ECE 5554 - Powertrain Control

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1) **Problem 1**

The transfer function derived from previous HW is used for estimating the initial PID settings (using Bode plot). The **bode plot** for the transfer function (left) with corresponding **margin values** (right) is shown below,

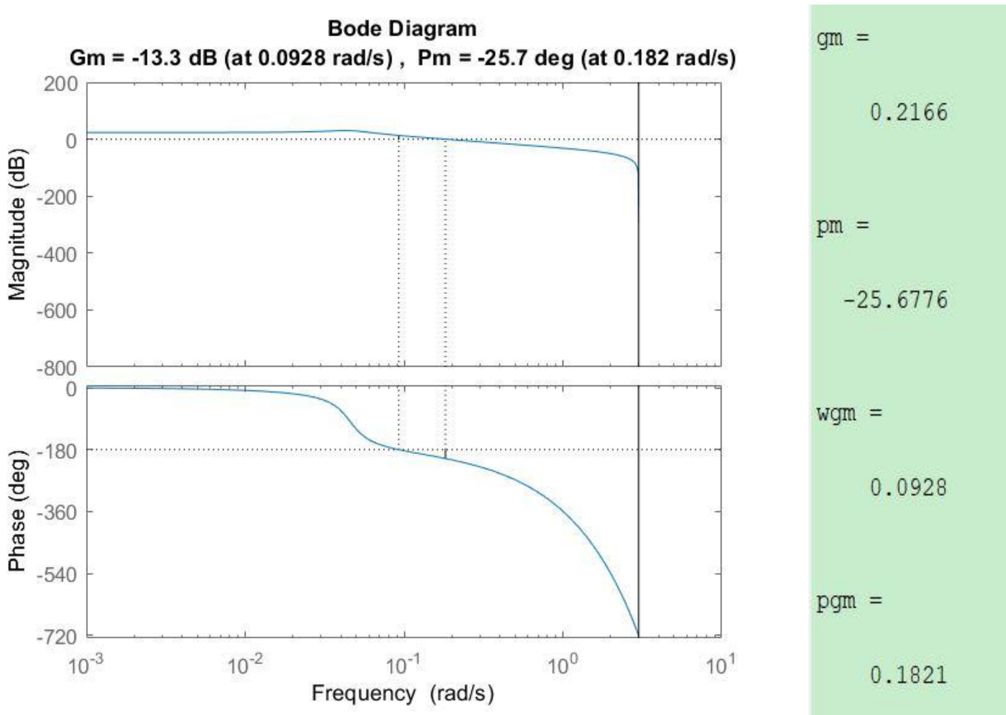

Fig1: Bode plot with corresponding Margin

Using **Gain margin (GM) and gain crossover frequency (W_{gm}),** we can calculate **Ultimate gain (K_u=0.2166) and Ultimate Period (P_u=67.67 rad)** and then we can derive initial PID setting using ZN method (We can also manually iterate the feedback gain to find K_u and P_u, the plots representing the K_u and P_u is shown in fig 2). The **initial PID estimates calculated using ZN method** are shown below.

TABLE 1: PID settings using ZN method

Controller	K_p	$K_i = K_p/ T_i$	$K_d = K_p*T_d$
P	0.1080	-	-
PI	0.0972	1.723e-3	-
PID	0.1296	0.0038	1.096

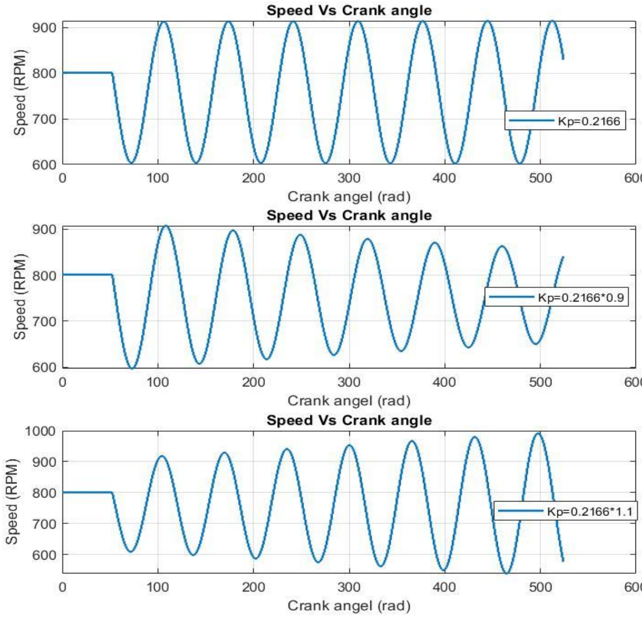

Fig2: Plots representing the ultimate gain and ultimate period (sustained oscillation)

Preliminary:

- The **PID output is saturated** to have the **throttle angle in between 6-20 degree**.
- In **discrete calculation, Trapezoidal method is used**.

P-Controller:

In this we compare the responses (mainly **steady state error and settling time**) for different **P-Controllers**. (Comparison between P and PI will be discussed later)

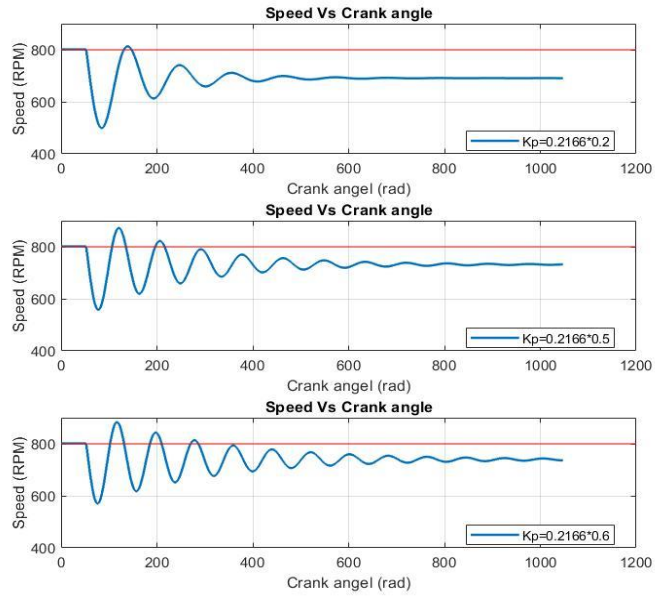

Fig3: Closed Loop Response for different P-controller (disturbance = +10Nm)

Inference: From the graph, we can see that, **as the gain is increased**, as expected, the **steady state error reduces**. But due to the increased gain, overshoot increases and leads to **increased settling time.** The comparison of different P controllers is shown in table 2.

TABLE 2: Comparison for different Kp

Kp	Settling time (rad)	Steady state error (RPM)
0.0432(*)	350-400	110
0.0682	400-450	90
0.0864	550-600	82
0.108(*)(ZN)	700-750	70
0.1296	1000-1050	61
0.1728	2000-2100	50

The response for selected (*) is shown below for reference along with the disturbance profile,

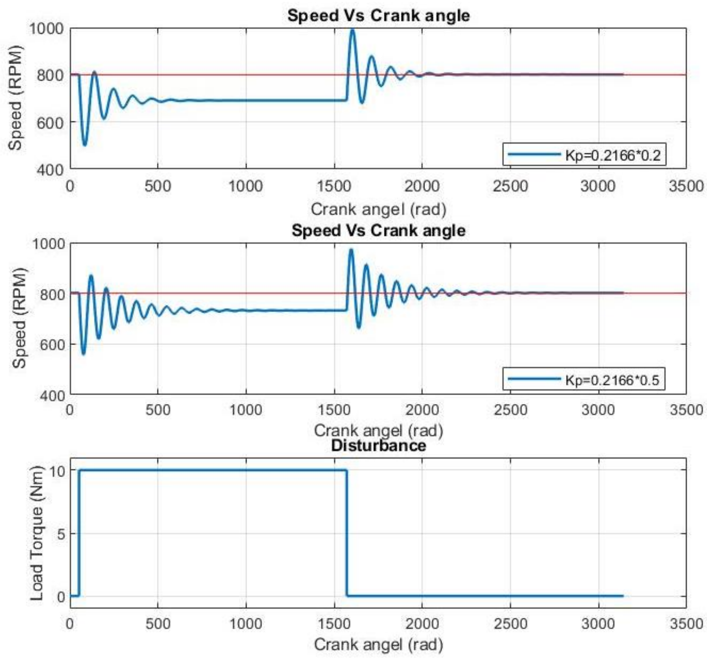

Fig4: Closed Loop Response for different P-controller (with disturbance)

PI controller:

Similar to P controller, using **ZN settings as initial estimate**, different PI settings are compared below,

TABLE 3: Comparison for different Kp, Ki

Kp	Ki	Settling time (rad)
0.0582	**0.0005323**	420
0.0582	**0.0004323**	400
0.0682	**0.0004323**	390
0.0782	**0.0004123**	520

The SS error is always zero. The best PI settings is **Kp = 0.0682 and Ki 4.322e-4**. **We cannot tune our controller more aggressive than this**, which will result in increased gain and might lead to stalling of the engine. In order to achieve faster response without compromising the gain, we need to add differential component to the controller. The response of PID will be discussed later. The response for chosen PI is shown below.

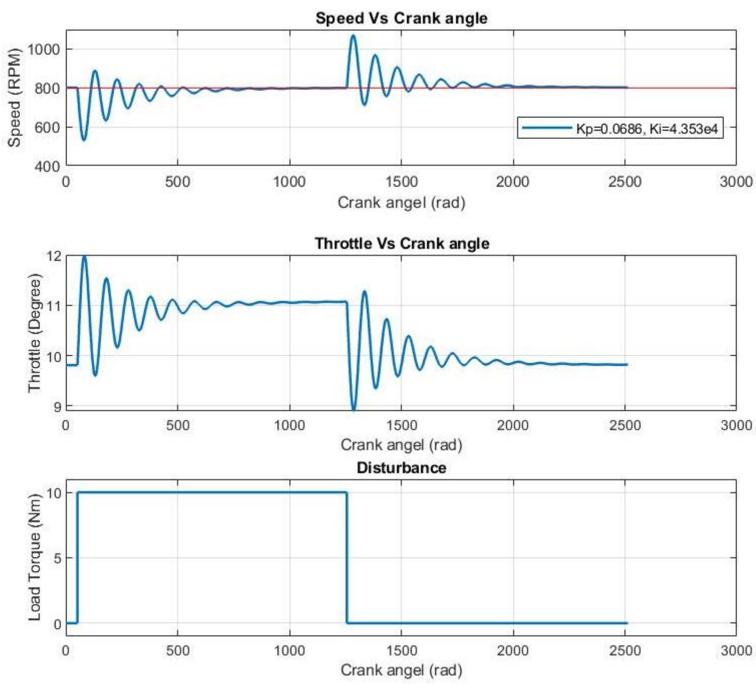

Fig5: Closed loop Response for PI controller

Comparison of P and PI:

From above section, we can infer that, **in case of P controller**, we will **always** have **steady state error.** If we **increase** the **gain**, steady state **error** can be **reduced** however it will **increase the overshoot.** The steady state error can be **eliminated by integration action**. In case of PI, we can reduce the **settling time by reducing the Integral gain (Ki)**. If Ki is reduced extensively, it will result is reduced integral action (equivalent to P only controller). To add on, one can improve the response by adding D action (PID), which will be evident from results in the upcoming sections.

PID controller:

Similar to P and PI, the response for different PID controllers is shown below (only the best response is shown), **Kp=0.1296, Ki=0.005883, Kd=2.296.** The following are the response spec.,

- **Settling time:** 250rad
- **SS error:** 0 rpm
- **Max excursion:** +/- 230 RPM, **All the parameter are in desired range**

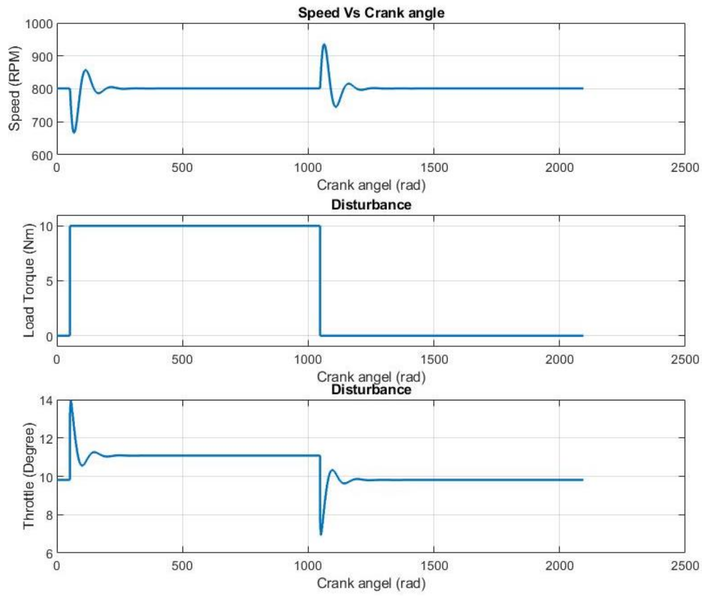

Fig9: CL Response for PID controller

Inference:

In this step, we added D action to the controller, which **anticipated the error** and added **additional control action** based on error changes at each step. As a result, the **system reaches** the steady state **faster**. Thus, combined effort

of P,I and D helps the system to reach SS **faster with lesser excursion and oscillations.**

<u>2) Problem 2</u>

In this problem, Feedforward controller and anticipator pulse will be added enhance the control action.

Note: since, the **discrete system is linearized** with at **Throttle 9.81 degree**, and **load torque 10Nm.** We have to include this equilibrium point in our calculation.

FEED FORWARD CONTROLLER:

The feedforward is created with lookup table with following values,

TABLE 4: FeedForward Control values (equilibrium point is considered)

Load Torque	Feed Forward Control (Throttle in Degree)
0	0
10	1.1550

The CL response of the FF+PID controller is shown below,

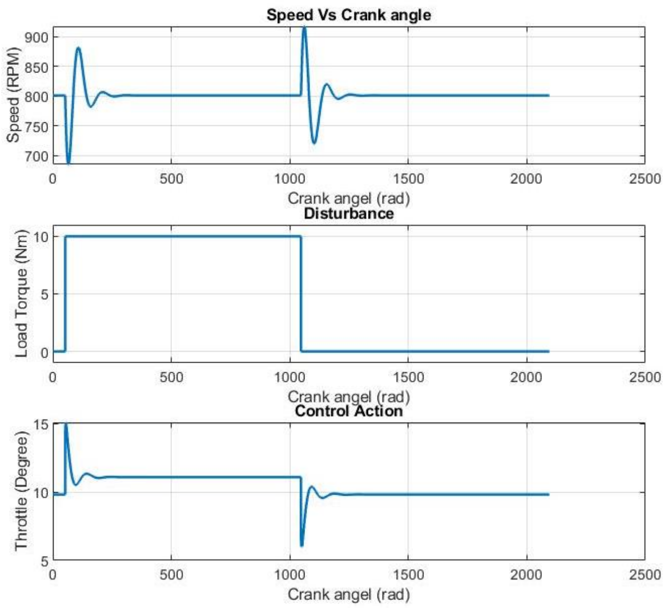

Fig10: CL response for PID+FF (Using lookup table)

The **individual effort of FF and PID** is shown below,

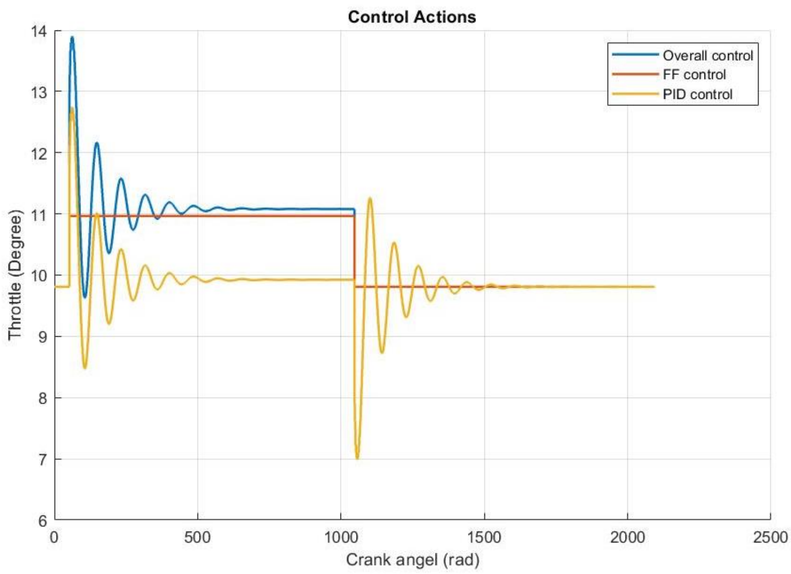

Fig11_a: Comparison of Control action of FF, PID (with overall control action)

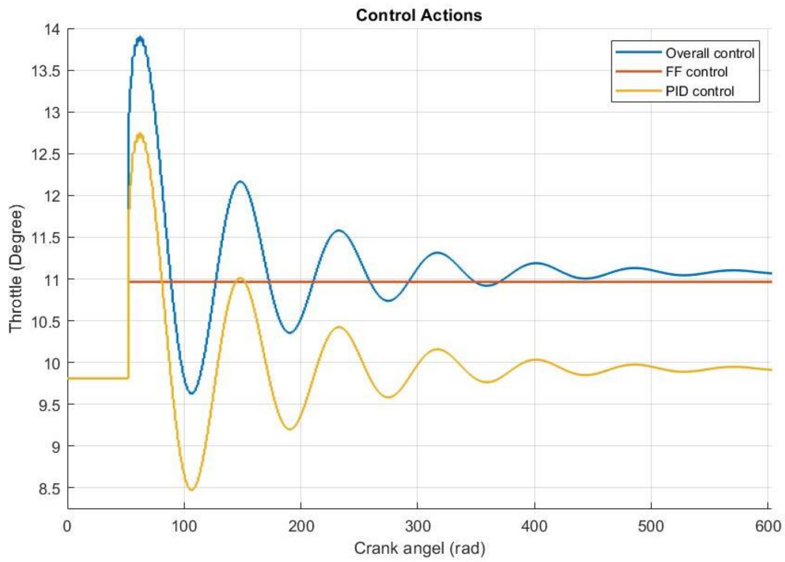

Fig11_b: Comparison of Control action of FF, PID (with overall control action) (Zoomed)

Because of FF controller, the effort need by PID controller is reduced.

ANTICIPATORY PULSE:

The same is repeated with Anticipator pulse, the results are as follows, (FF is removed for this part. however, the effort of FF + Anticipatory pulse will be discussed later)

For different magnitudes (1, 3, 6, 8 degree), with constant width (5 sec) and timing (Before 5 sec w.r.t disturbance) is shown below.

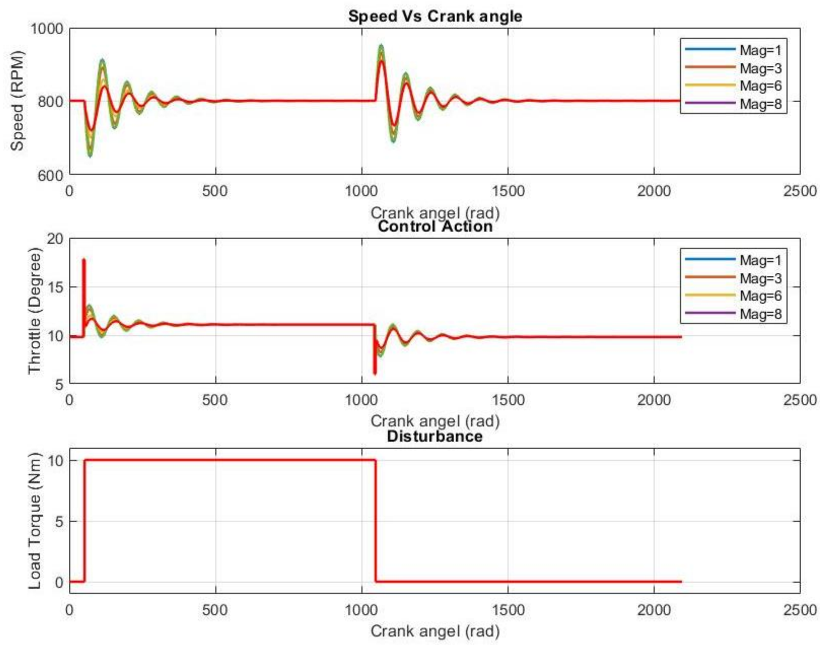

Fig 12_a: Effect of magnitude of Anticipatory Pulse (with constant Width and Timing)

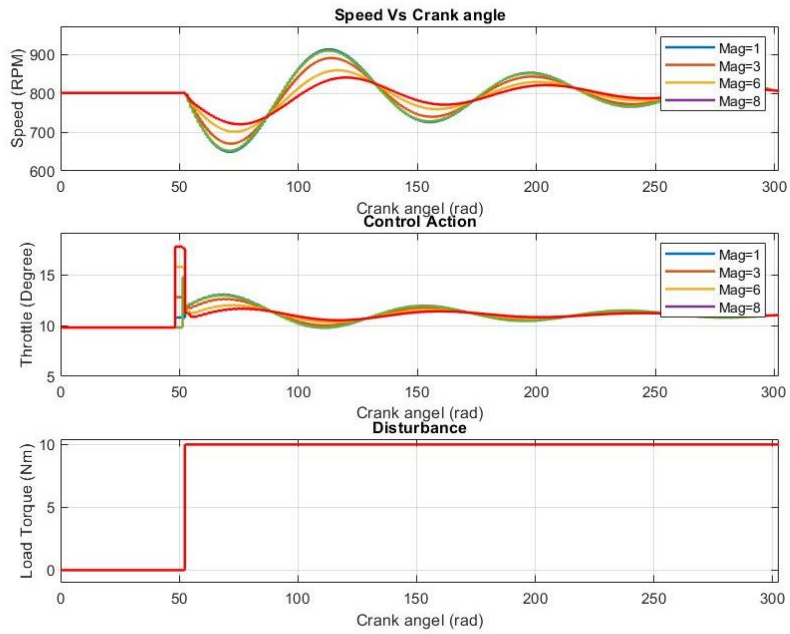

Fig 12_b: Effect of magnitude of Anticipatory Pulse (with constant Width and Timing) (Zoomed)

Inference (Magnitude of Anticipatory Pulse (AP)):

From fig 12, we can infer that, as we **increase the magnitude of AP**, the system **reaches the Steady state faster.** The intuition behind this is that the AP will take control action before PID does i.e. control action is applied in advance which aids the system to reach SS faster. We can further increase the magnitude of AP for better performance, however, we will be wasting fuel. Reasonable choice of magnitude can be decide based on trade-off between time (faster response) and fuel (Control).

For different width (1, 3, 5, 10 sec), with constant magnitude (5 degree) and timing (Pulse ends exactly before disturbance), is shown below,

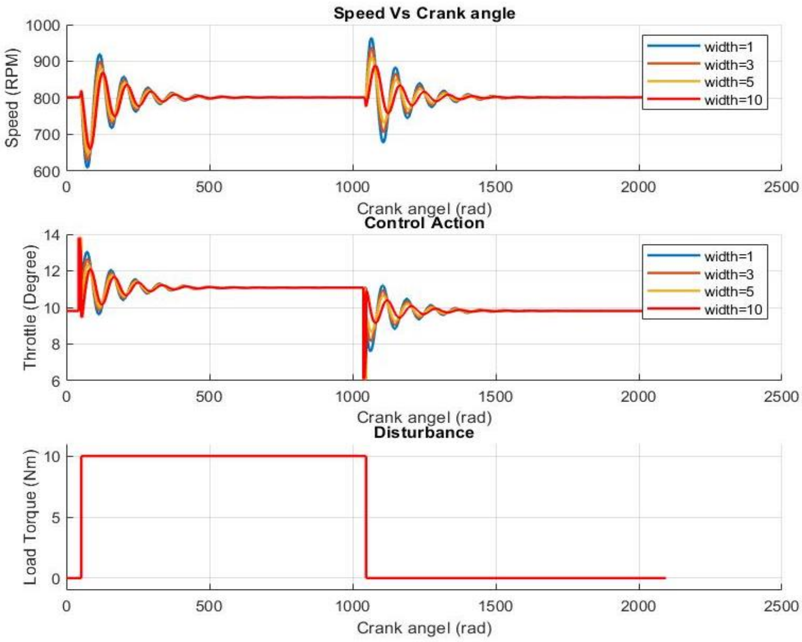

Fig 13_a: Effect of width of Anticipatory Pulse (with constant magnitude and Timing)

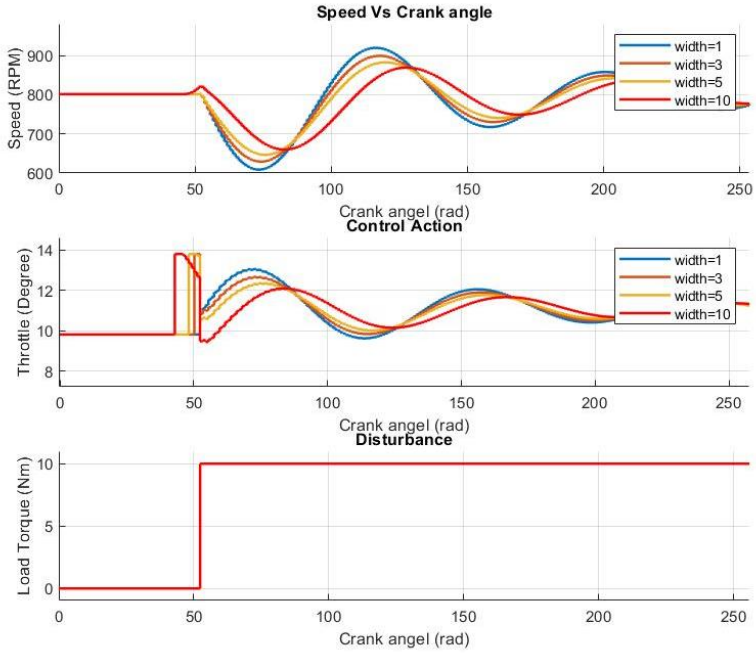

Fig 13_b: Effect of width of Anticipatory Pulse (with constant magnitude and Timing) (Zoomed)

Inference (Width):

From fig 13, we can infer that, as **we increase the width**, the **system reaches the SS faster.**

For different timings (4, 2, 0 sec before w.r.t disturbance) with constant magnitude (5 degree) and width (2sec), is shown below,

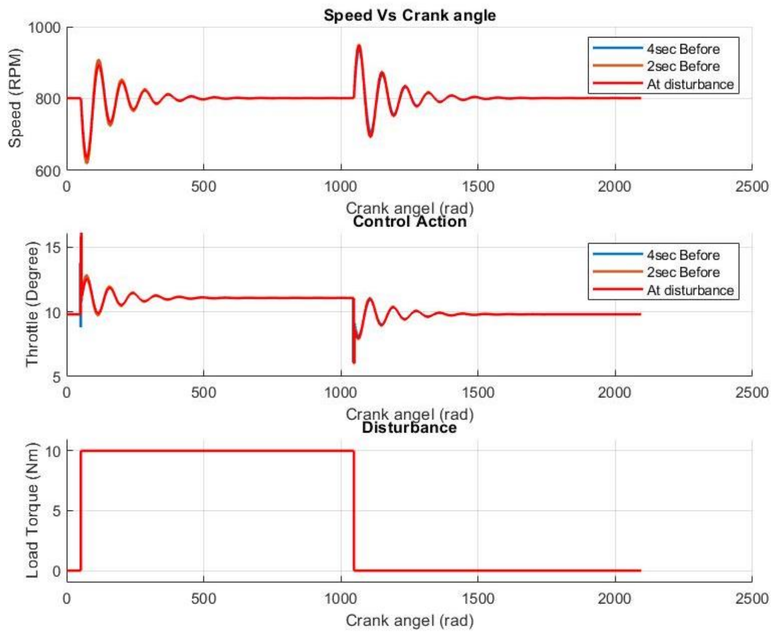

Fig 14_a: Effect of Timing of Anticipatory Pulse (with constant magnitude and width)

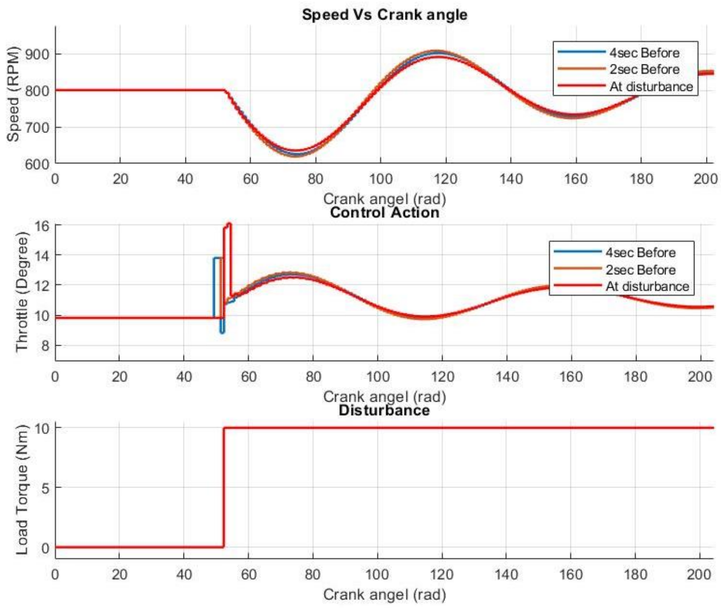

Fig 14_b: Effect of Timing of Anticipatory Pulse (with constant magnitude and width) (Zoomed)

Inference (Timing):

We can infer that, we have to apply the AP at the time timing (a few sec before w.r.t disturbance**). Applying too early or too late will result is insignificant effect (Obvious).** In our case, **for the considered condition,** applying the AP **2 to 4 sec before the disturbance** will be a **reasonable** choice.

Overall Anticipatory Pulse:

The following plot shows all the above mentioned AP settings,

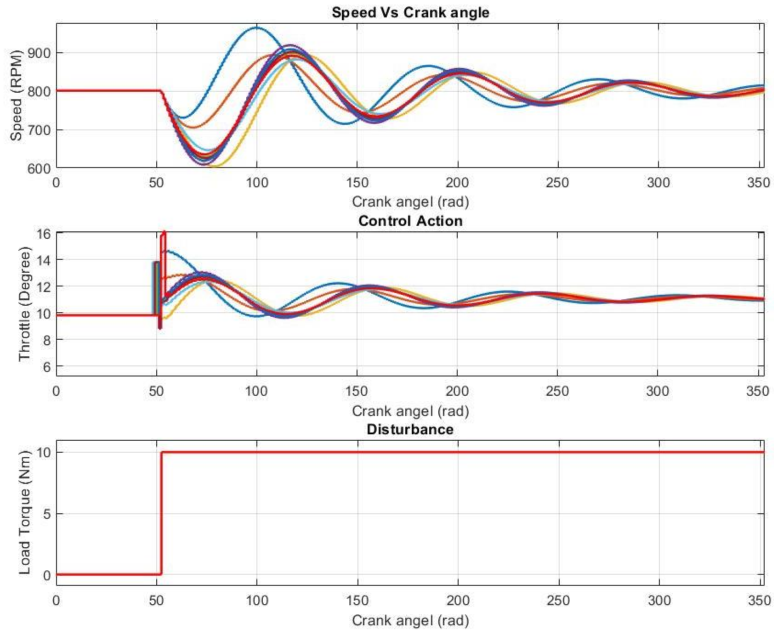

Fig 15: Effect of Anticipatory pulse

For our case, Magnitude of 3-5 degree, width of 2-3 sec, timing of 4 sec before w.r.t disturbance will be a reasonable choice. Note that, the specification of AP might vary depending on the application.

Individual effort of AP, FF and PID (if applied together)

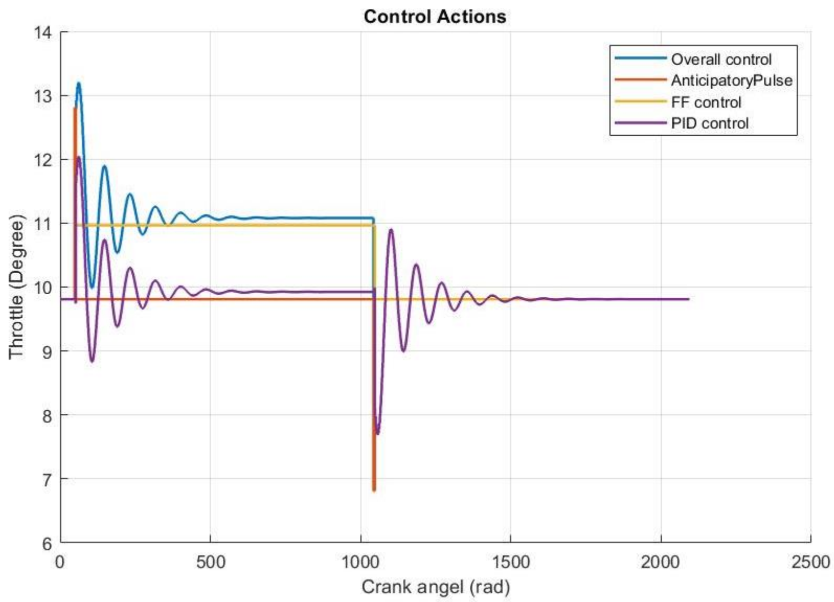

Fig 16_a: Effort of AP, FF and PID

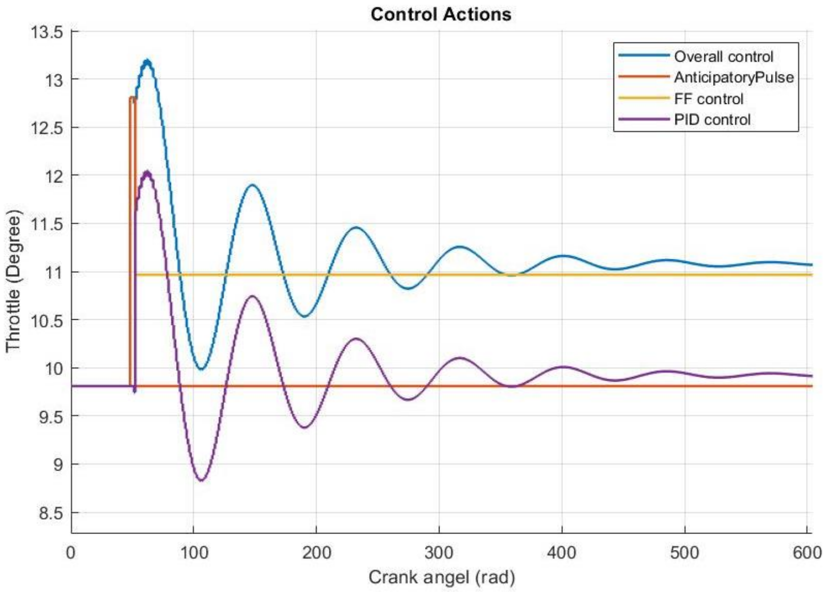

Fig 16_b: Effort of AP, FF and PID (Zoomed)

Inference:

From graph we can infer that, **as we add AP and FF**, the **control** action need **by PID is reduced.** If we compare fig 11 and fig 16, we can infer that, AP has enhanced the control action. Thus, in general, FF and AP aids PID in taking control action. Proper section (as mentioned earlier) we can achieve **faster response with lesser excursion and oscillations.**

<u>3) Problem 3</u>

Trigger system id generated to activate the discrete PID at every pi/3 radians. The PID block is slightly modified for this part.

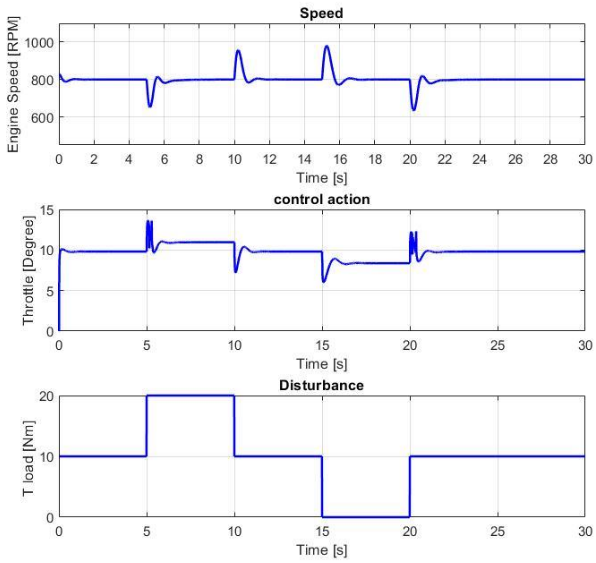

Fig 17_a: CL response of PID for Nonlinear continuous system

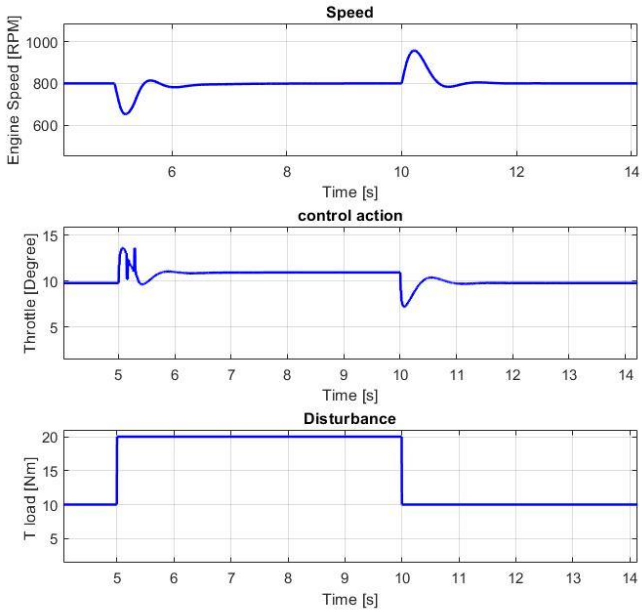

Fig 17_b: CL response of PID for Nonlinear continuous system (Zoomed)

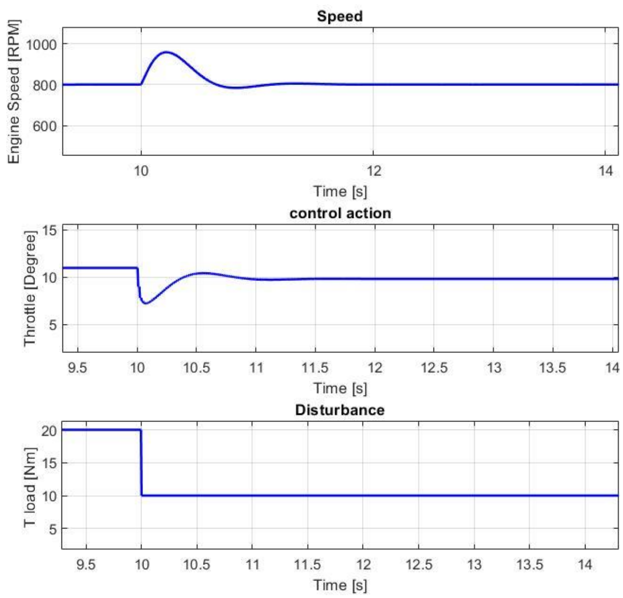

Fig 17_c: CL response of PID for Nonlinear continuous system (Zoomed)

The PID values are as follows; **Kp=0.10896; Ki 0.1986; Kd=2.329e-2;**

The **PID** has to be **re-tuned** in order to use **for Non-linear continuous system**. Without re-tuning, the control action were oscillatory, which is evident since we tuned our controller for linearized system at specific operating condition (we must also account for sampling time). Nevertheless, **after retuning**, from the fig 17, we can infer that we have **achieved** the **desire specifications.**

On comparing fig 17 with fig 9, we can infer that the response of Nonlinear is slightly poor (but fairly close) since we have to take the control action over a large range (Although, we can retune our PID further for better results, the obtained results are satisfactory with the given specifications). In this case, the control action (throttle) for NonLinear sys is comparatively lesser (1-2 degree approx) than that of discrete system. Similarly, the excursion in NL slightly greater (20 RPM approx) than that of Discrete system. However, the variation in response between Nonlinear and Discrete is small, thus, we can say that both the response are fairly close.

<u>4) Problem 4</u>

The Openloop response of Nonlinear continuous and Discrete linearized system is compared in this section.

The load torque is varied as shown below,

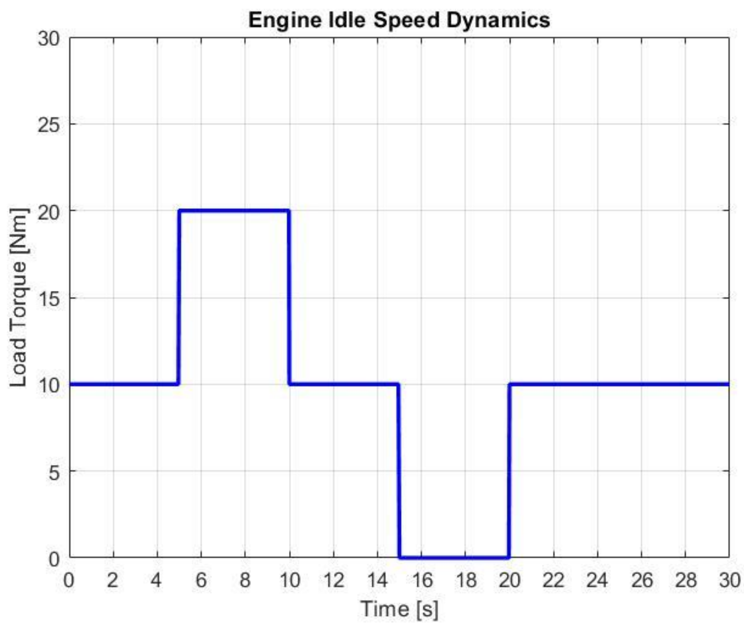

Fig18: Load torque profile

The response for above torque profile is shown below

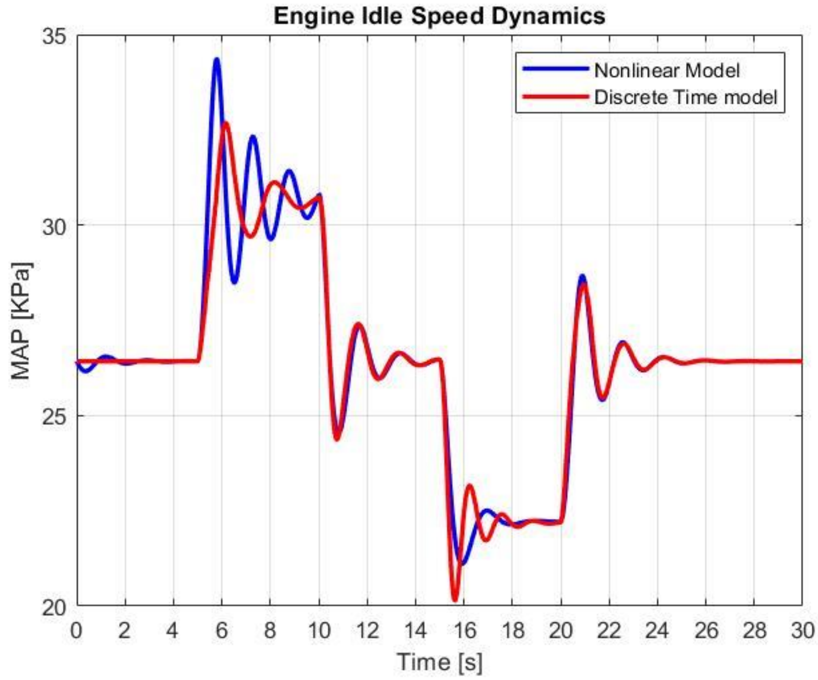

Fig 19: Comparison of MAP for Nonlinear continuous and Discrete Linearized system

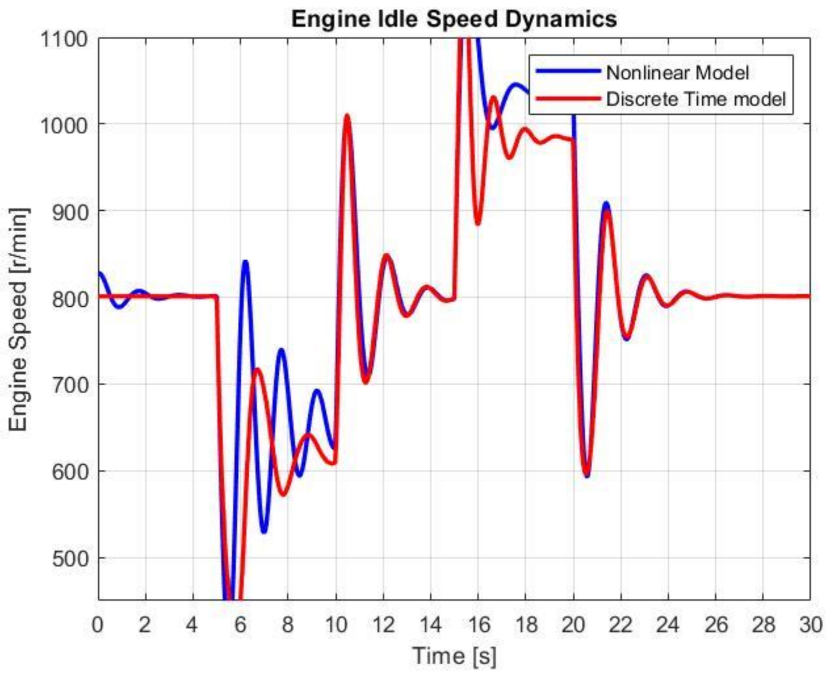

Fig 20: Comparison of Speed for Nonlinear continuous and Discrete Linearized system

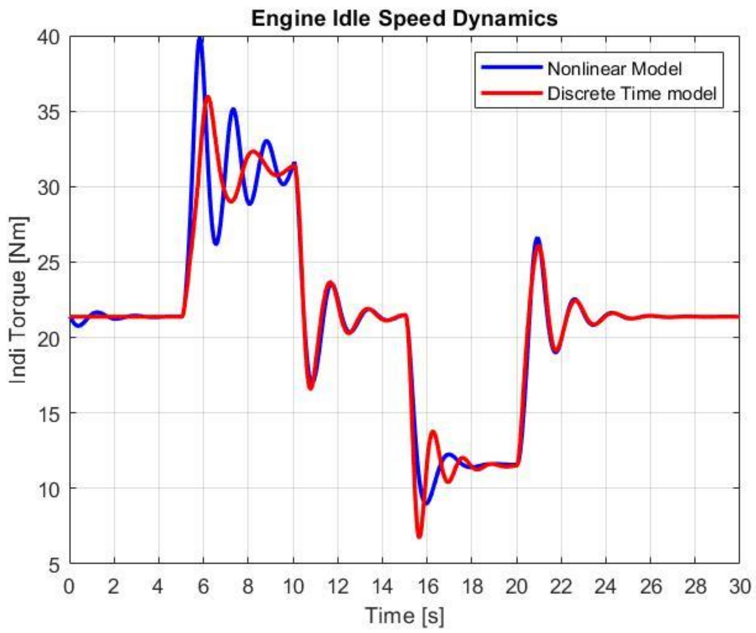

Fig 21: Comparison of Indi Torque for Nonlinear continuous and Discrete Linearized system

Thus, from above figures, we can infer that, both **Nonlinear Continuous system and Discrete Linearized system** shows **similar response,** as expected, **near the linearization region** (around 800 RPM) and **differ slightly in other regions**. The results are obvious **since we linearized** the system **around 800RPM.**