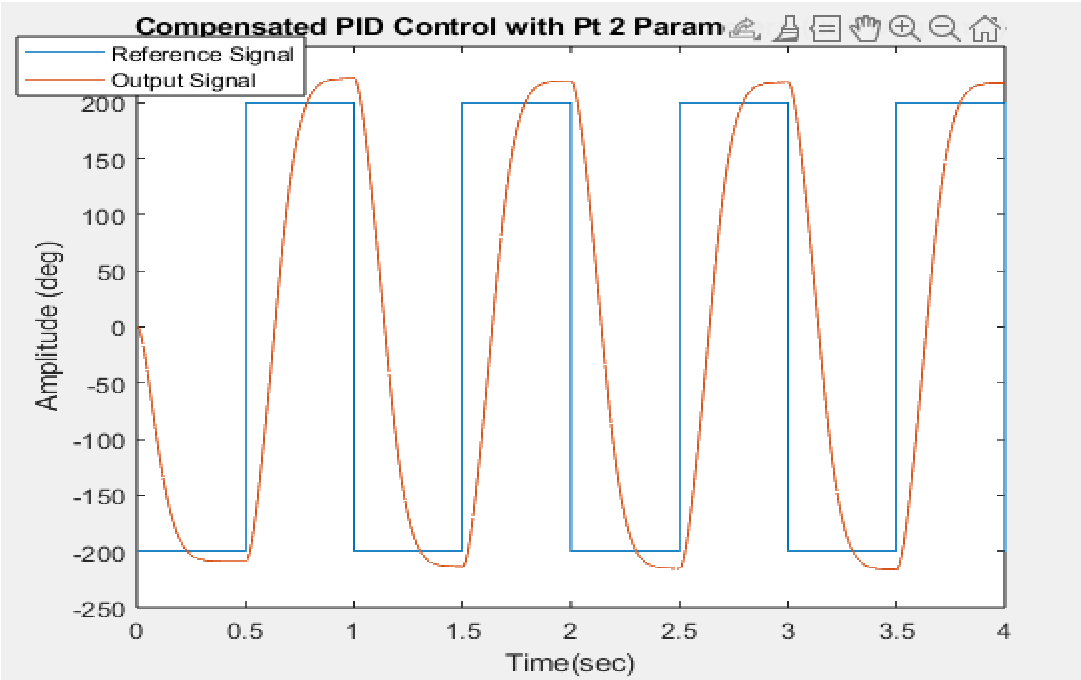

Figure 14. Compensated PID Control With Pt 2 Parameters

4.

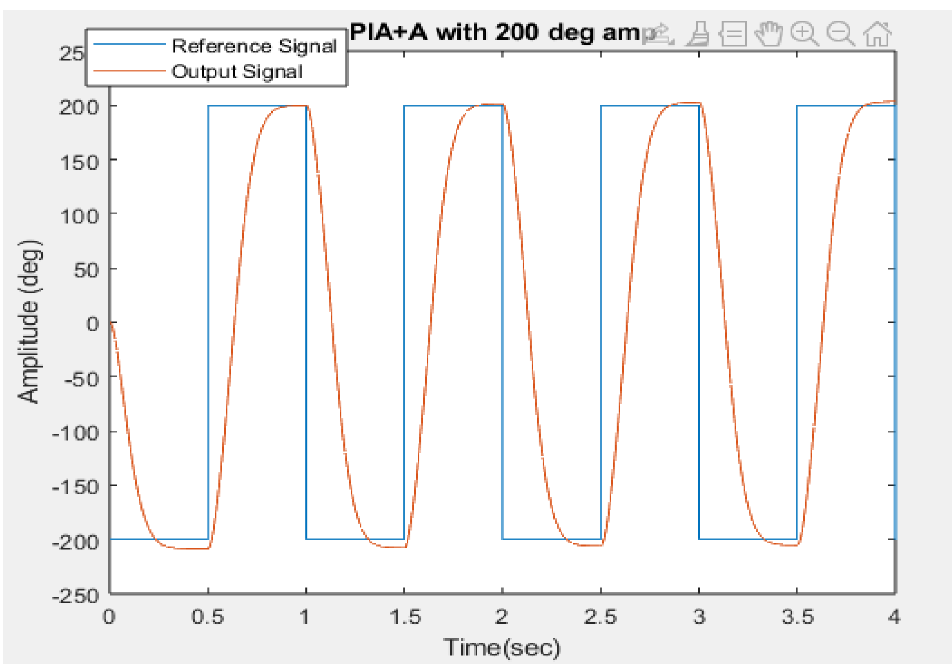

Figure 15. PIA+A With 200 Degree Amplitude

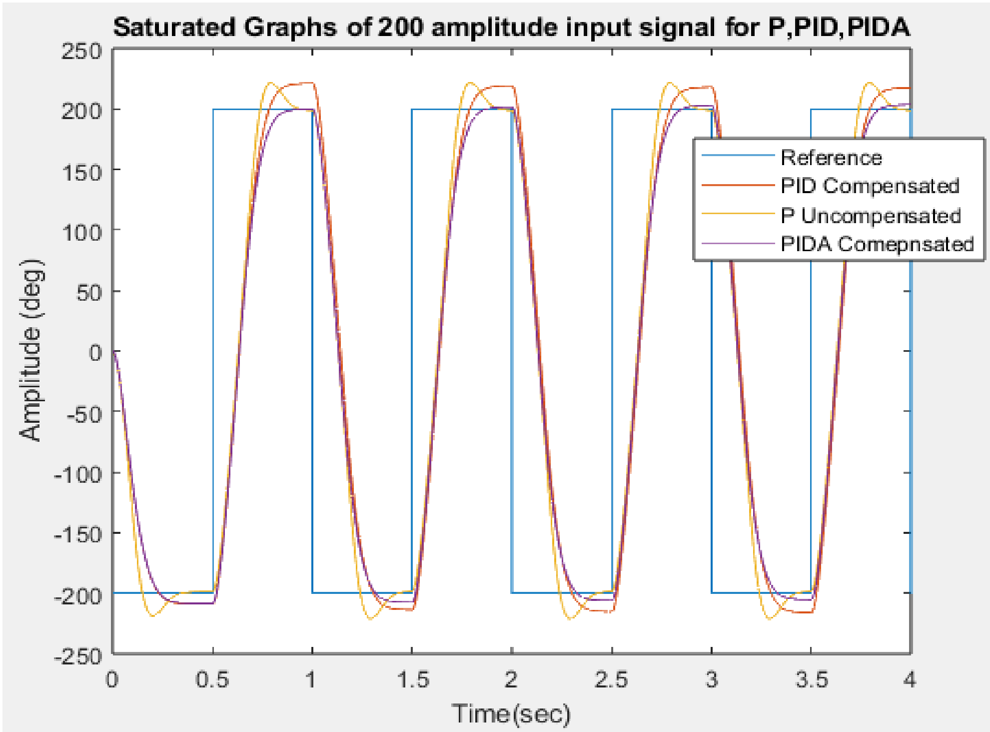

Figure 16. P, PID, PID+A with 200 Degree Amplitude

<u>Gear Backlash and Static Friction (Stiction):</u>

1.

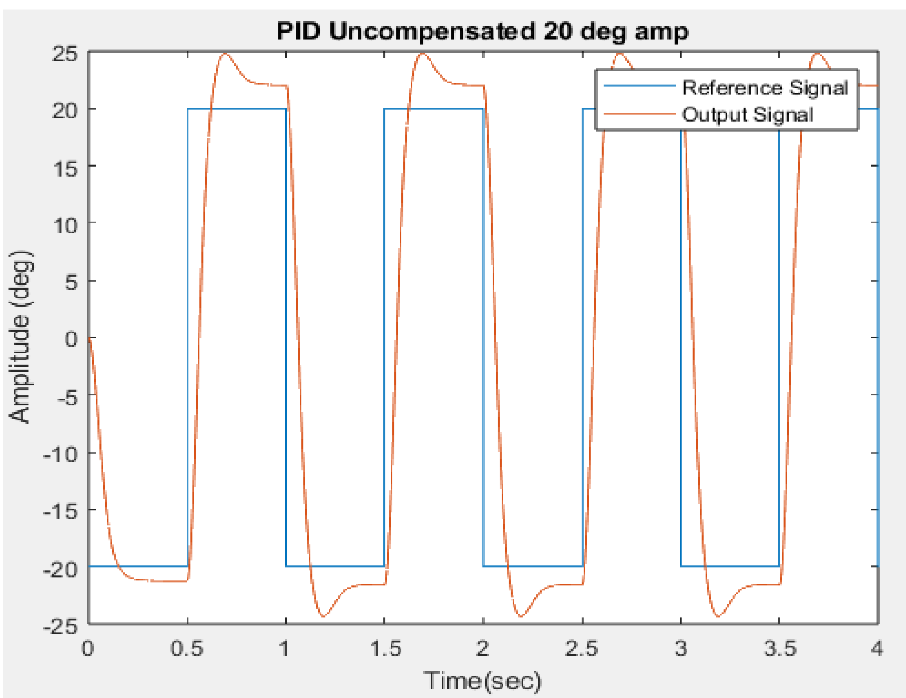

Figure 17. PID Uncompensated 20 Degree Amplitude

2.

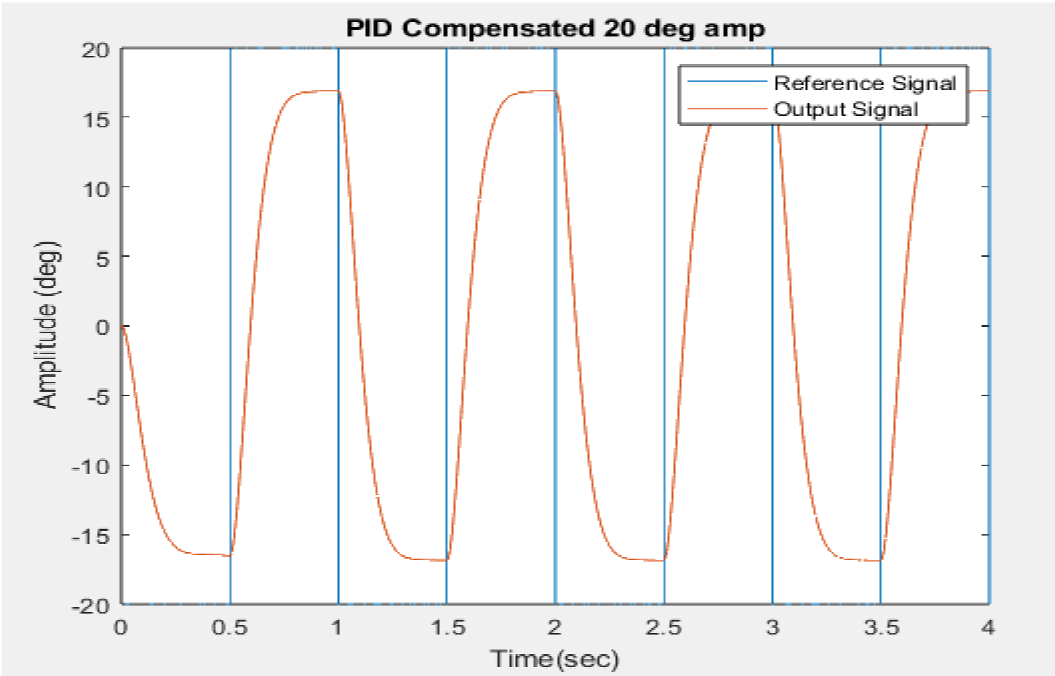

Figure 18. PID Compensated 20 Degree Amplitude

3.

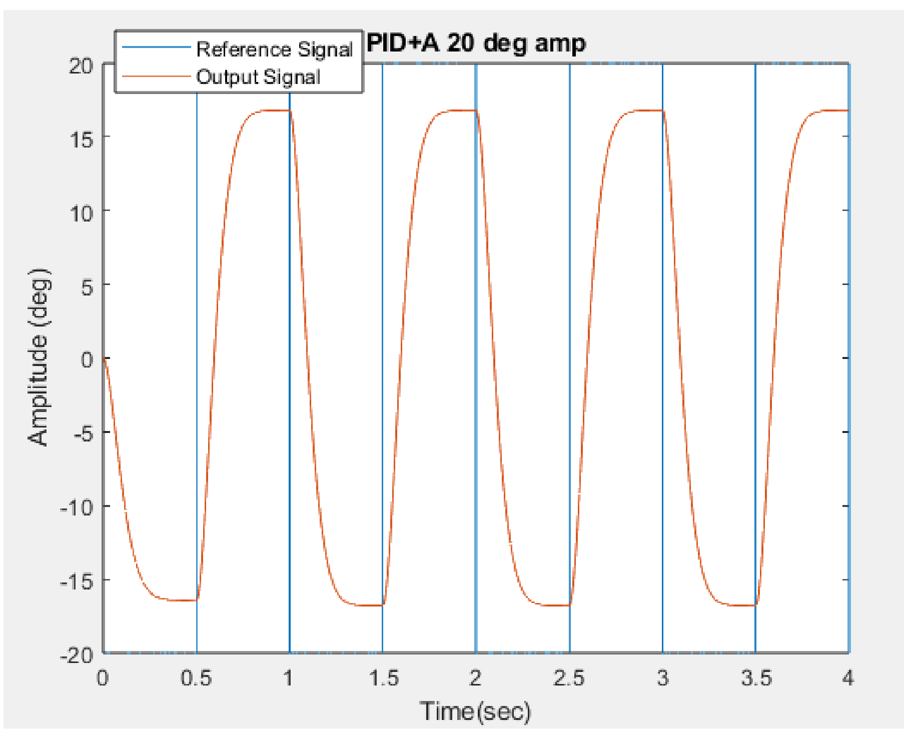

Figure 19. PID+A 20 Degree Amplitude

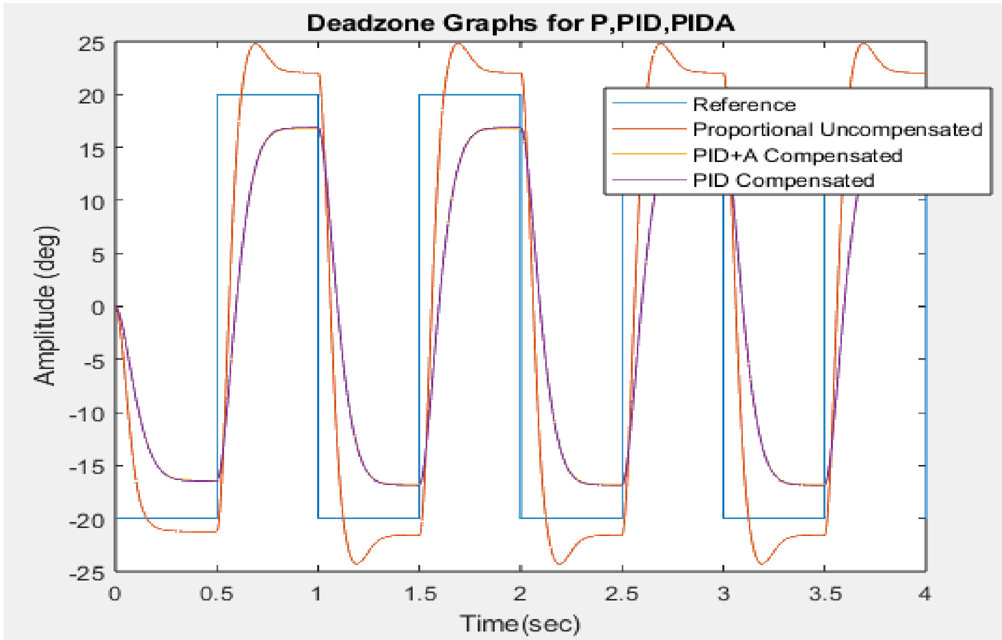

Figure 20. Deadzone graphs for P, PID, PID +A

Part B Real-Time Servo:

PART 1: Uncompensated Servo Module Response in Nominal Range

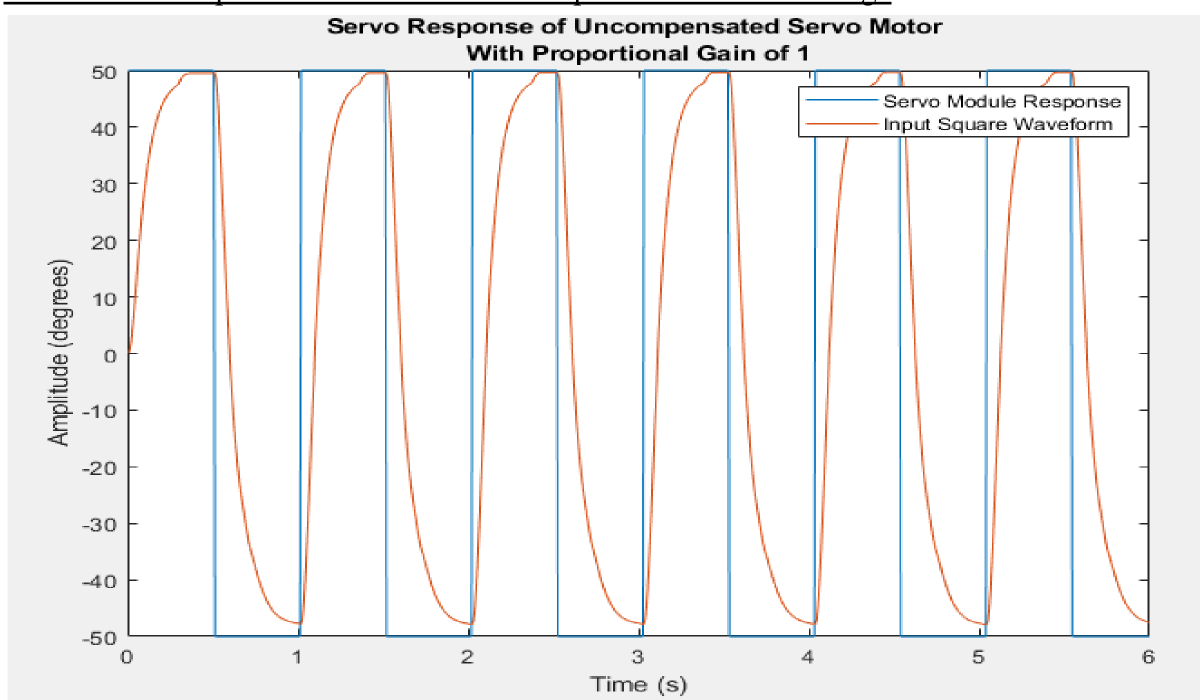

Figure 21. Servo Response of Uncompensated Servo Motor With Proportional Gain of 1

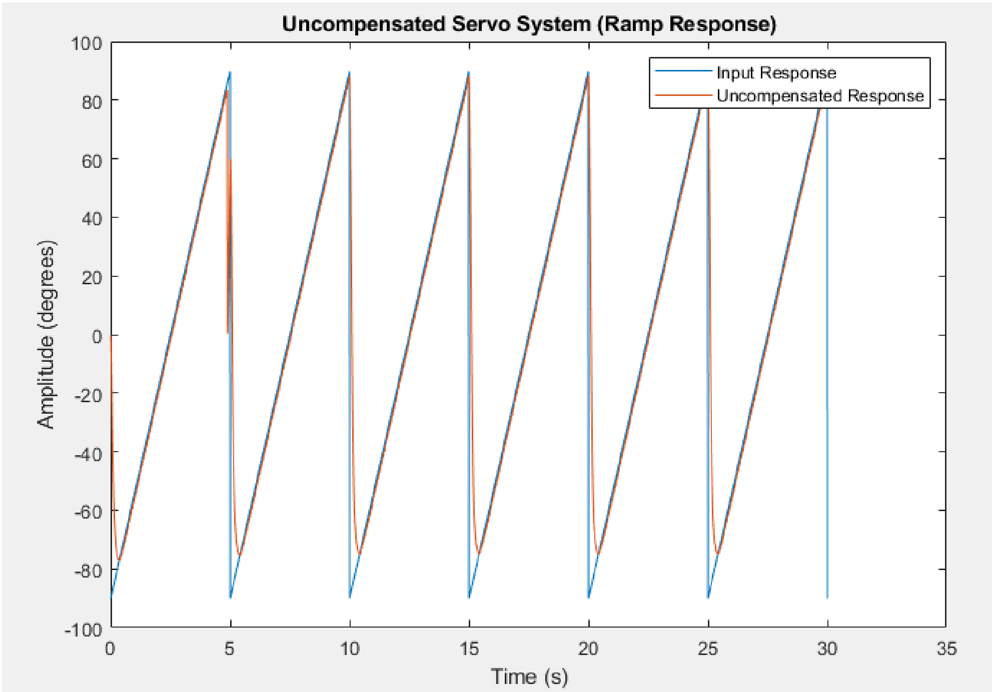

Figure 22. Uncompensated Servo System (Ramp Response)

Table 4: Time Response Characteristics for Uncompensated System (Real-time Servo)

Uncompensated System	Rise-time ***Trise*(10−90%)**	Percent Overshoot PO%	Settling-time ***Tsettle***(±2%)	Steadystate error *ess*(*step*)	Steadystate error *ess*(*ramp*)
Proportional Controller ***KP*** = 1	0.35	0.96	0.47	0.68%	2.14

PART 2: Compensated Servo Module Response in Nominal Range

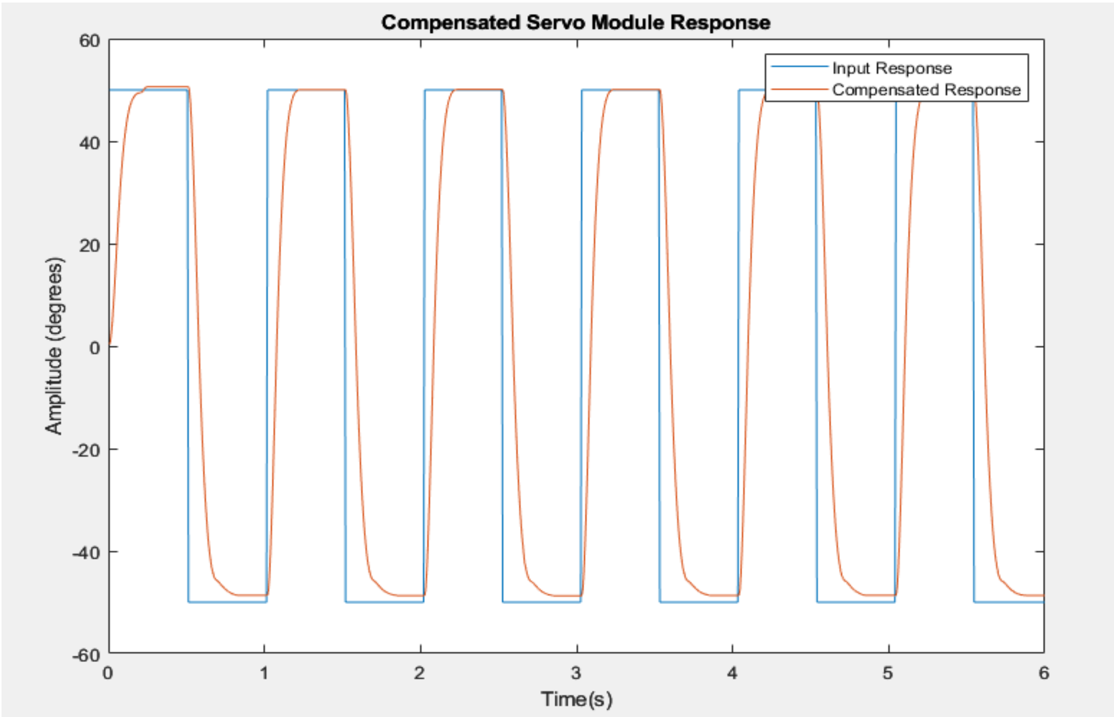

Figure 23. Compensated Servo Module Response

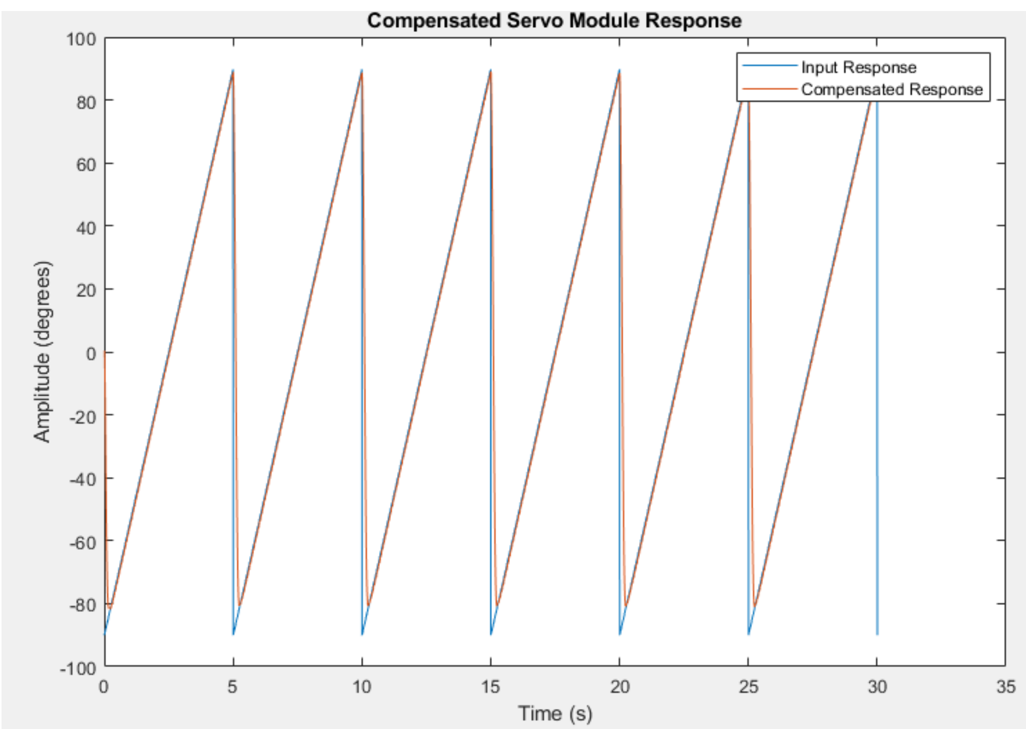

Figure 24. Compensated Servo Module Response

Table 5: Time Response Characteristics for Compensated System (Real-time Servo)

Compensated System	**Proportional Gain (K_P)**	**Rise-time T_{rise} (10−90%)**	**Percent Overshoot PO%**	**Settling-time T_{settle}(±2%)**	**Steady state error $e_{ss}(step)$**	**Steady state error $e_{ss}(ramp)$**
Proportional Controller	1.58	0.12667	0.16 %	0.25334 s	0.1544%	0.0239 rad

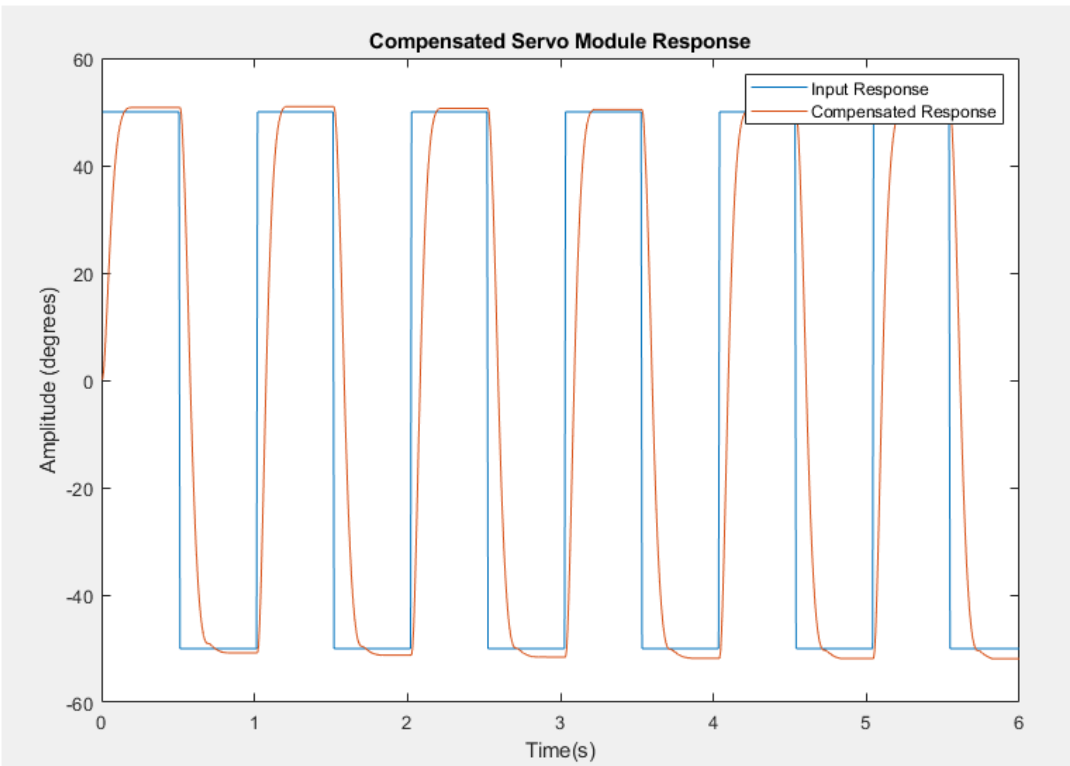

Figure 25. Compensated Servo Module Response

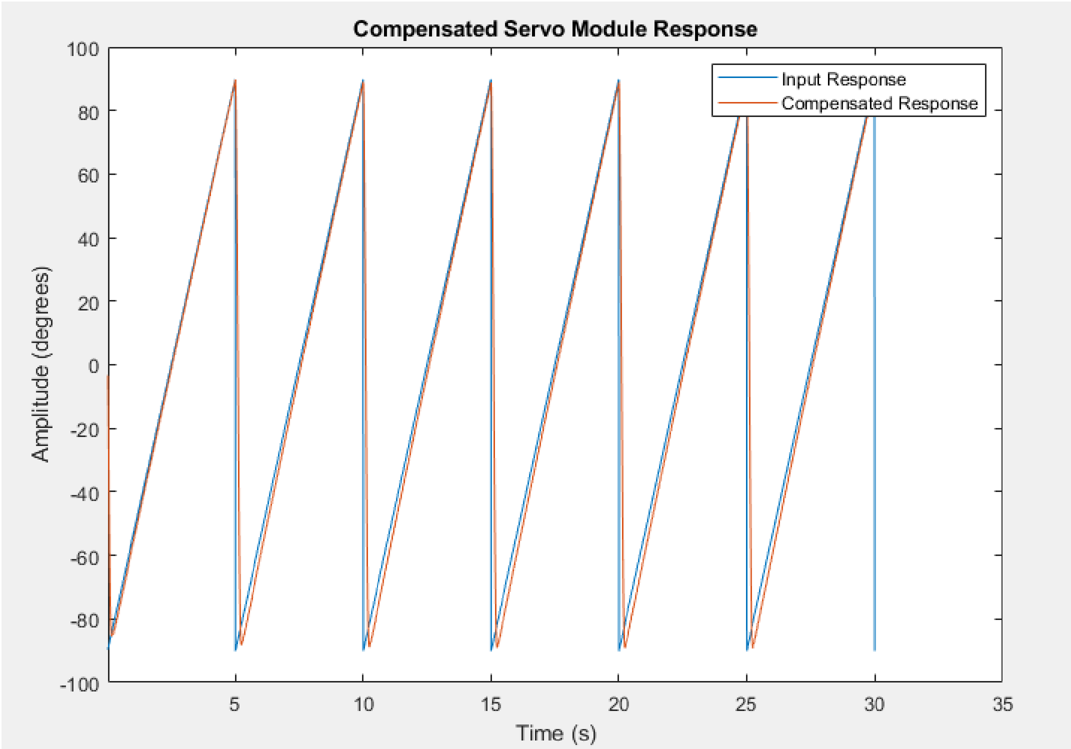

Figure 26. Compensated Servo Module Response

Table 6: Time Response Characteristics for Compensated System (Real-time Servo)

Compensated System	**Proportional Gain *KP***	**Derivative Time Constant *τd***	**Integral Time Constant *τi***	**Rise-time *Trise* 10−90%**	**Percent Overshoot PO%**	**Settling-time *Tsettle* (±2%)**	**Steady state error *ess* (*step*)**	**Steady State error *ess* (*ramp*)**
PID Controller	1.8	2.5	0.004	0.193365 s	0.85 %	0.267 s	0.86 %	0.02145 rad

Part 3: Compensated Servo Response outside Nominal Range

Saturation:

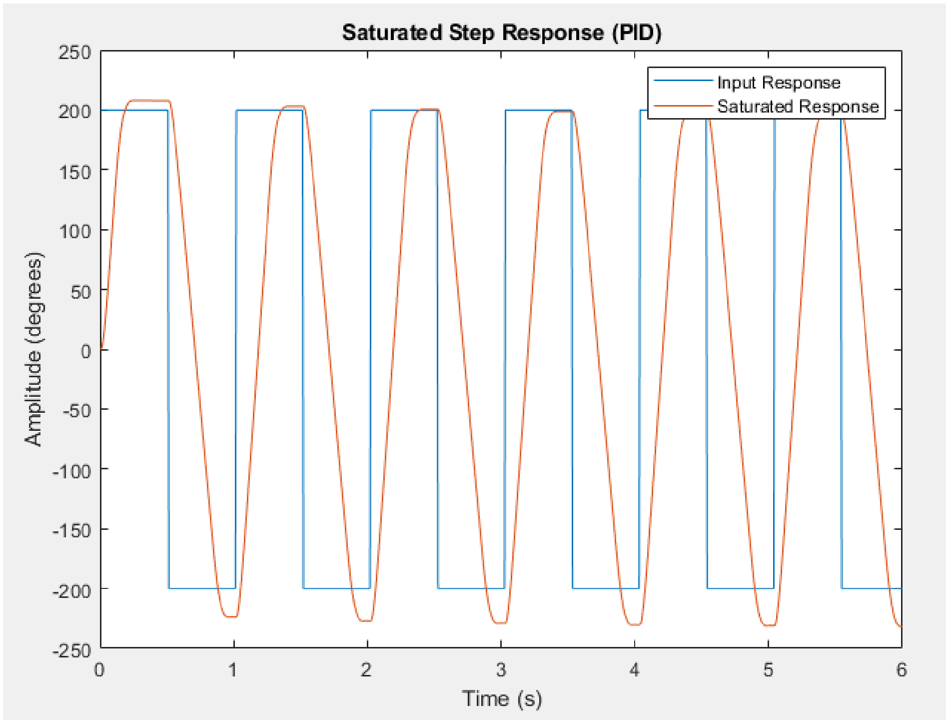

Figure 27. Saturated Step Response (PID)

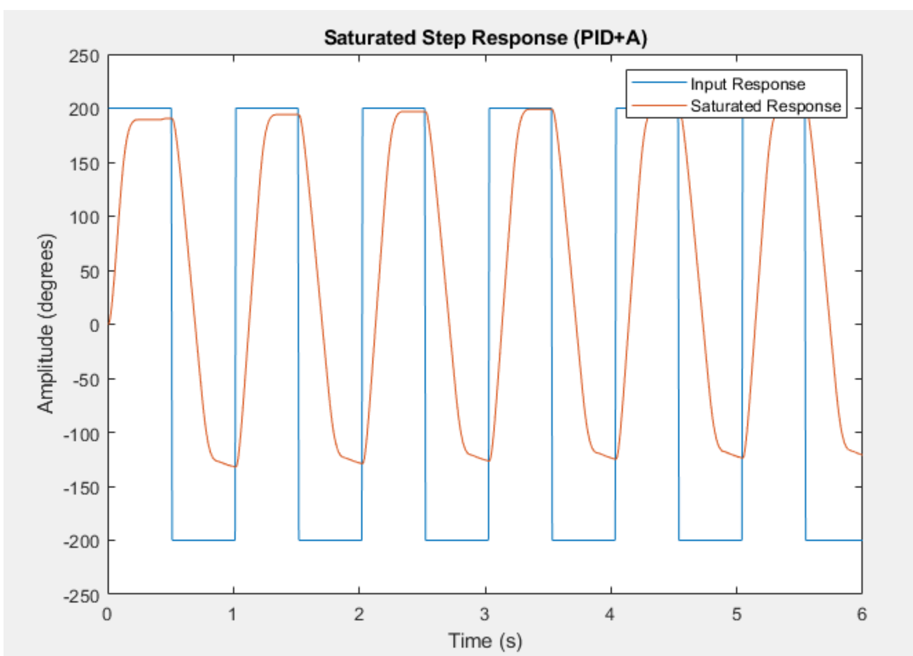

Figure 28. Saturated Step Response (PID+A)

Gear Backlash and Static Friction (Stiction):

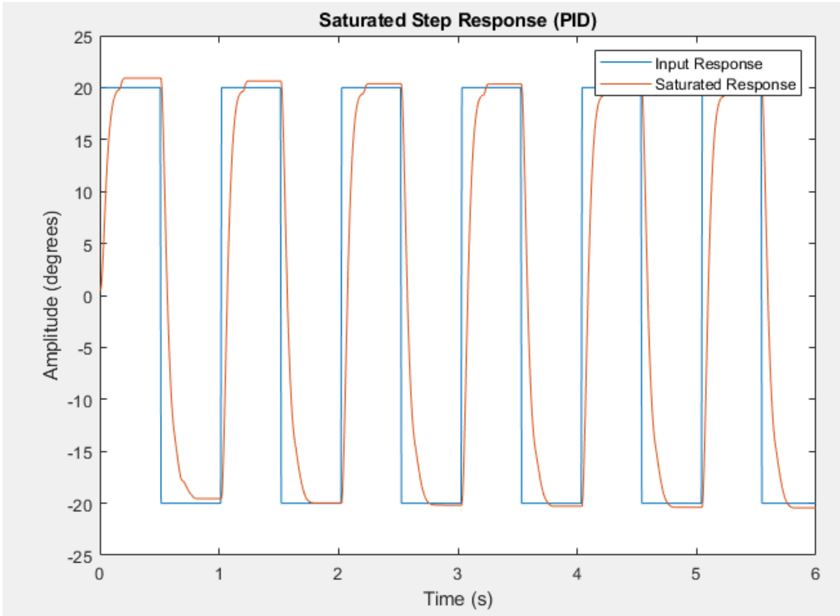

Figure 29. Saturated Step Response (PID)

Post-Lab Calculations and Discussions

Part 1: Uncompensated Simulated Servo Response in Nominal Range

1.

For the uncompensated servo, there were no nonlinearities that were apparent due to the fact that the response was within the nominal range. There was no saturation or dead-zone that can be seen in the graph.

2.

Table 7: Time Response Characteristics for Uncompensated & Compensated Systems (Simulated Servo)

Specifications	**Uncompensated System (P)**	**Compensated System (P)**	**Compensated System (PID)**
Percent Overshoot < 10%	22.92%	5.37%	0%
$T_{rise}(10\text{–}90\%) < 0.2$	0.135	0.1	0.164

secs			
Settling Time < 0.3 secs	0.349	0.334	0.295
ess(step) = 0	1.08	4.4	0.18
ess(ramp) < 1 rad/s	3.31	4.07	0.04

Part 2: Compensated Simulated Servo Response in Nominal Range

1. The step steady state error and the ramp steady state error of the proportional control were significantly greater than the PID control

2. The method that we used was the "Trial & Error" method. After a few tries we were able to find the appropriate gain value, derivative time constant and integral time constant to meet all of the required specs.

3. After tuning the anti-windup setting, we concluded that it did not make a significant difference. It only reduced the steady state error but not to a significant degree.

4. The final settings of the controller that gave us the best possible response for a square wave input are Kp = 0.5, $\tau_i = 2$, $\tau_d = 0.002$.

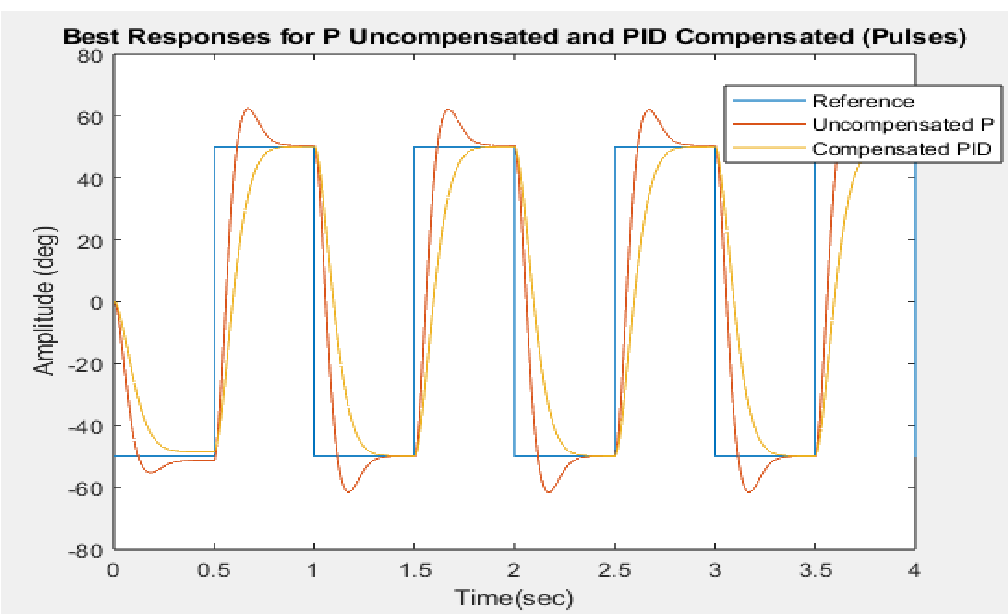

Figure 30. Best Responses for Proportional only Uncompensated system and PID Compensated for Pulse input

5.

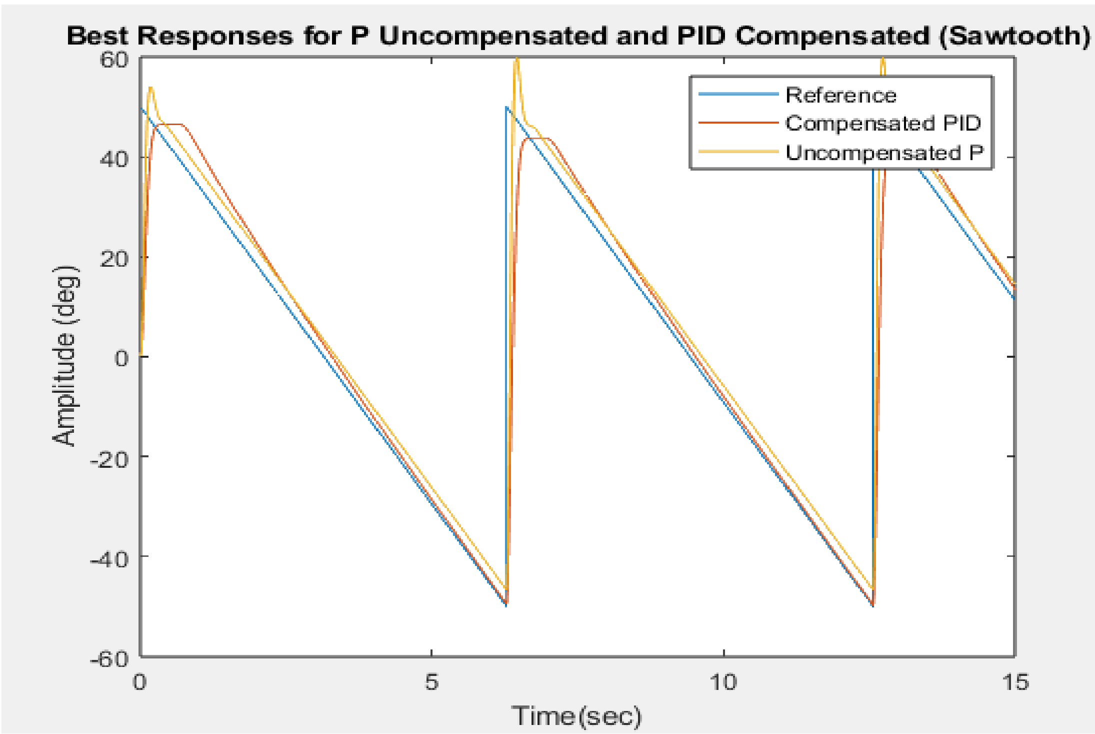

Figure 31. Best Responses for Proportional only Uncompensated system and PID Compensated for Sawtooth input

6. **Table 8** Time Response Characteristics for Uncompensated & Compensated Systems

Compensated System	**Proportional Gain *KP***	**Derivative Time Constant *τd***	**Integral Time Constant *τi***	**Rise-time *Trise* 10−90%**	**Percent Overshoot PO%**	**Settling-time *Tsettle* (±2%)**	**Steady state error *ess* (*step*)**	**Steady State error *ess* (*ramp*)**
Uncompensated Proportional Controller ***KP*** = 1	1	0	10^10	0.35	0.96s	0.47 s	0.68%	2.14 rad
Proportional Controller (Compensated)	0.8	0	10^10	0.1	5.37	0.334	4.4	4.07
PID Controller (Compensated)	0.5	0.002	2	0.164	0	0.295	0.18	0.04

For the Uncompensated Proportional Controller, only 2 specifications were met, which were the percent overshoot and the steady state error which was met just about. For the Compensated Proportional Controller only 2 specifications were met, which were the percent overshoot and the rising time. For the Compensated PID Controller, all 5 specifications were met. This was achieved by using the trial and error method. The reason why the specs were not met in those above mentioned controllers were due to the specific parameters that were given to us and also the gain being within the nominal range, which limits the range of possible values of gain.

7. In the P controller of the compensated system, an extra specification was met which was the rising time. As for the PID controller of the compensated system, all 5 requirements were met which is a huge improvement from the uncompensated system. The step steady state error reached very close to 0 or technically 0 and the ramp steady state error was within 0.3 rads. The transient response performance also improved.

Part 4: Uncompensated Simulated Servo Response in Nominal Range

1.
When an input of 50 degrees of square was implemented on the real time servo, no non-linear effects were observed, as it operated in the nominal range as predicted by the Matlab simulation.

2.From the table –, we can see that the uncompensated system meets the design requirements for percent overshoot, where it is less than 10%. It meets the step error percentage, as it has a step error of 0.68%, which is quite close to zero. It fails to meet the rise time, settling time, and ramp error specifications. The system provides a settling time of 0.47 seconds, when less than 0.3 seconds is required. The rise time must be under 0.2 seconds, but the system provides 0.35 seconds. Finally, less than 0.03 radians are required for the ramp error, but the system provides an error of 2.14 radians.

Part 5: Compensated Servo Module Response in Nominal Range

1.
From tables 5 and 6, we can see that the percent overshoot increases by 85% from 0.16% in the proportional only control to 0.85% in the PID control. Likewise, the step error percent increased from 0.1544% in the proportional only control to 0.86% in the PID control. The settling time increases as well, by a small margin of 0.0136 seconds from the proportional only control to the PID control. The rise time increased from 0.12667 seconds in the proportional control to 0.19336 seconds in the PID control. The ramp error increased from proportional to the PID controller, a change in 0.00025 radians is seen.

It can be observed that all performance metrics increased from the proportional to the PID control; however, using the PID settings mentioned in table 6, we were able to meet the design requirements of the lab project.

2.
To achieve the required performance metrics, the trial and error method was used. Beginning with arbitrary values for the proportional, time and derivative constants, the system response of the real time servo was plotted on matlab, where each individual performance metric was calculated. If the performance metrics did meet the requirements, the proportional, time and derivative constants were modified until the metrics met the requirements of the lab project.

3.
We did experiment with the anti-windup controller, at settings of 0.3, 0.8, and 1; however, it did not make a huge difference in our compensated system response.

4.
The final settings of the controller that gave us the best possible response for a square wave input are Kp = 1.8, $\tau_i = 2.5$, $\tau_d = 0.004$.

5.

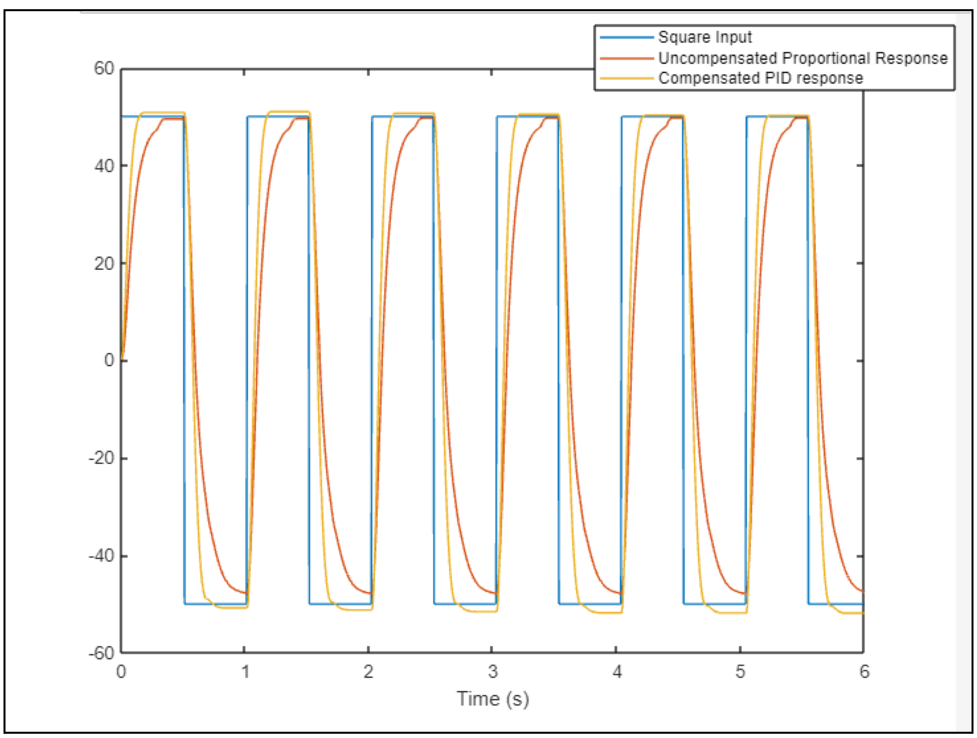

Figure 32. Graph of the square wave input, uncompensated only proportional response, compensated PID response, given in blue, orange, and yellow respectively.

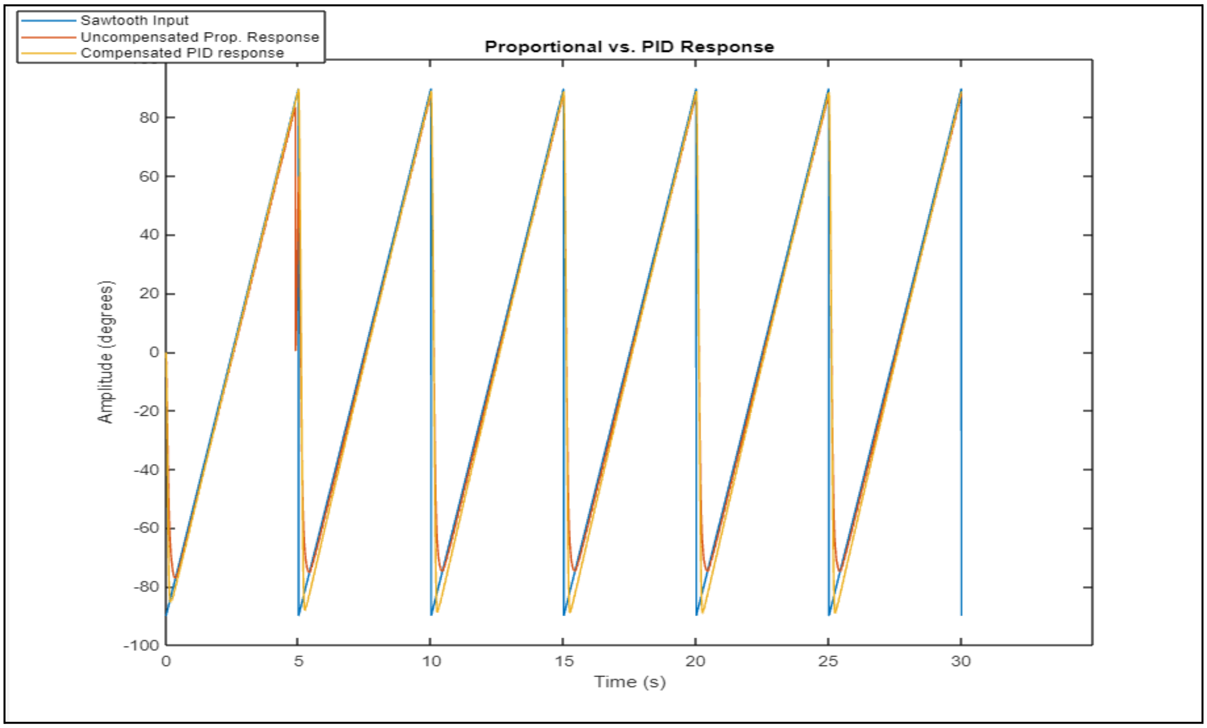

Figure 33. Graph of the sawtooth input, uncompensated only proportional ramp response, compensated PID ramp response, given in blue, orange, and yellow respectively.

As we can see from the figures 32 and 33, as well as the tables above, we get a better performance from the compensated PID system, compared to the uncompensated proportional only system in both the square and sawtooth input waves.

6. **Table 9** Time Response Characteristics for Uncompensated & Compensated Systems

Compensated System	**Proportional Gain *KP***	**Derivative Time Constant *τd***	**Integral Time Constant *τi***	**Rise-time *Trise* 10−90%**	**Percent Overshoot PO%**	**Settling-time *Tsettle* (±2%)**	**Steady state error *ess* (*step*)**	**Steady State error *ess* (*ramp*)**
Uncompensated Proportional Controller ***KP*** = 1	1.0	0	10^10	0.135	22.92	0.349	1.08	3.31
Proportional Controller (Compensated)	1.58	–	–	0.12667s	0.16 %	0.25334 s	0.1544%	0.0239 rad

PID Controller (Compensated)	1.8	2.5	0.004	0.193365 s	0.85 %	0.267 s	0.86 %	0.02145 rad

From the table 9 above, it can be seen that the rise time, percent overshoot, settling time, and steady state step and ramp error are met by the compensated proportional and PID controller. The uncompensated proportional controller meets the percent overshoot, steady state error, but fails to meet the rise time and settling time requirements. Unfortunately, due to only one parameter being available to change, we were unable to meet all the performance requirements.

7.
From the table and graphs above, it can be seen that as the performance of each metric improves from the uncompensated system to the compensated system, as the steady state step and ramp error decrease quite dramatically. However, the compensated proportional one controller was found to have the best performance across all metrics.

Part 6: Compensated Servo Module Response outside Nominal Range

1.
We can see from figures 27 and 28, it can be seen that the saturation effects are quite high, and the performance specifications have not been met, when the input is 200 degrees square wave. It can also be noted that the anti-windup factor has very little effect in controlling the saturation of the system response of the real time servo. It can be seen that the system takes longer to settle than in the nominal range, and the steady state error seems to be larger than the steady state error in the nominal range.

2.
We can see from the figure 29, that the system is in the deadzone, when the input is a square wave with an amplitude of 20 degrees. It can be seen that the performance metrics have not been met, with a long rise time, and a larger steady state error, than the system in the nominal range.

Part 7: Observed Differences between Simulated Servo and Servo Module Behaviors

One of the differences between the simulated version and the real version was the steady state error. The number for the simulated version seems more logical compared to the real version. When comparing the saturated versions of both we can see that the percent overshoot in the simulated version is much higher than the real version. Same with the dead-zone versions. The settling time was lower in the simulated version.

Conclusion

In conclusion, through the experiments of this lab, it was found that the controller that met the performance requirements the best was the compensated proportional only controller. Followed by the PID controller, and the uncompensated proportional controller. Through this lab, it was also found that the system saturates when the input amplitude is higher than the nominal range input amplitude of 50 degrees. The system also entered the dead zone when the input amplitude is lower than the nominal range amplitude.