Introduction to Robotics ME 639

Industrial Project final Presentation

Project Title: Development of Series Elastic Actuator Unit & Controller

Team Name: Top Guns

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Instructor: Prof. Harish PM

Teaching Assistant: Suraj Borate

Problem Statement:

In general, actuators are built to be as stiff as possible to increase the bandwidth. When a robot works in a structured environment, its automation is easier than in a non-structured environment in which its modeling is quite difficult and presents a high computational effort. To overcome this difficulty, Series Elastic Actuator (SEA) has been applied in compliant robotic grasping. SEA contains an elastic element in series with the mechanical energy source like drive motor. Such an elastic element gives SEAs tolerance to impact loads, low mechanical output impedance, passive mechanical energy storage, and increased peak power output. Series Elastic Actuators provide many benefits in force control of robots in unconstrained environments. These benefits include high force fidelity, extremely low impedance, low friction, and good force control bandwidth.

Industry name: **ISRO**

Objectives:

- **To design and develop a SEA unit consisting of drive motor, gear train unit, compliance element such as linear/torsional spring, position encoder.**
- **To develop a controller for the SEA**

Rationale / Approach / Ideas:

1. Design of the Actuator- SolidWorks
2. Design of the Controller-Simulink
3. Simulation of the Actuator-Simscape or Hyperworks for visualisation

Deliverables:

Initial:

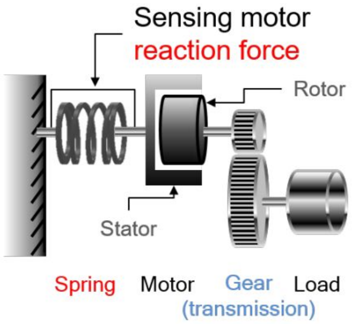
- A brief explanation of the concept (including type of robot, number of links and joints, and other such details)
- Figures/drawings/sketches/CAD showing the concept
- Relevant equations of the robotics solution
- Codes incorporating the solution
- Representative plots/or other representative results from the codes
- Explanation of the solution and the results

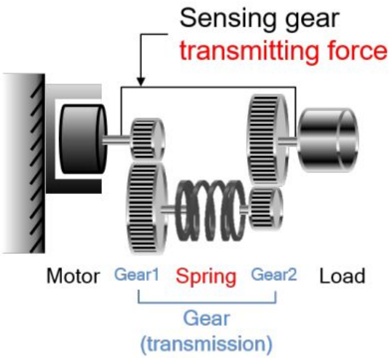
Extra:

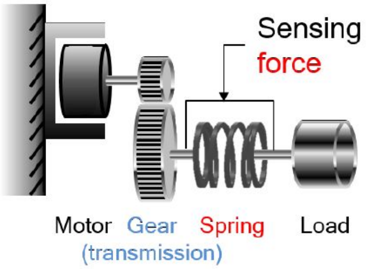
- Literature review of different configuration
- Analysis of different control strategies

Different Configurations:

- ❑ Reaction Force Sensing Series Elastic Actuator(RFSEA)
- ❑ Transmitted Force Sensing Series Elastic Actuator(TFSEA)
- ❑ Force Sensing Series Elastic Actuator(FSEA)-**Chosen Configuration**







Source:[1]

Why FSEA??

- **Force Sensitivity:**
  - Highest magnitude of force sensitivity compared to other two configurations
- **Compliance:**
  - FSEA, TFSEA & RFSEA shows similar response in the lower frequency range.
- **Transmissibility:**
  - Torque transmission efficiency of FSEA is slightly lower than RFSEA & TFSEA in the high frequency range and almost similar in the low frequency range.
- **Compactness & Application:**
  - Compact and generic (from application point of view).

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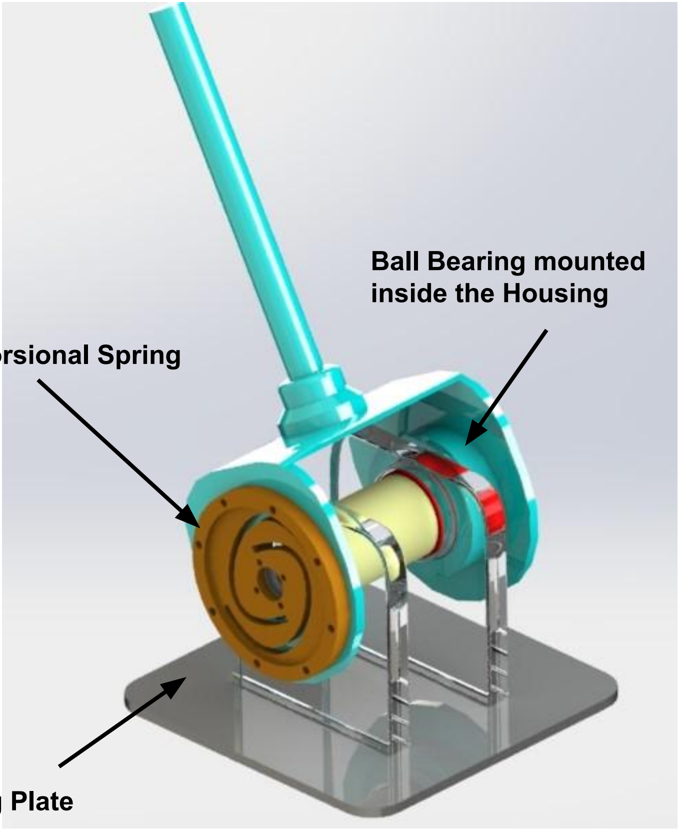
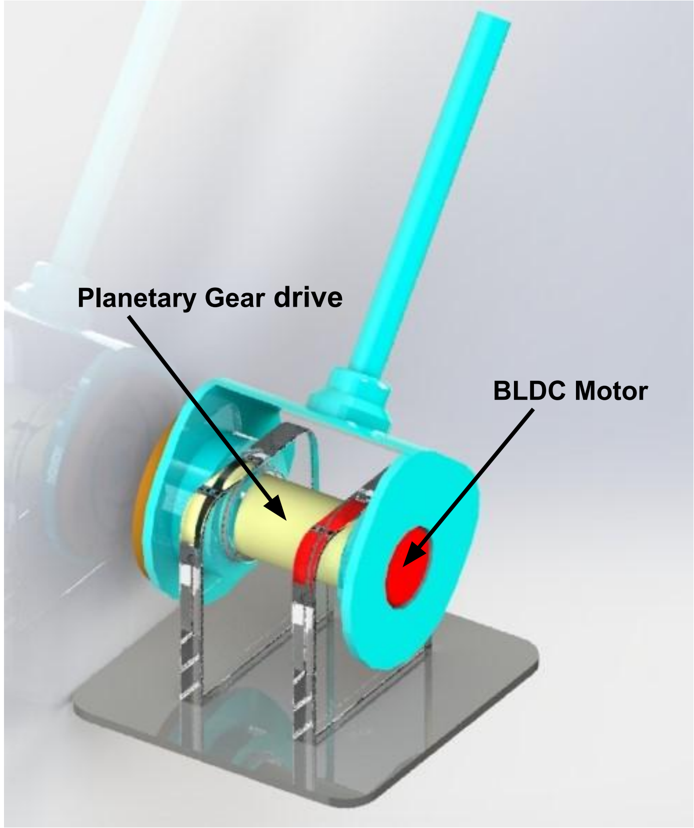
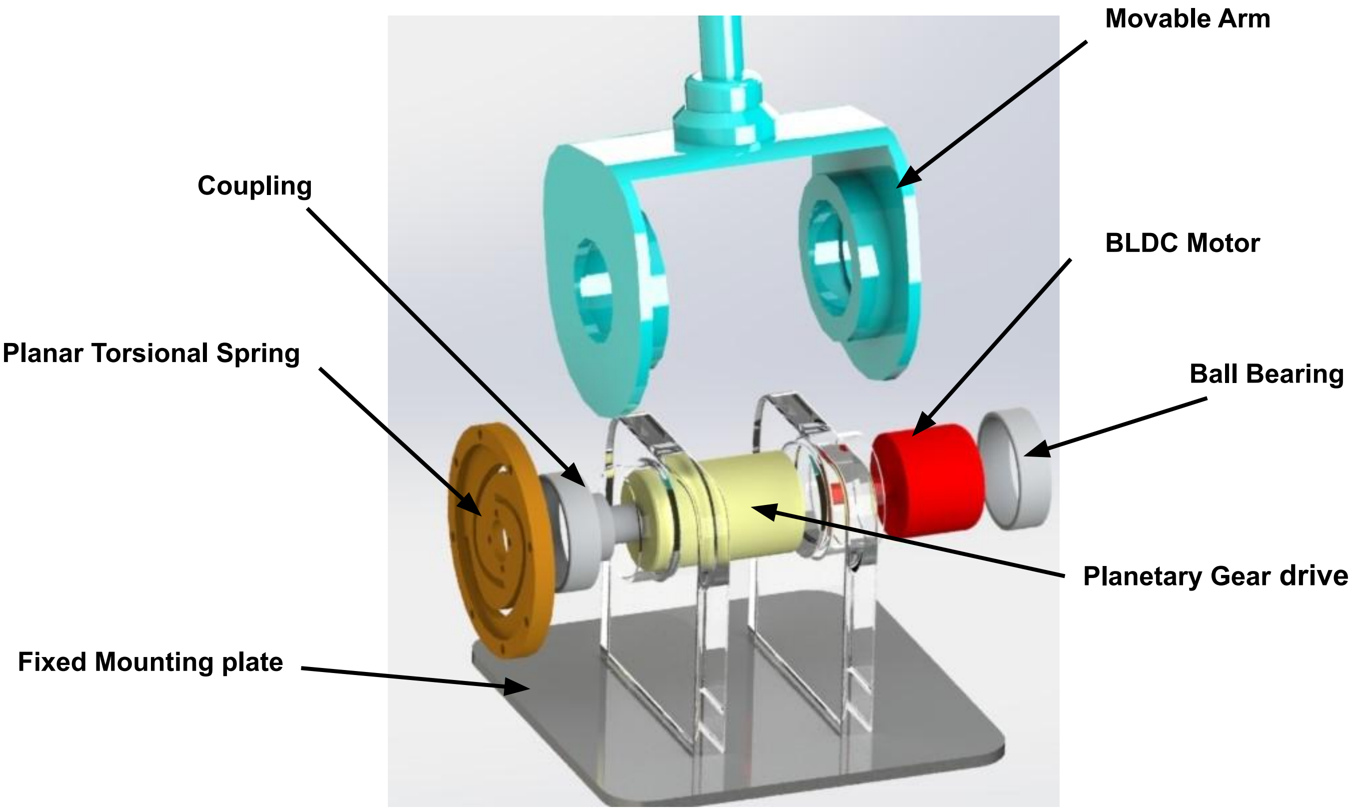
CAD Design of the FSEA



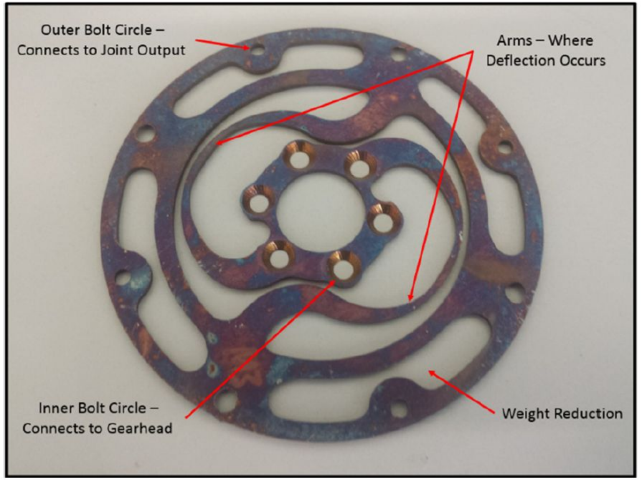


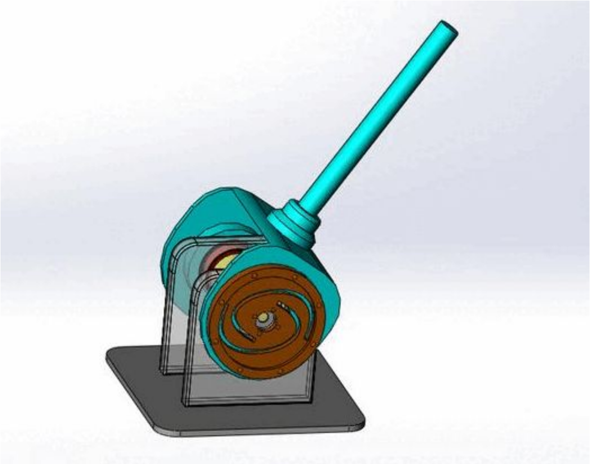
Exploded View



Spring

- Spring under consideration is Planar torsional spring.
- Spring constant is linearly proportional to the thickness of the geometry.





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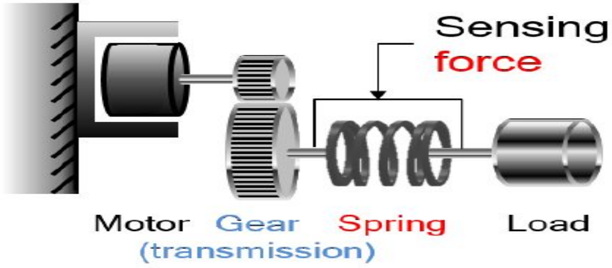
Differential equations of selected configurations

- FSEA configuration:

$$\tau_s = k(N^{-1}\theta_m - \theta_l)$$

$$J_m\ddot{\theta}_m + B_m\dot{\theta}_m = \tau_m - N^{-1}\tau_s$$

$$J_l\ddot{\theta}_l + B_l\dot{\theta}_l = \tau_l + \tau_s$$



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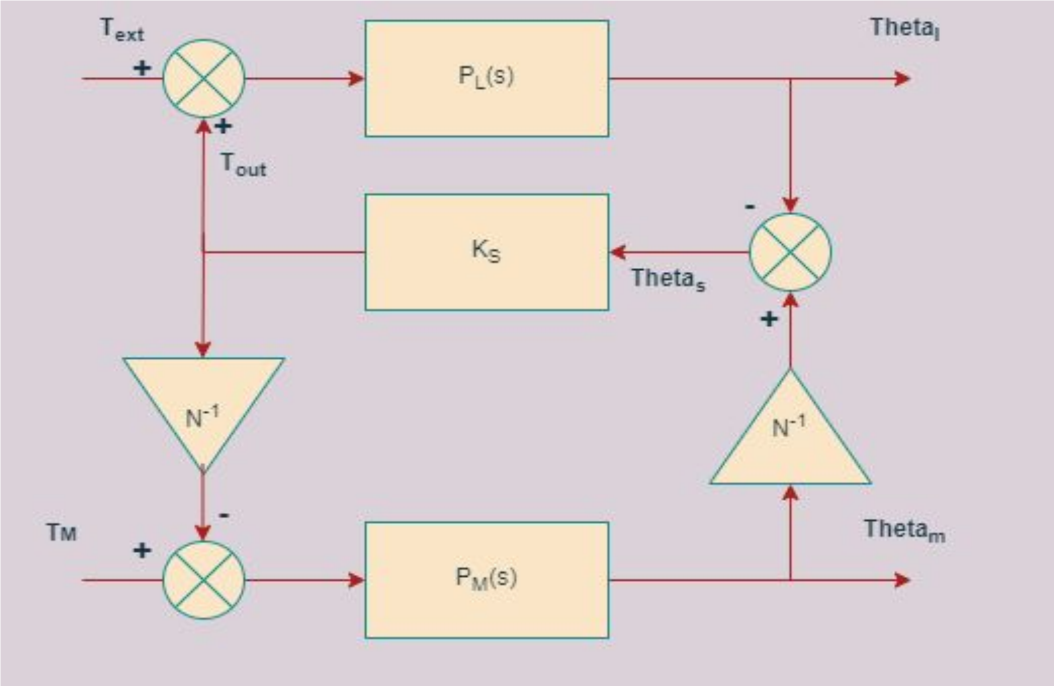
FSEA

	$\theta_m(s)$	$\theta_s(s)$	$\theta_l(s)$	$\tau_s\ (s)$
$\tau_m(s)$	$\frac{P_m(s)\left[P_l(s)+K_s^{-1}\right]}{D(s)}$	$\frac{N^{-1}P_m(s)K_s^{-1}}{D(s)}$	$\frac{N^{-1}P_m(s)P_l(s)}{D(s)}$	$\frac{N^{-1}P_m(s)}{D(s)}$
$\tau_l\ (s)$	$\frac{N^{-1}P_m(s)P_l(s)}{D(s)}$	$\frac{P_l(s)K_s^{-1}}{D(s)}$	$\frac{P_l(s)\left[N^{-2}P_m(s)+K_s^{-1}\right]}{D(s)}$	$\frac{P_l(s)}{D(s)}$

where $D(s) = P_l(s) + N^{-2}P_m(s) + K_s^{-1}$.

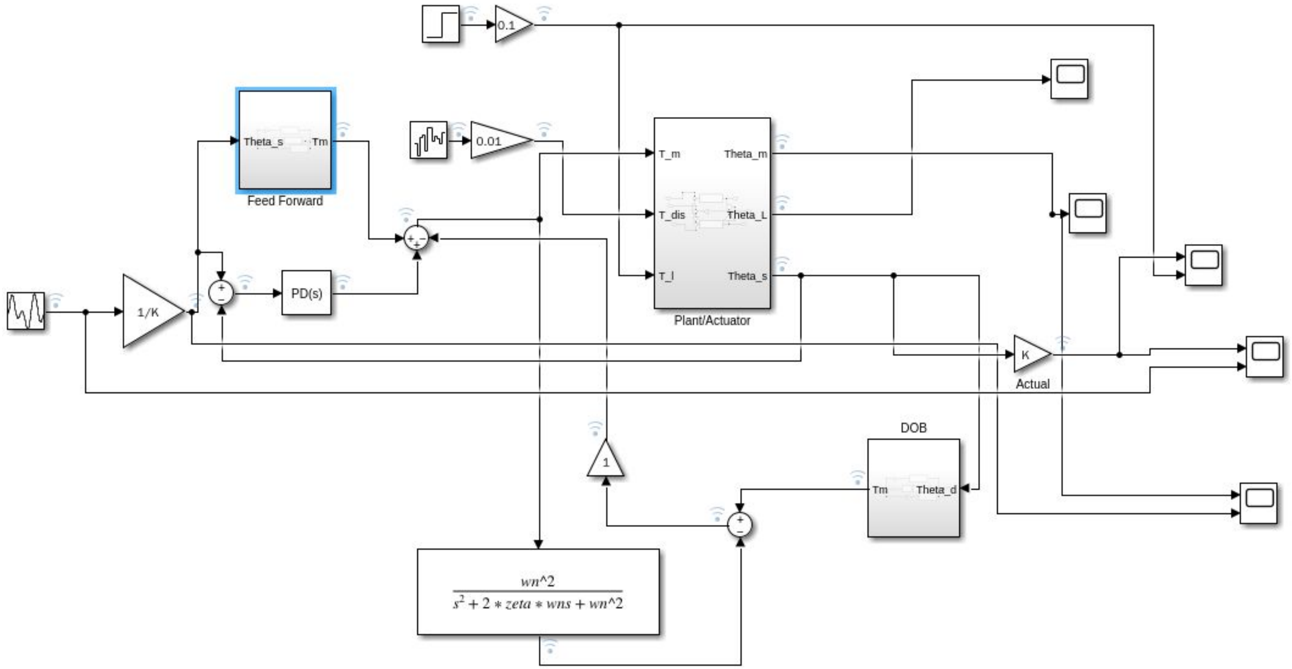
PL(s)= $\frac{1}{J_l s^2 + B_l s}$

PM(s)= $\frac{1}{J_m s^2 + B_m s}$



SCHEMATICS:

COMPLETE SYSTEM WITH DOB AND PID



SCHEMATICS:

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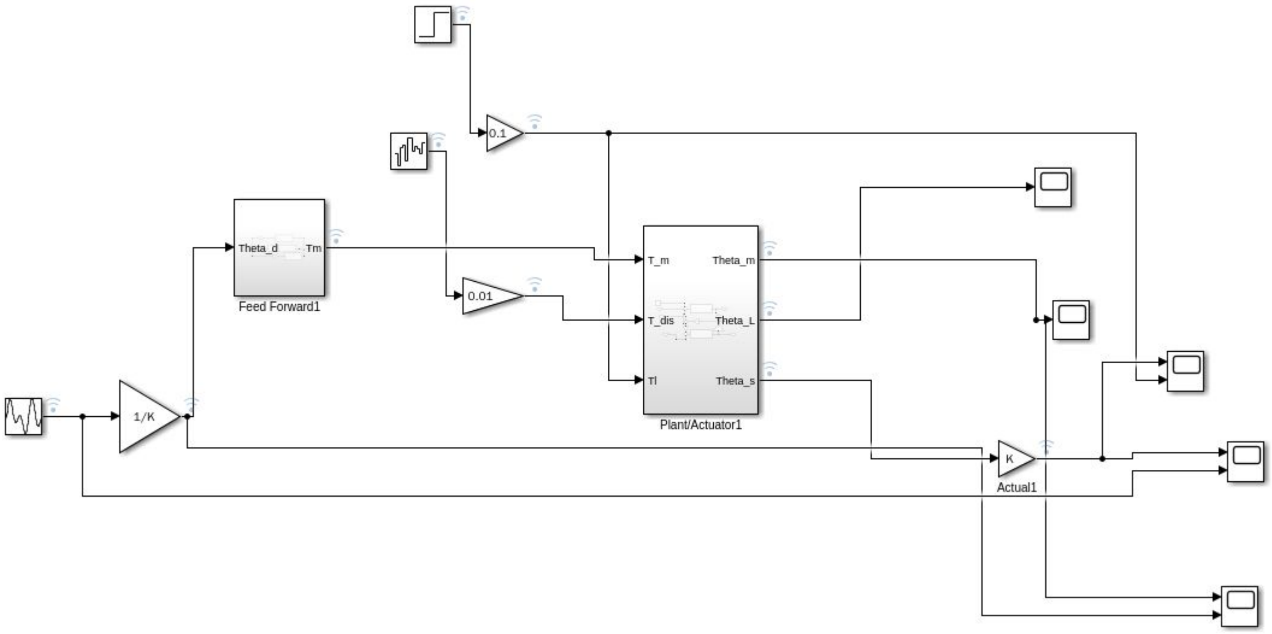
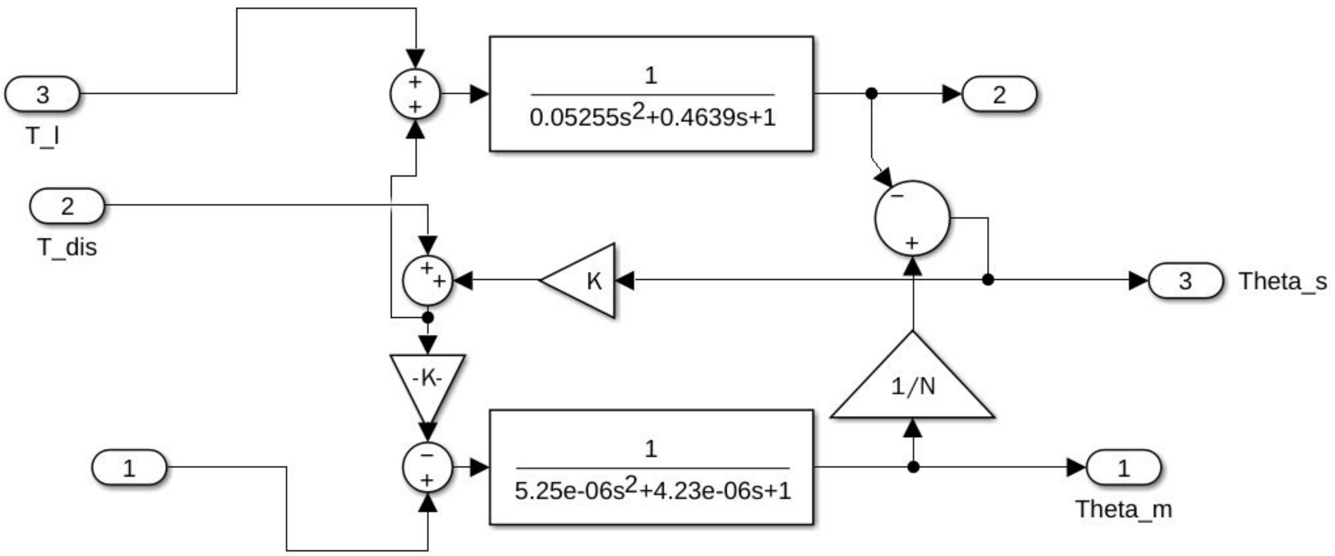
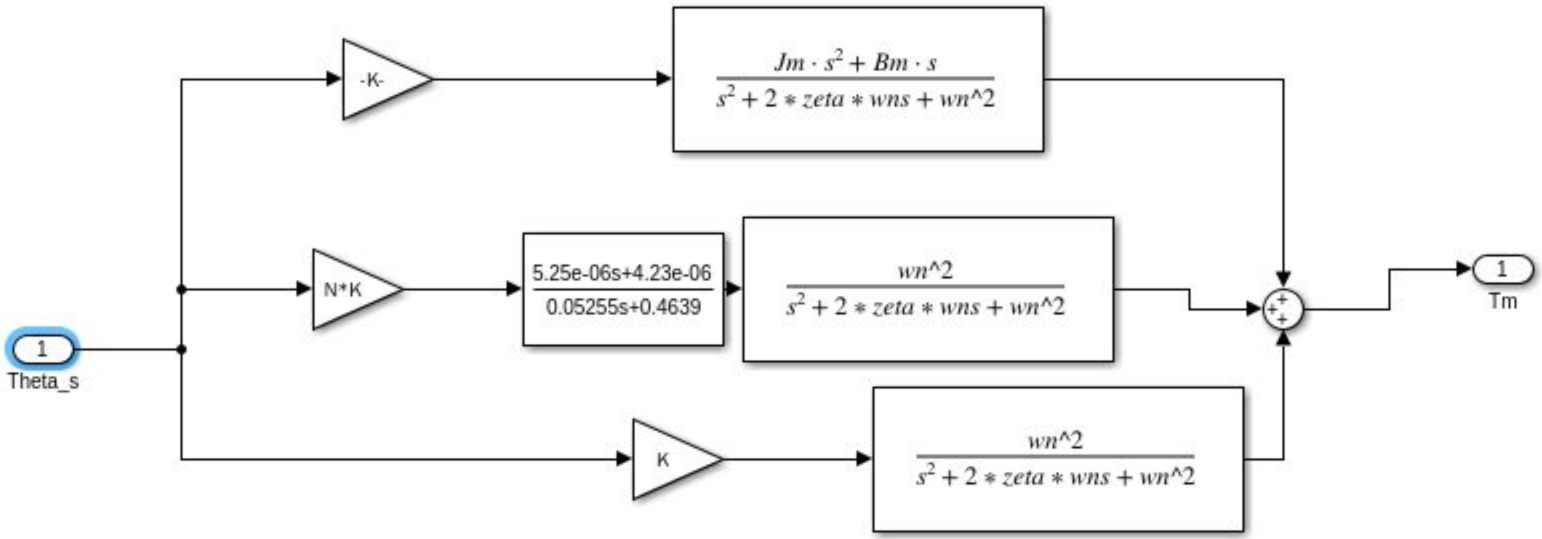


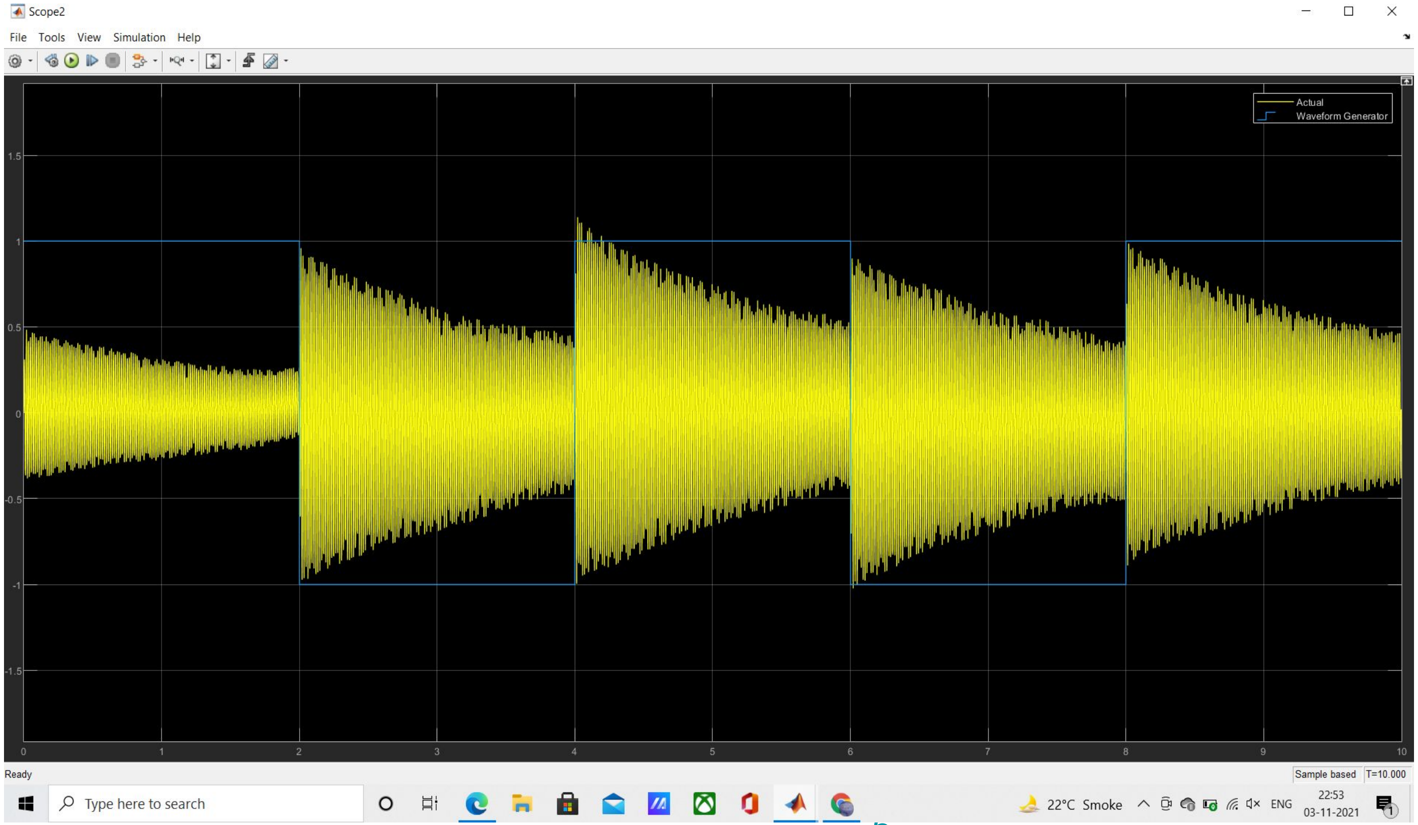
SCHEMATICS: PLANT/ACTUATOR



SCHEMATICS: FEED FORWARD

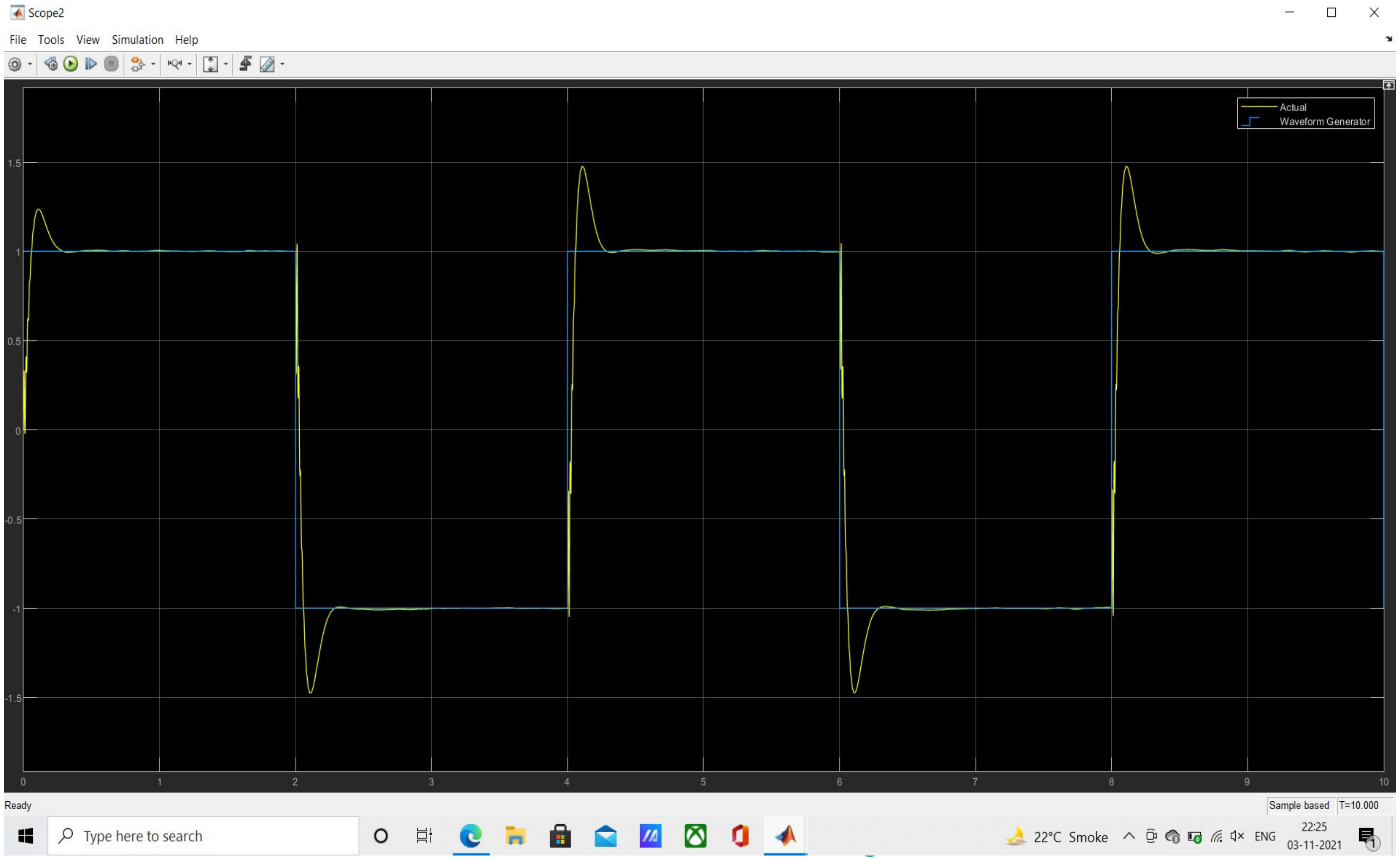


Key Results 1 before Feedback and DOB control:



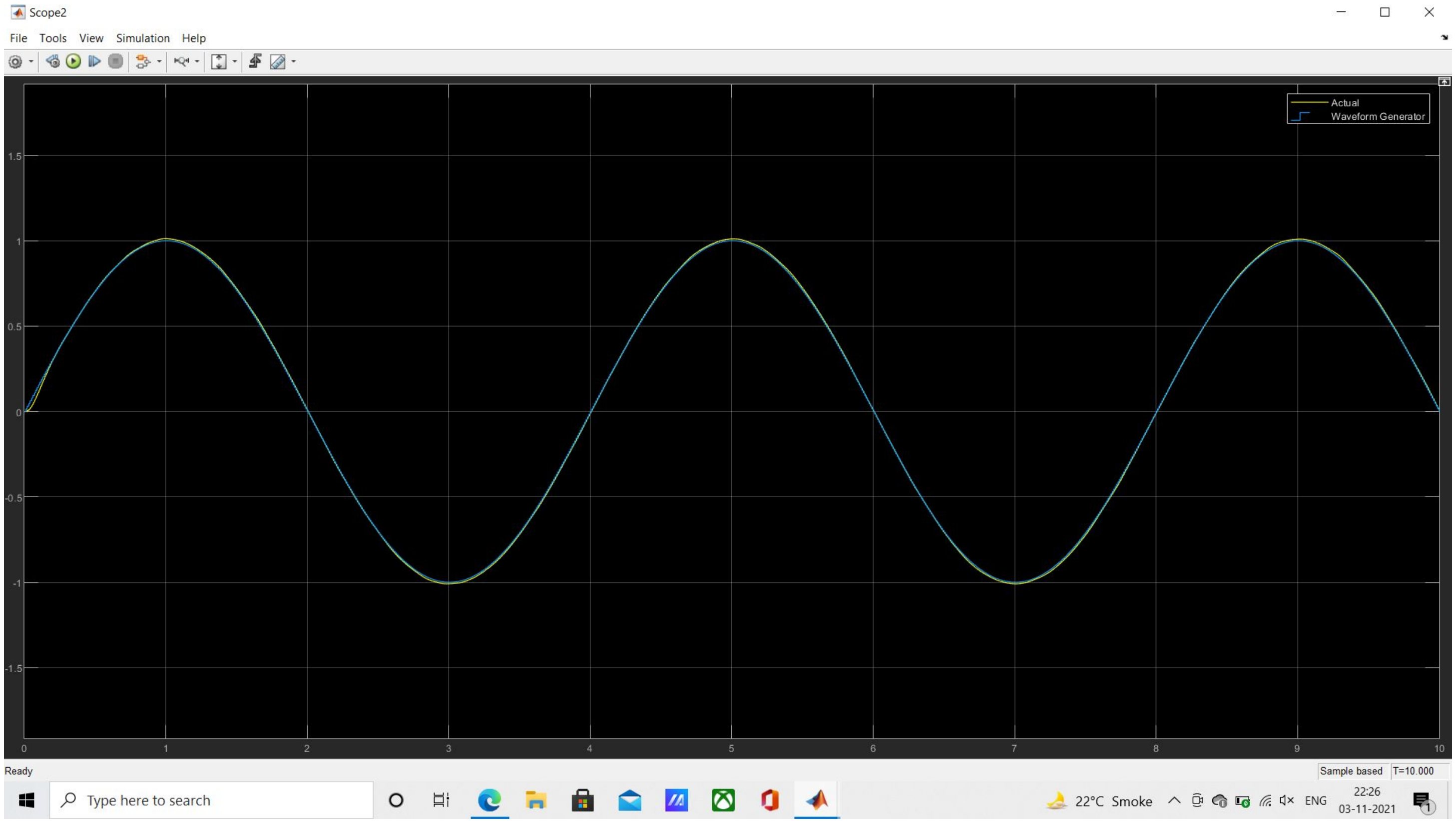
Blue is T Desired
Yellow is Toutput

Key Results 2 after Feedback and DOB control for SQUARE input Torque:



Blue is T Desired
Yellow is Toutput

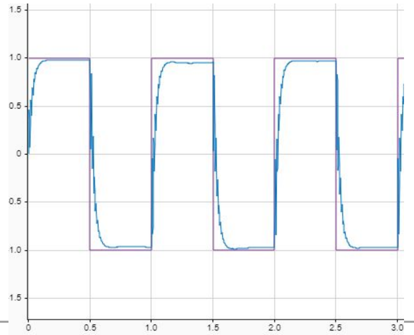
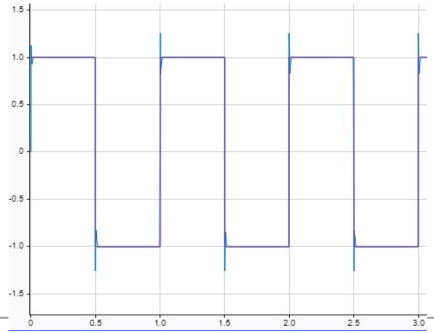
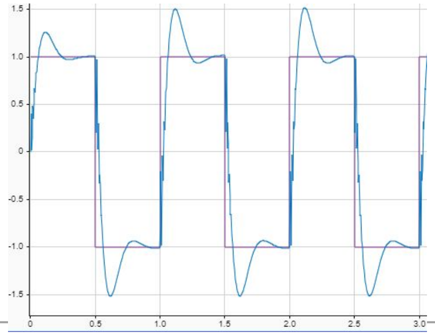
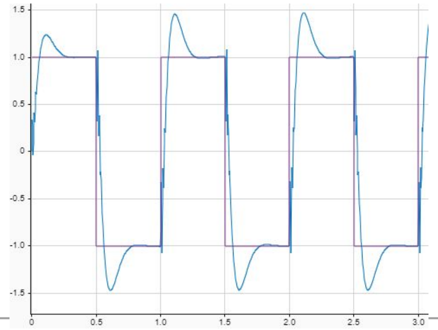
Key Results 3 after Feedback and DOB control for Sinusoidal input Torque:



Blue is T Desired
Yellow is Toutput

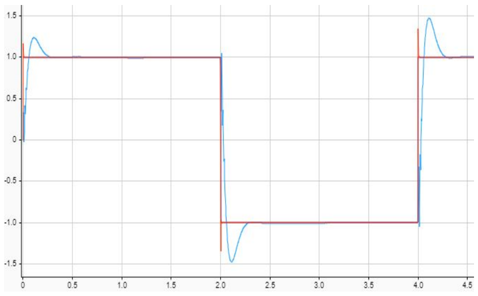
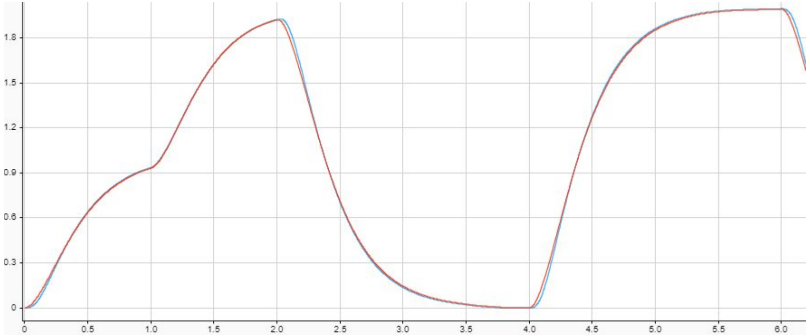
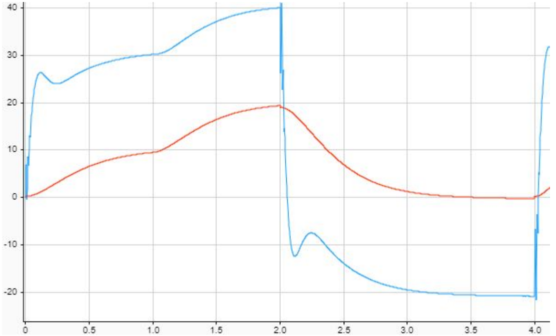
Square Wave response comparison for P, PD, PI, PID feedback

Stiffness, k =0.48 Nm/rad, Square Wave Amplitude = 1Nm, frequency= 1Hz

P	PD	PI	PID
			
• Small Settling time • Steady state error • No overshoot	• Overshoot (25%) • Smallest settling time • Jerky response • No steady state error	• Overshoot(50%) • Largest settling time • Smooth response • No steady state error	• Overshoot(45%) • Large settling time • Smooth response • No steady state error

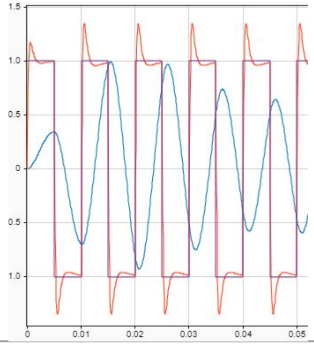
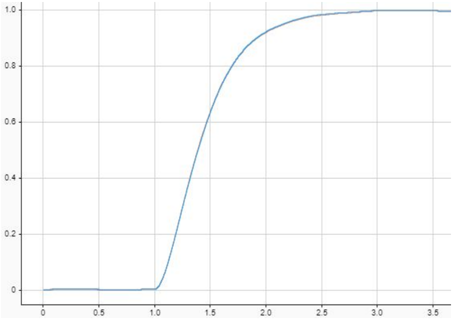
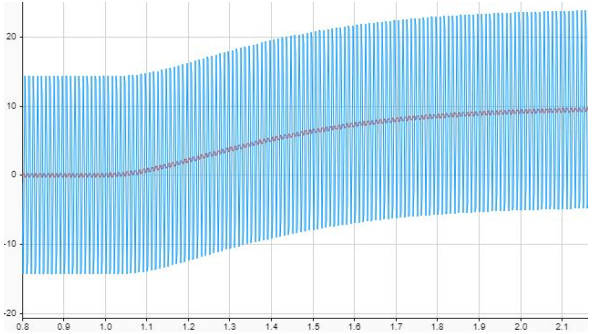
Square Wave response comparison for k=0.48 Nm/rad and k =48Nm/rad at 0.25Hz

Purple - Desired, Orange - k=48, blue - k=0.48

Output spring torque	Load displacement	Motor displacement
		
• Low stiffness spring results in more settling time than higher stiffness • Overshoot is more in low stiffness	• Load side displacement remains same for both the spring stiffness • Load displacement independent of spring stiffness	• Motor displacement of low stiffness is about double of higher stiffness. • Low stiffness system has more oscillations in motor displacement

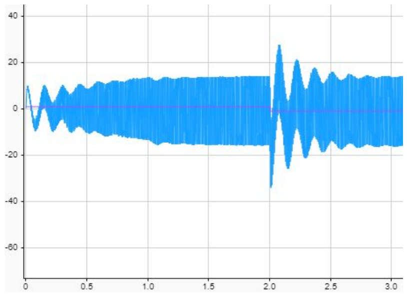
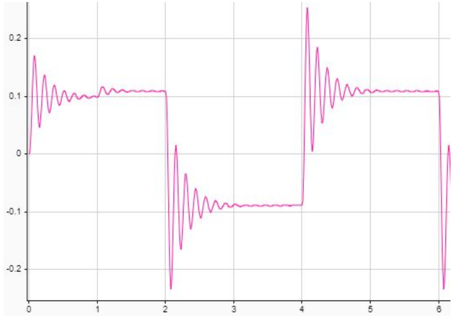
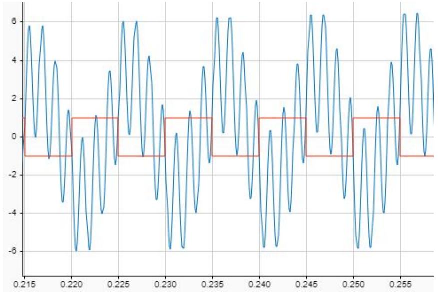
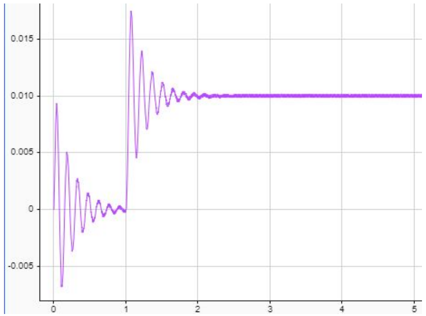
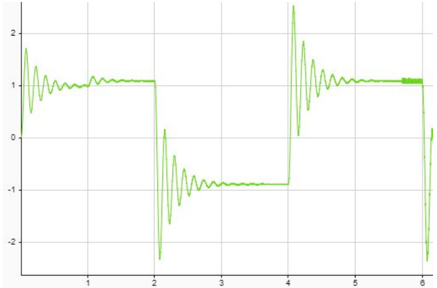
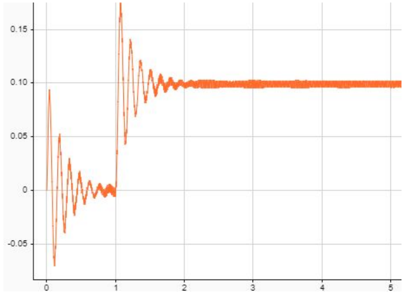
Square Wave response comparison for k=0.48 Nm/rad and k =48Nm/rad at 100Hz

Purple - Desired, Orange - k=48, blue - k=0.48

Output spring torque	Load displacement	Motor displacement
		
● Low stiffness unable to regenerate on time whereas the high stiffness is stable at high frequency. ● Higher stiffness -> stable at higher frequency	● Load side displacement remains same for both the spring stiffness ● Load displacement independent of spring stiffness	● Motor displacement of low stiffness is about double of higher stiffness. ● Low stiffness system has more oscillations in motor displacement

Square Wave response for Very High stiffness(Rigid) without feedback

Stiffness, k =10000 Nm/rad

<table>
<tr><td colspan="2">Frequency = 0.25 Hz</td><td colspan="2">Frequency = 100Hz</td></tr>
<tr><td>Output spring torque</td><td>Load displacement</td><td>Output Spring Torque</td><td>Load displacement</td></tr>
<tr><td>
</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Large deviation from desired response
High oscillatory response</td><td>Motor displacement

</td><td>Overshoot is high
Oscillatory</td><td>Motor displacement

</td></tr>
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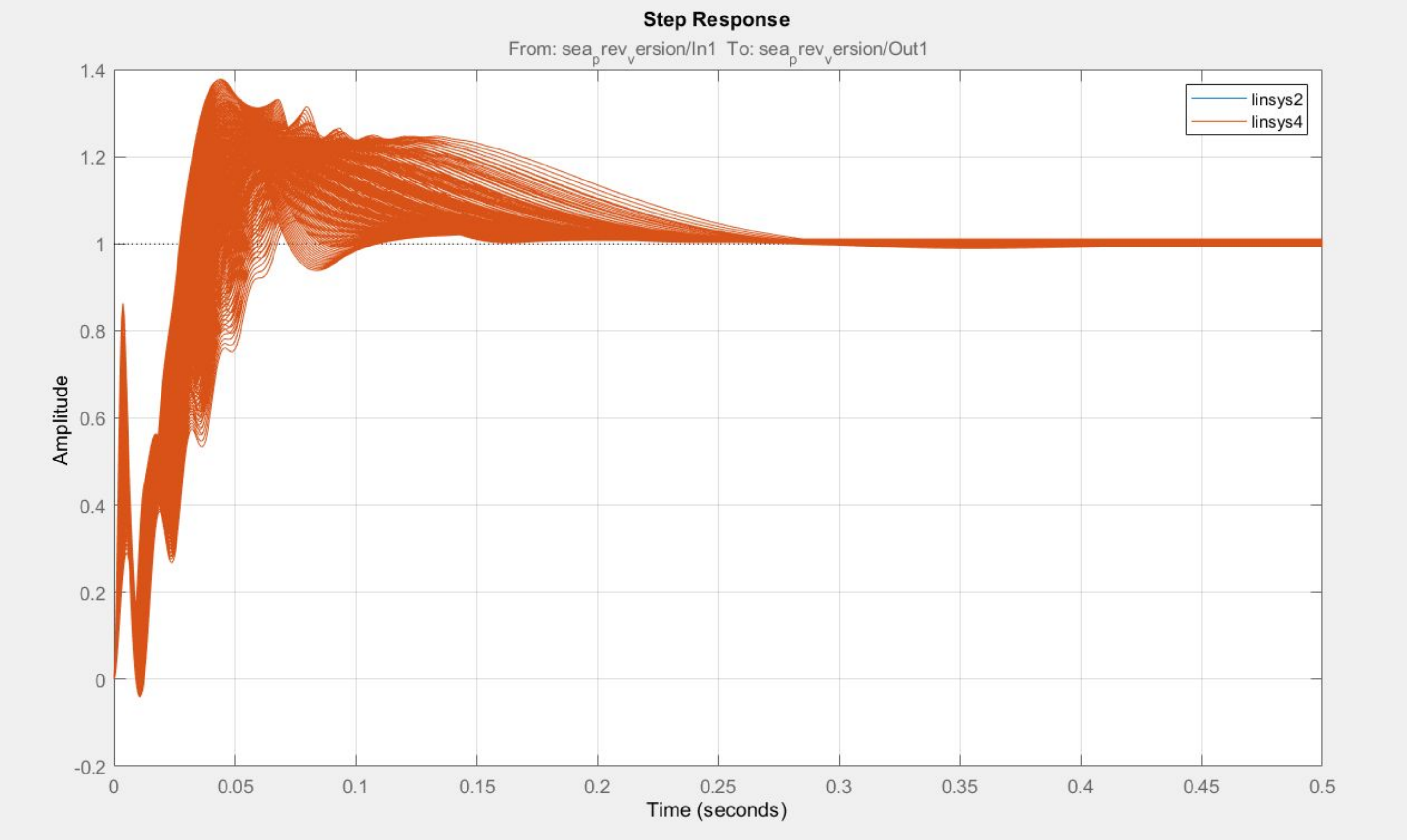
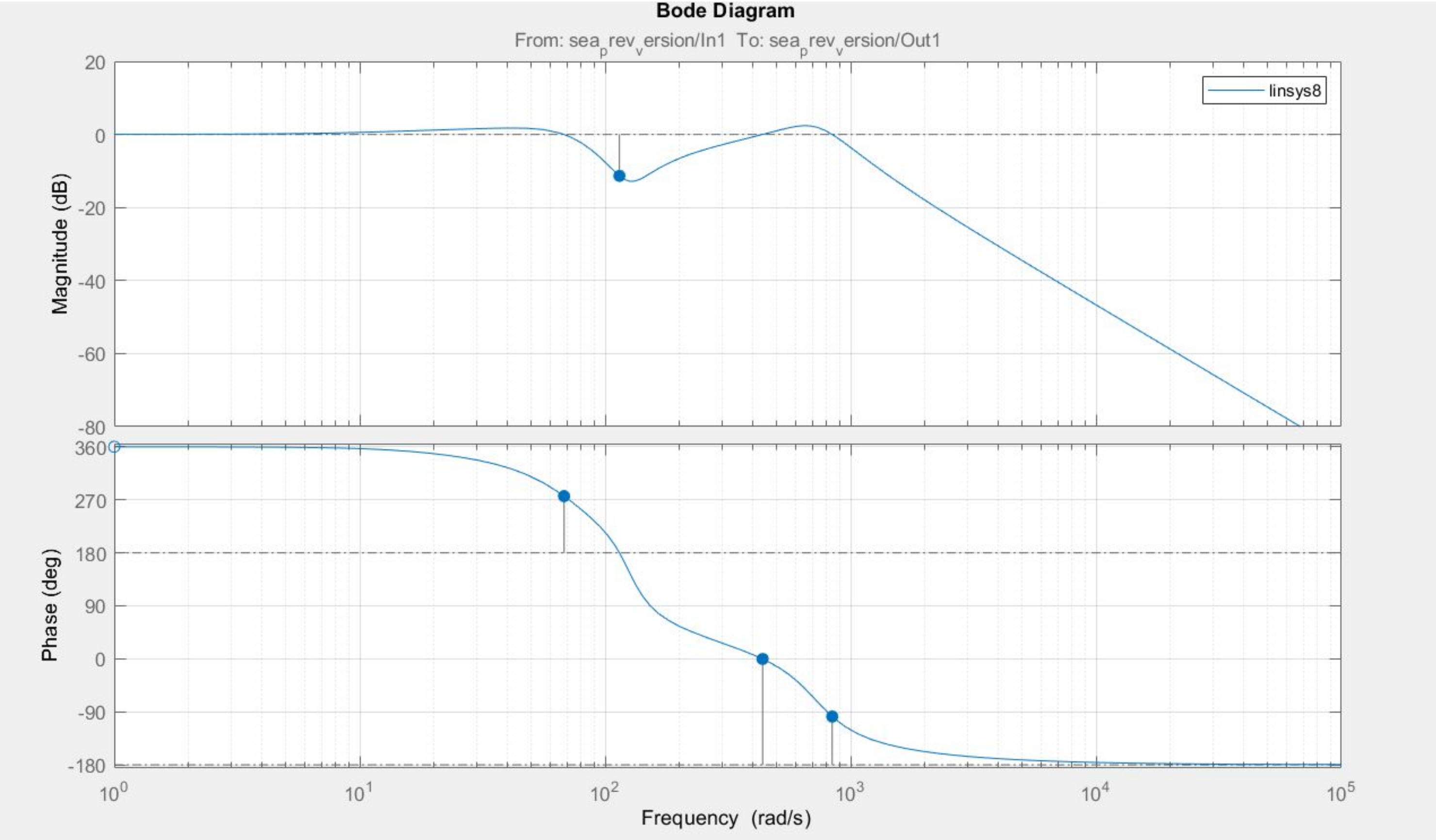
Step Response:

2nd order filter:
Zeta range(0.38-0.78)
Wn range(280-680)

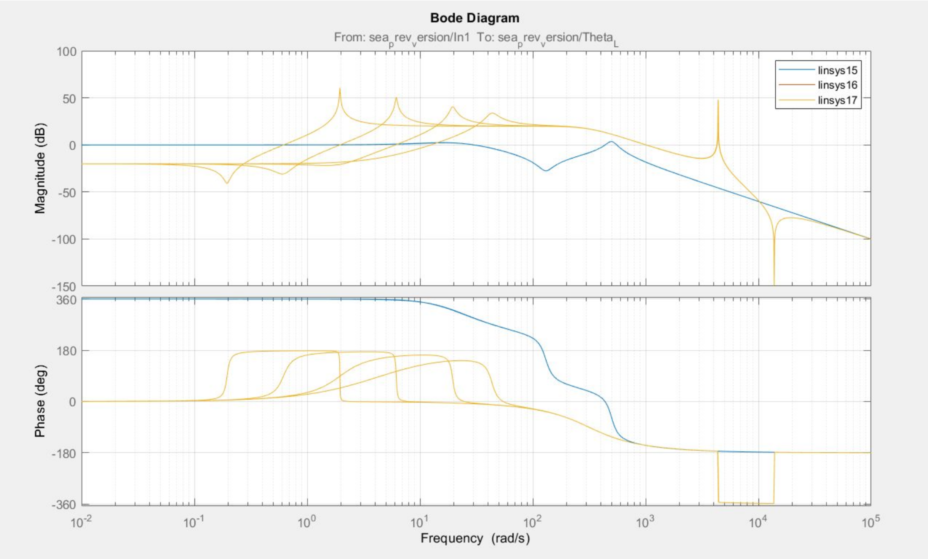
Its observed that the variation of the above results in better response at higher frequency

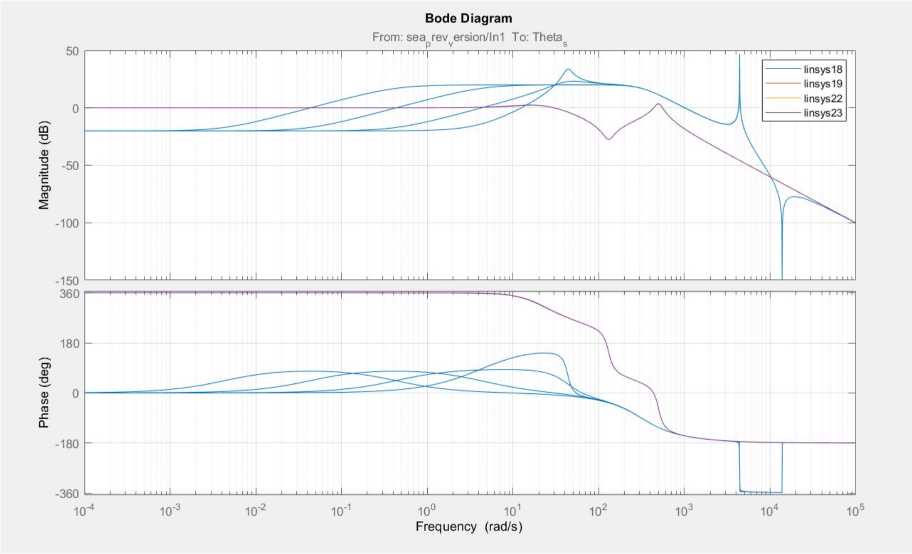


STABILITY: Wpc >Wgc



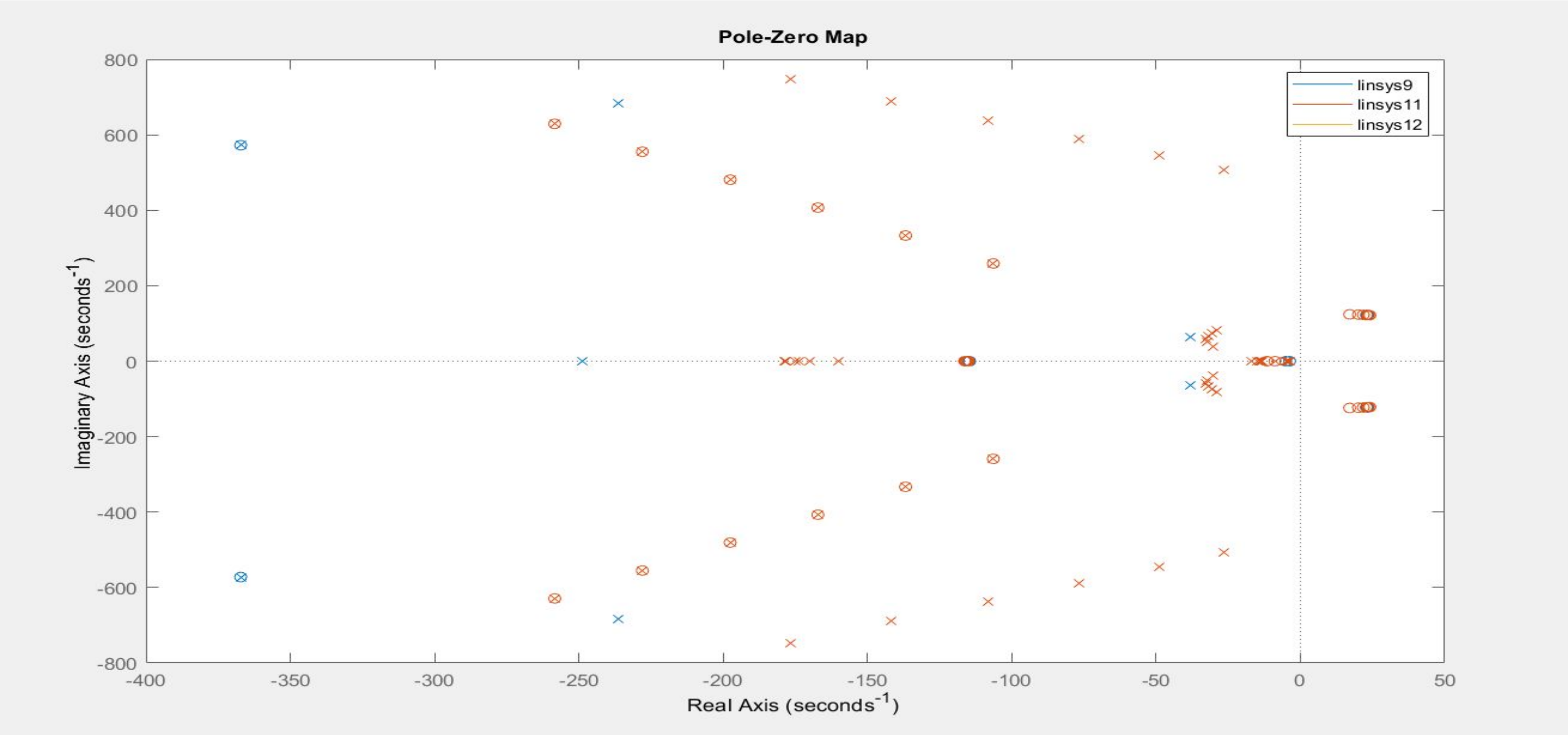
ROBUSTNESS:





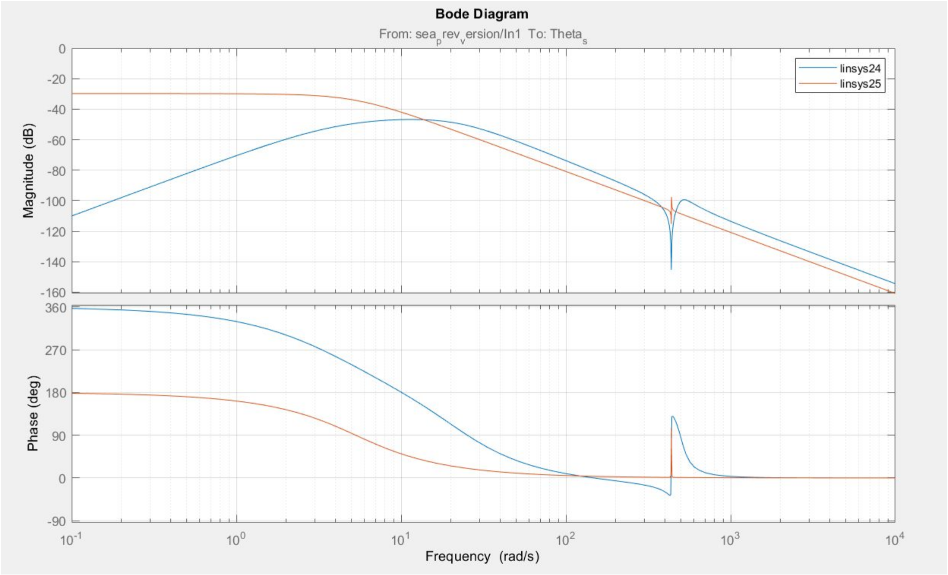
We observe the Robustness of SEA wrt a Stiff Actuator With respect to variation in Jl and Bl

Pole zero comparison:

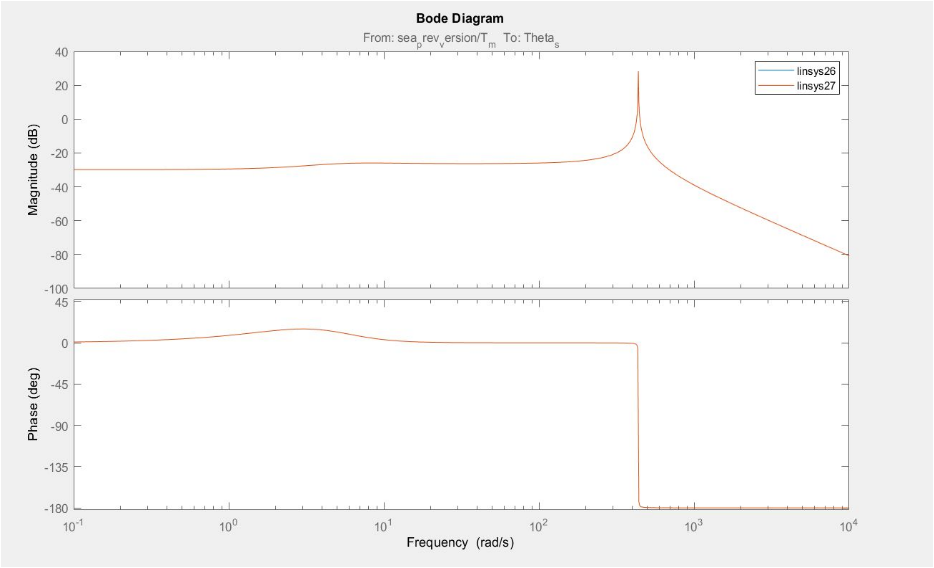


We observe that the Tm as input and ThetaL vs ThetaS which shows has poles more away from origin

Force Sensitivity:θs(s)/Tl(s)



Transmissibility:Ts(s)/Tm(s)



We observe that the Force sensitivity is better in Stiff actuator compared to SEA Transmissibility is same

References:

1. Lee, C., Kwak, S., Kwak, J. and Oh, S., 2017, September. Generalization of series elastic actuator configurations and dynamic behavior comparison. In Actuators (Vol. 6, No. 3, p. 26). Multidisciplinary Digital Publishing Institute.
2. Qiu, F., Michizono, S., Miura, T., Matsumoto, T., Omet, M. and Sigit, B.W., 2015. Application of disturbance observer-based control in low-level radio-frequency system in a compact energy recovery linac at KEK. Physical Review Special Topics-Accelerators and Beams, 18(9), p.092801.
3. Oh, S. and Kong, K., 2016. High-precision robust force control of a series elastic actuator. IEEE/ASME Transactions on mechatronics, 22(1), pp.71-80.
4. Williamson, M.M., 1995. Series elastic actuators.
5. Cummings, J.P., Ruiken, D., Wilkinson, E.L., Lanighan, M.W., Grupen, R.A. and Sup, F.C., 2016. A compact, modular series elastic actuator. Journal of Mechanisms and Robotics, 8(4).
6. https://robots.ieee.org/robots/valkyrie/
7. Sergi, F., Tagliamonte, N.L. and Guglielmelli, E., A Novel Compact Torsional Spring for Series Elastic Actuators for Assistive Wearable Robots.