DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

EE5103R-COMPUTER CONTROL SYSTEMS

DESIGN OF TRACK FOLLOWING CONTROLLER IN HARD DISK DRIVES

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OBJECTIVE:

The main objective of this report is to design an digital controller for HDD(Hard Disk Drive) of a VCM(Voice Coil Motor) meeting certain time domain and frequency domain design specifications. This report also provides the following details:

1. Frequency responses of the compensated open loop transfer function indicating the :

   I. ***Gain Margin and Phase Margin.***
   II. ***Sensitivity Transfer Functions.***

2. Unit Step Response of the system for a given step input.

3. The Effect of Various Sampling Frequencies on System Performance.

COMMERCIAL HARD DISK DRIVE:

FIG 1: HARD DISK DRIVE

A typical Commercial 3.5” Hard Disk Drive is shown in the above figure. A brief description of all the components is given below:

The servo mechanical system for accessing data in a typical modern HDD as illustrated in figure below. It has the following list of components.

- ***SPINDLE MOTOR.***
- ***VOICE COIL MOTOR.***
- ***READ-WRITE HEAD POSITIONING ACTUATOR.***
- ***SUSPENSION.***

1.1 VOICE COIL MOTOR(PRIMARY):

The voice coil motor or the primary actuator has a coil which is suspended in the magnetic field produced by permanent magnets fixed on the hard disk. The voice coil motor works on the principle of *Faraday's Law* i.e when current carrying coil is placed in an external magnetic field it experiences a torque.
There are basically two different type of VCM's namely a linear VCM and a rotary VCM. The actuator arm of a linear VCM moves in and out whereas the arm of the rotary VCM moves sidewise.

1.2 PIEZOELECTRIC ACTUATOR(SECONDARY):

The **piezo-electric actuator(Secondary) is** used for precise positioning of the read/write head. It works as follows:

- During the Read/write operation the ***PES(Position Error Signal)*** obtained from PZT actuator tells you how much you are offset from the center of the track .
- The servo information is obtained from the servo sector on the disk.
- The exact track where the read/write has to be moved forms the reference input to the controller.
- The difference between the above two forms the error. The controller has to function in such a way to reduce the error so as to perform read or write operation on the exact track.

1.3 SPINDLE MOTOR:

Spindle motor is used for spinning stacks of disk in HDD. It is nothing but a brushless DC motor fitted with pre-loaded ball bearing capable of running at 10,000 RPM or more.

1.4 SUSPENSION:

HGA (Head Gimbal Assembly) suspension holds hard drive read/write heads. Read/write head is attached to the flexure. Flexure can gimbal around dimple. Head flies over spinning disk surface. Hinge and load beam provide downward force to balance lift from flying head. Suspension length about **10-14.5 mm** , thickness of **25-100 µm** .Typical width about **4-6 mm.**

PROBLEM STATEMENT:

The model of a Voice Coil Motor (VCM) P(s) in a HDD, obtained from frequency response measurements is given

$$P(s) = \frac{1\times10^8}{s^2}\frac{(2\pi5\times10^3)^2}{s^2+2(0.05)(2\pi5\times10^3)s+(2\pi5\times10^3)^2}$$

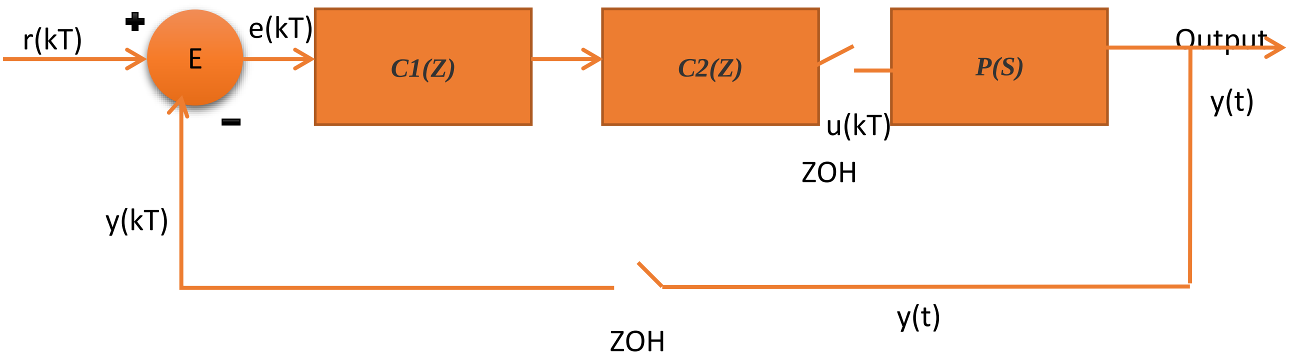
The main objective is to design a Digital Controller C(Z) to meet the following Time Domain and Frequency Domain Specifications:

Assume Sampling frequency as 20 kHz

1. Gain margin (GM)> *10dB* and phase margin (PM)>*40°*
2. Gain crossover frequency>*500Hz*
3. peak of sensitivity transfer function <*10dB*
4. 10% settling time <10ms. Less than 20% overshoot and zero steady-state error

SYSTEM IDENTIFICATION AND CONTROLLER SELECTION:

On analyzing the plant, it is evident that it is a double integrator model producing a resonant frequency at 5khZ.Ideally two controllers have to be designed one for eliminating the resonant frequency at 5khz and the other controller without resonant mode.



The overall Closed loop control system is depicted above .In my design there are two digital controllers one being a notch filter for suppressing the resonant mode at 5 KHz and a PID controller for controlling the remainder of the system.

The frequency response of the plant shows that the notch kicks in at exactly 5khz and on plotting the response of the plant we get the same as seen below.

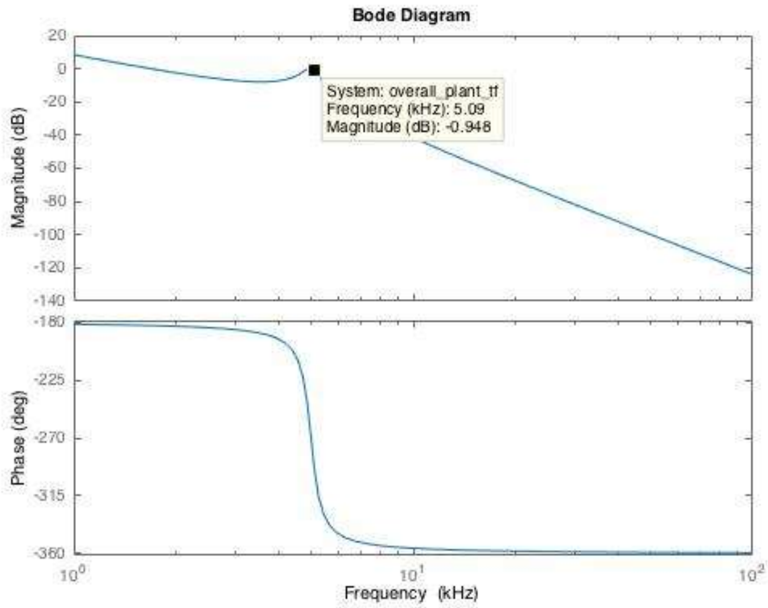


FIG 2: FREQUENCY RESPONSE OF THE PLANT

NOTCH FILTER DESIGN:

A notch filter is a band stop filter that attenuates the input at a desired frequency. A Band-stop filter is a filter which passes most frequencies without altering them, and only attenuates those in a particular range to very low levels.

Notch filters are mostly used to reduce the gain of mechanical resonant nodes. The notch filter is used to get rid of the resonance in the given system. In our case the plant produces a sharp notch at 5KHz and design of notch filter should be in such a way that it eliminates the notch at 5khz.

The general notch filter transfer function takes the form:

$$N_i(s) = \frac{(2\pi fD,i)^2}{(2\pi fR,i)^2}\frac{s^2+2\zeta R,i(2\pi fR,i)s+(2\pi fR,i)^2}{s^2+2\zeta D,i(2\pi fD,i)s+(2\pi fD,i)^2}$$

Where ,
fD,i=Damping Frequency at ith mechanical resonance
fR,i=Resonant Frequency at ith mechanical resonance,$\zeta = \text{Damping Ratio}$ and it varies from $\frac{1}{\sqrt{2}} < \zeta D, i < 1;$
for our design let us take

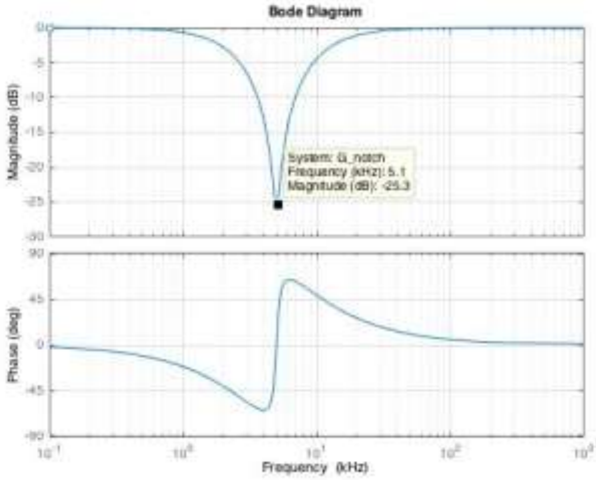
fD,i = fR,i=5000 , ζR, i = 0.05 and $\zeta D, i = 1$

substituting the above values in the above equation, we get the overall notch filter transfer function as follows:

$$N_i(s) = \frac{s^2+3140s+(2\pi*5000)^2}{s^2+62800s+(2\pi*5000)^2}$$

DESIGN IMPLEMENTATION IN MATLAB:

The frequency response of the notch filter is shown below



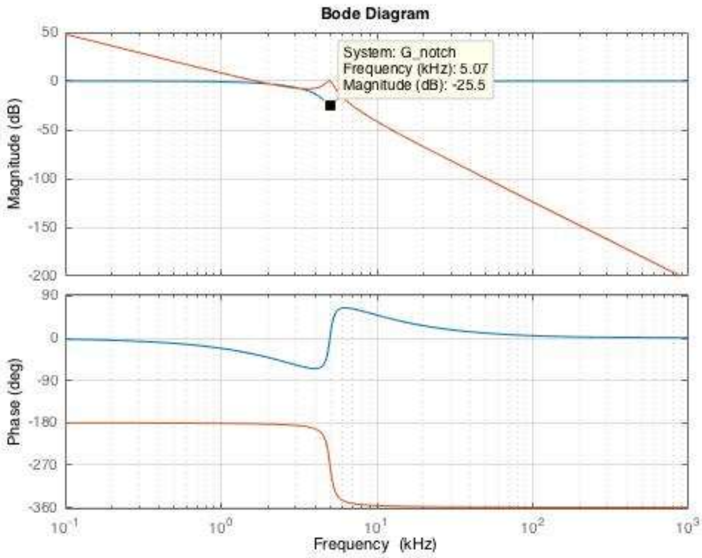


FIG 3: FREQUENCY RESPONSE OF THE NOTCH FILTER AND PLANT

From the plots it is evident that the notch filter suppresses the energy exactly at 5khz.

OVERALL SYSTEM WITH NOTCH FILTER:

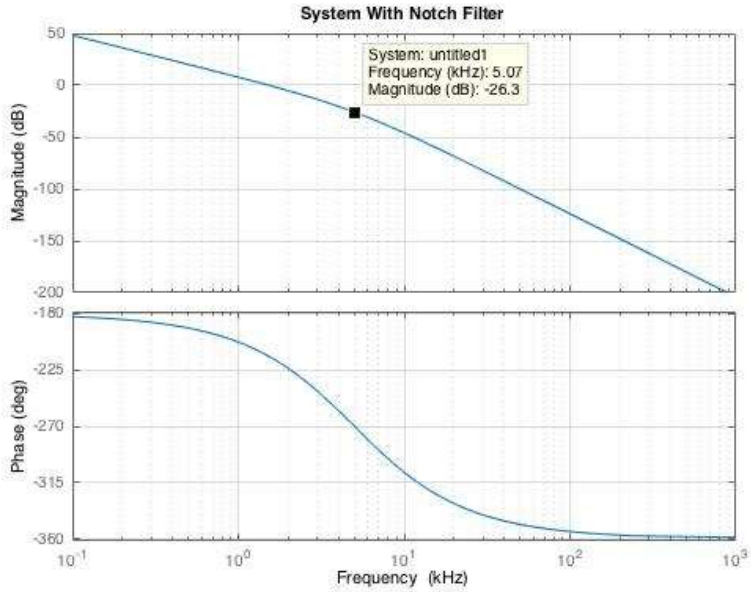


FIG 4: FREQUENCY RESPONSE OF THE SYSTEM WITH NOTCH FILTER

The overall system after implementing the notch filter is shown in the above figure. We could see the sharp notch that is being produced is now eliminated at 5kHz.

The next step is to design an controller. The controller that has been chosen is an PID Controller. The PID controller here is designed based on dominant pole method based on design specifications and it is described below.

PID CONTROLLER DESIGN BASED ON DOMINANT POLE METHOD:

The Time domain specifications are described below and Damping ratio and Undamped Natural frequency are calculated based on the specifications:

Rise time - It is the time taken by the signal to rise from a specific low value to a high value, generally the values are 10% to 90% of the step height.

$$\mathbf{t_r} \cong \frac{\mathbf{1.8}}{\boldsymbol{Wn^2}}$$

Max Overshoot - Overshoot happens when a signal exceeds its target value.

$$\mathbf{M_p} = e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}}$$

Settling Time - Time elapsed from the application of the step input to the time taken for the output to reach the desired value and remain within a specific error band.

$$\mathbf{t_s} \cong \frac{-\boldsymbol{ln}(\mathbf{0.05})}{\boldsymbol{\zeta}\mathbf{Wn}} \text{ for 5\% tolerance}$$

Using the given information we design a 2nd order reference system with the desired time domain specification.
Given that the system should have less than 20% overshoot

$20\% > e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}}$ $\rightarrow$ $\ln(0.20) > \frac{-\pi\zeta}{\sqrt{1-\zeta^2}}$ on solving we get $\zeta > 0.456$

choosing **ζ = 0.80**,
and since 10% of settling time < 10ms we choose settling time
t_s = 10ms
we calculate Wn $\rightarrow$ $10*10^{-3} = \frac{-ln(0.10)}{\zeta Wn}$
we get **W_n = 287.5Hz**

the remaining part of the plant for which the controller has to be designed is given by

$G(s) = 10^8/s^2$

The dominant pole is given by $S_d = -\zeta Wn \pm jWn\sqrt{(1-\zeta^2)}$
Substituting **ζ = 0.80 and W_n = 287.5,** We get

$S_d = -230 \pm j172.5$

Magnitude, $D=|S_d|=287.5$ and phase, $ß=143.2^0$

Magnitude of the plant at dominant pole $=A_d=|G(S_d)| = 10^8/s^2\ |S=S_d=1210$

Phase of the plant at dominant pole $= Ø_{(Sd)} = -286.4^0$

W.K.T, PID Transfer Function, $G_c(s) = K_P + K_i/s+K_d s$

Overall open loop transfer function ,$G_0(s) = G_c(s)\ G(s)$

$= (K_P + K_i/s+K_d s)(10^8/s^2)$

Taking steady state error to be less than 0.1 as the required specification for the steady state error is 0 ,

Taking $e_{ss} < 0.1$,

K_p, position constant and e_{ss} are related as

$e_{ss} = 1/(1+K_p)$

solving for K_p, We get $K_p = 9$

$$K_p = \lim_{s \to 0} G(s)G_c(s)$$

substituting G(s),Kp and Gc(s),

$$\mathbf{K_i = 54 * 10^{-8}}$$

$K_d = \sin\emptyset_{(Sd)}/DA_d \sin ß + K_i/D^2$

Substituting the values we have $\mathbf{K_d = 4.6*10^{-6}}$

$K_p = -\sin(ß+ \emptyset_{(Sd)})/ A_d \sin ß – 2* K_i \cos ß/D$

Substituting we get $\mathbf{Kp = 8.26 *10^{-4}}$

All the values of the K_p,K_i and K_d are substituted

Thus the overall transfer function of the controller in S-Domain is

$G_c(s)= 8.26 *10^{-4}+54 * 10^{-8}/s +4.6*10^{-6}/s$

OVERALL IMPLEMENTATION OF THE SYSTEM AND CONTROLLER IN CONTINUOUS DOMAIN IN MATLAB:

Since both the controllers have been designed, the next step is to implement them in Matlab.

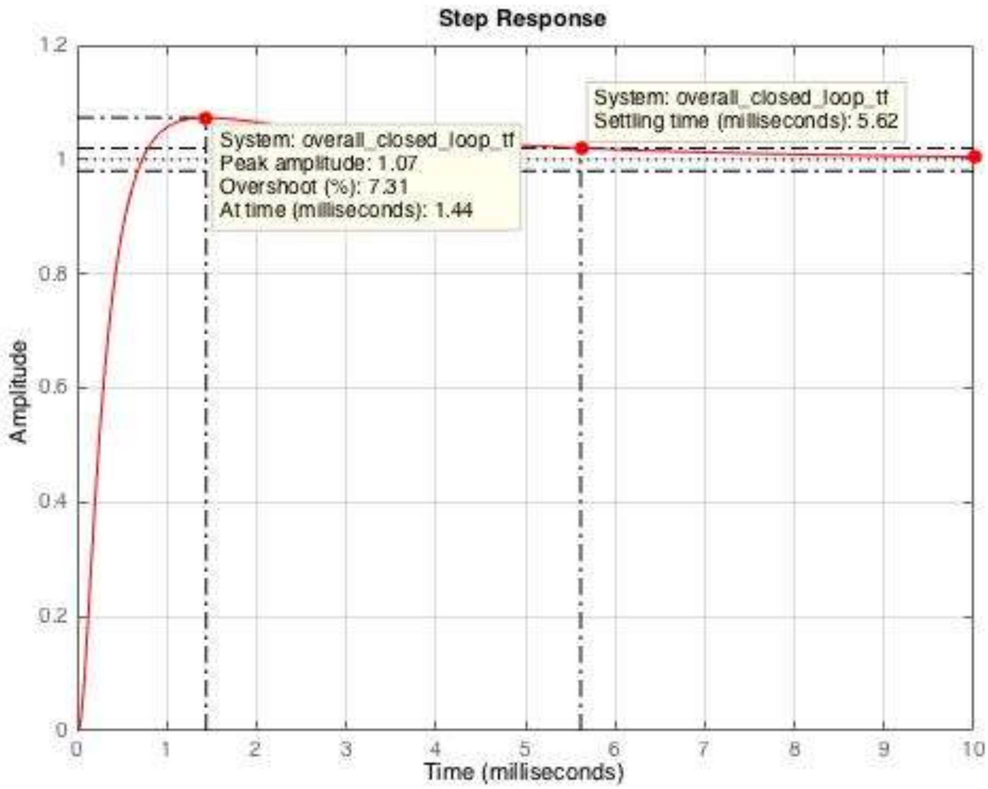


FIG 5: UNIT STEP RESPONSE

The step response of the system for unit step input is shown in the above figure. From the figure it is clearly evident that all the time domain specifications are met .The step response of the system has

I. *An peak overshoot of* ***7.31%*** which is *<20%*
II. A settling time of ***5.62ms*** which is less than *10ms*
III. ***Zero steady state error*** *as the output has a final value of 1.*

FREQUENCY RESPONSE OF THE COMPENSATED TRANSFER FUNCTION P(S)C(S):

The bode plot for the open loop compensated transfer function of the plant and the compensator is shown below:

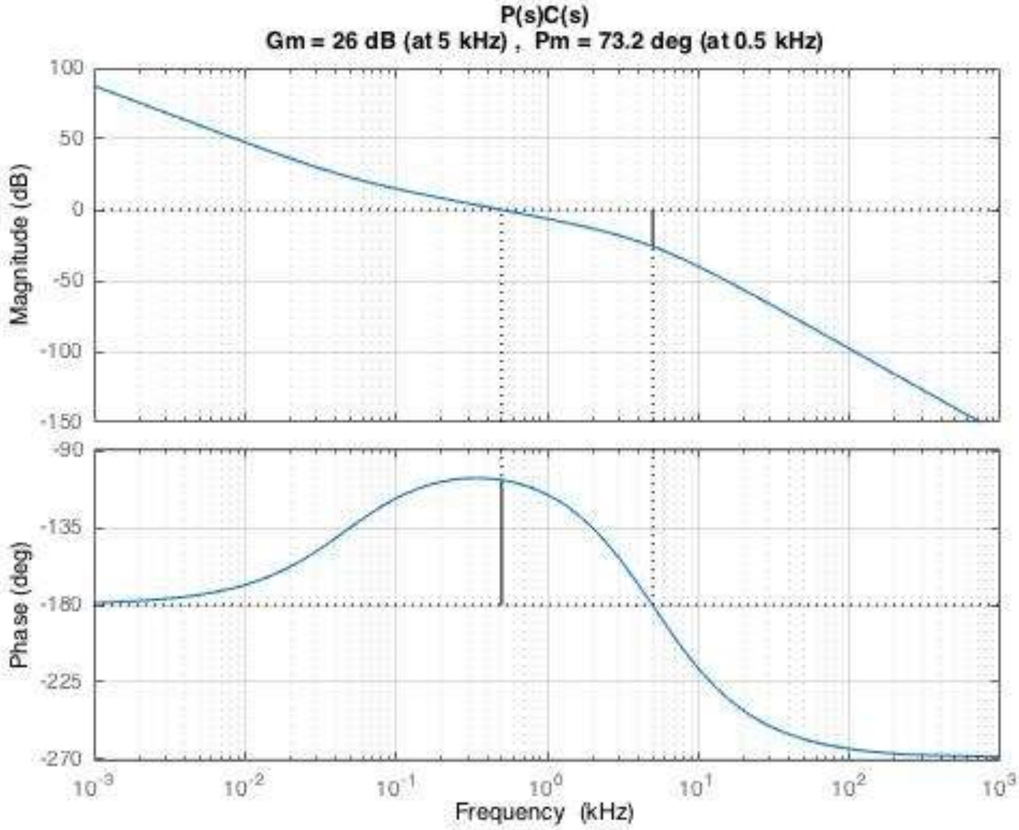


FIG 6: FREQUENCY RESPONSE

The stability margins in the continuous domain has the following values:

I. An ***Gain Margin of 26 dB*** which is greater than ***10 dB.***

II. ***An Phase Margin of 73.2257^0*** which is ***greater than 40^0.***

III. A ***Gain cross over frequency of 501Hz***which is greater than ***500Hz***.

IV. A Phase cross over frequency of ***5000Hz***.

DISCRETIZATION OF THE SYSTEM:

All the Specifications are met in the continuous domain. The next step is to discretize the plant and the compensator and check whether the same works fine in discrete domain.

We basically have five methods of approximations namely:

I. Forward Rule.
II. Backward Rule.
III. Bilinear or Tustin.

IV. *ZOH equivalence.*

V. *Pole-Zero Mapping.*

ZOH EQUIVALENCE :

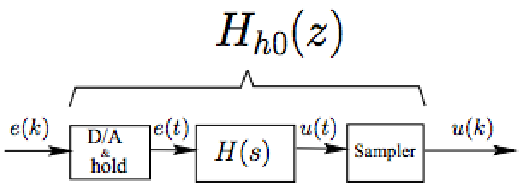


Figure 6.2: Hold equivalent.

In this method the continuous samples are held constant until the next sampling instant. The discrete equivalent is calculated using the formula

$$H_{h0}(z) = (1 - z^{-1})\mathcal{Z}\left\{\frac{H(s)}{s}\right\}$$

BILLINEAR TRANSFORMATION:

The most commonly used method for approximation is Tustin method.The transformation is given by

s -> 2/T(Z-1/Z+1)

For our model, I choose ZOH and Tustin as the approximation technique.

In Matlab C2D is used for discretizing the model and the unction is described below:

```
Ex:C_Discrete1=c2d(C,Ts1,'tustin')
```

The Discretized overall transfer functions of the Controller is given below:

C_Discrete1 =

0.2376 z^4 - 0.5793 z^3 + 0.6634 z^2 - 0.5341 z + 0.2124
---
z^4 - 0.2409 z^3 - 0.9855 z^2 + 0.2409 z - 0.01451

The overall block diagram in Simulink is as follows:

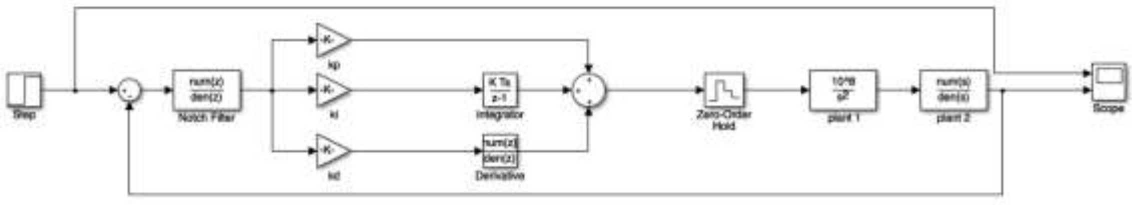


FIG 7: BLOCK DIAGRAM OF THE SYSTEM IMPLEMENTED IN SIMULINK

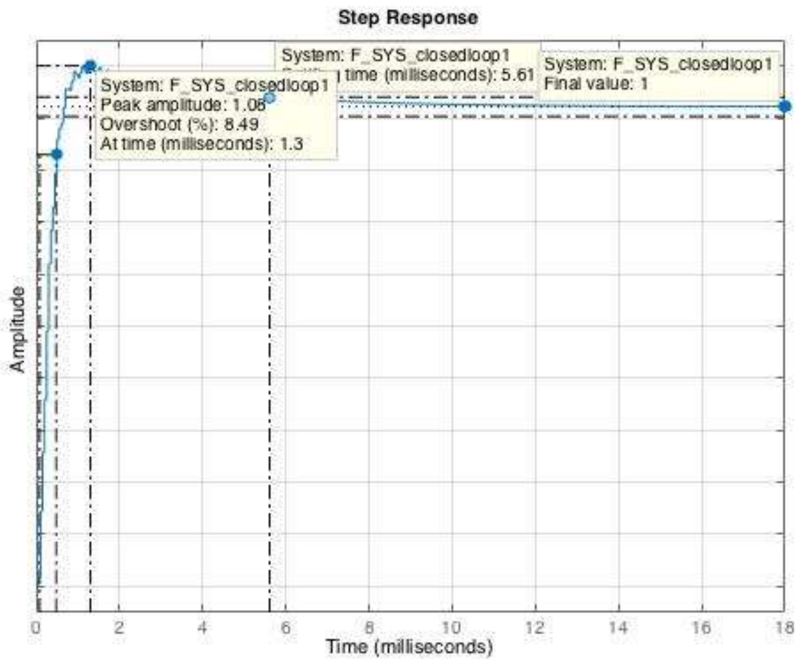


FIG 8: STEP RESPONSE IN DISCRTE DOMAIN

The step response of the system (***after discretization***) for an unit step input is shown in the above figure. From the figure it is clearly evident that all the time domain specifications are met .The step response of the system has

I. *An peak overshoot of* ***8.49%*** which is *<20%*
II. A settling time of ***5.61ms*** which is less than *10ms*
III. ***Zero steady state error*** *as the output has a final value of 1.*

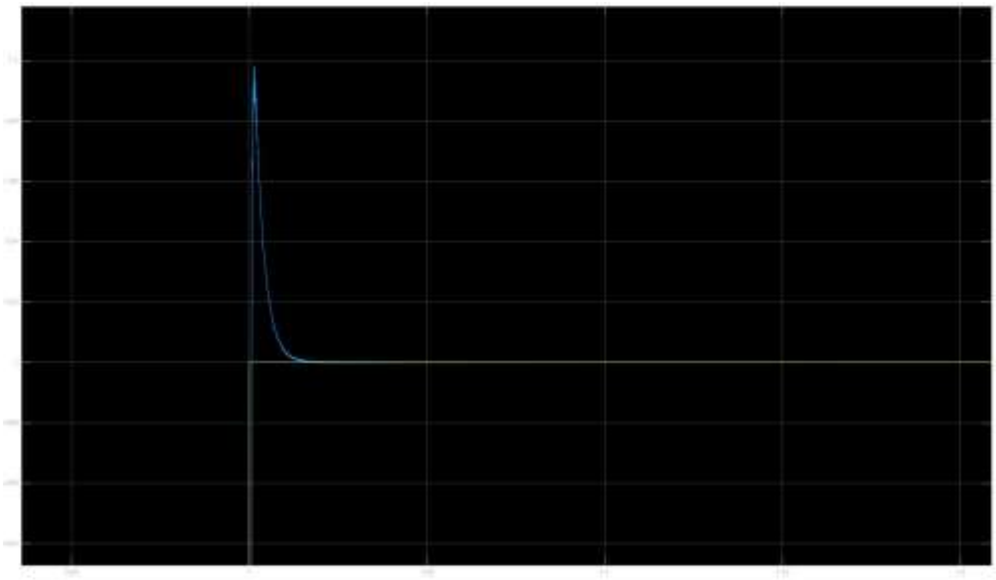


FIG 9: DESIGN IN SIMULINK

__FREQUENCY RESPONSE OF THE COMPENSATED TRANSFER FUNCTION P(Z)C(Z):__

_The bode plot for the open loop compensated transfer function of the plant and the compensator (***In Discrete Domain***) is shown below:

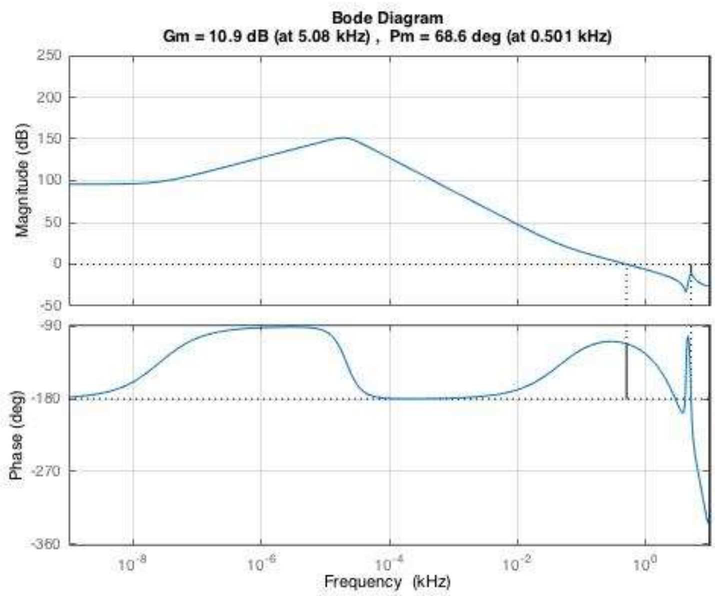


FIG 10: FREQUENCY RESPONSE IN DISCRETE DOMAIN

The stability margins in the Discrete domain has the following values:

I. An ***Gain Margin of 10.9dB*** which is greater than ***10 dB.***

II. ***An Phase Margin of 68.615^0*** which is ***greater than 40^0.***

III. A ***Gain cross over frequency of 501 Hz*** which is greater than ***500 Hz***.

IV. A Phase cross over frequency of ***5080 HZ.***

<u>SENSITIVITY TRANSFER FUNCTION:</u>

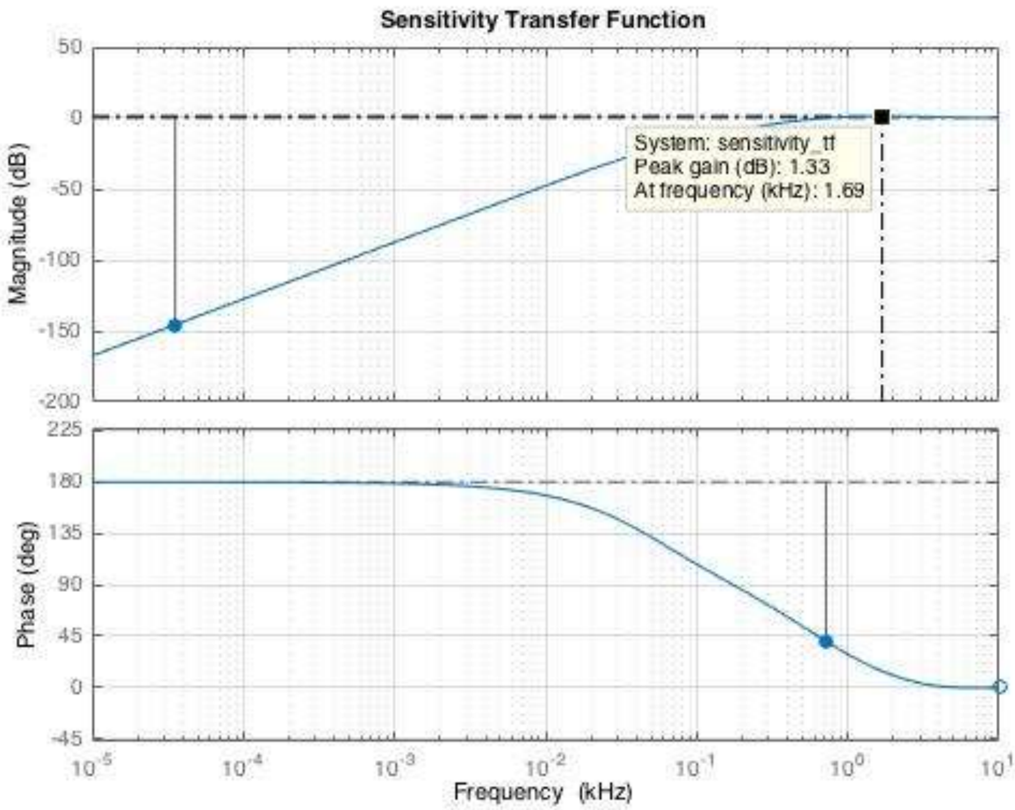


FIG 11: SENSITIVITY TRANSFER FUNCTION

Sensitivity transfer function is the measure of how the controller can withstand external disturbances and still produce an optimal control output to control the system thereby making it stable. The general sensitivity transfer function takes the form

1/1+P(s)C(s)

where P(s) is the transfer function of the plant and C(s) is the transfer function of the controller.

The frequency response of the sensitivity transfer function is plotted below and from the plot it is clearly evident that the peak of the sensitivity transfer function is ***1.33 dB which is less than 10dB.***

EFFECT OF SAMPLING FREQUENCY ON SYSTEM PERFORMANCE:

Sampling rates (sampling frequency) have a direct significant effect on discrete controller. The sampling frequency should be sufficiently large so as to be able to successfully and exactly represent the analog system in discrete domain.

The effects of different sampling rates on step response of the system are shown below.

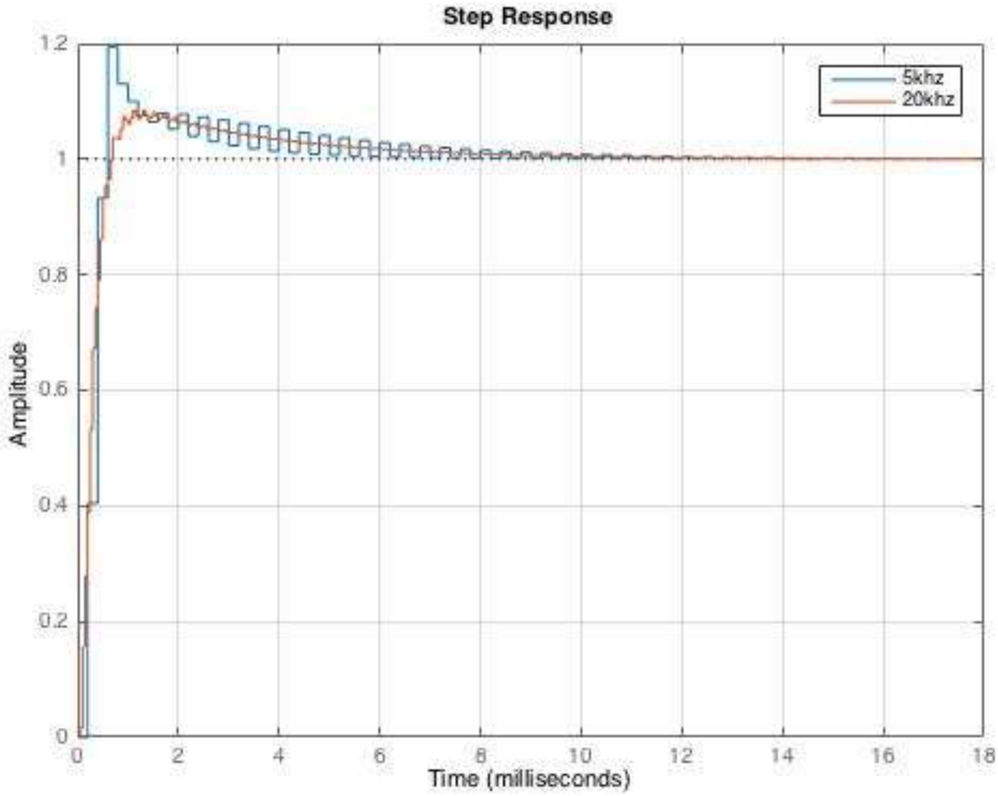


FIG 12: SAMPLING AT 5 AND 20 KHz.

Here the response is very slow when sampling frequency is less of the order of 5khz.When the Sampling frequency is high enough of the order of say 20khz response is better and the observer offers better performance.

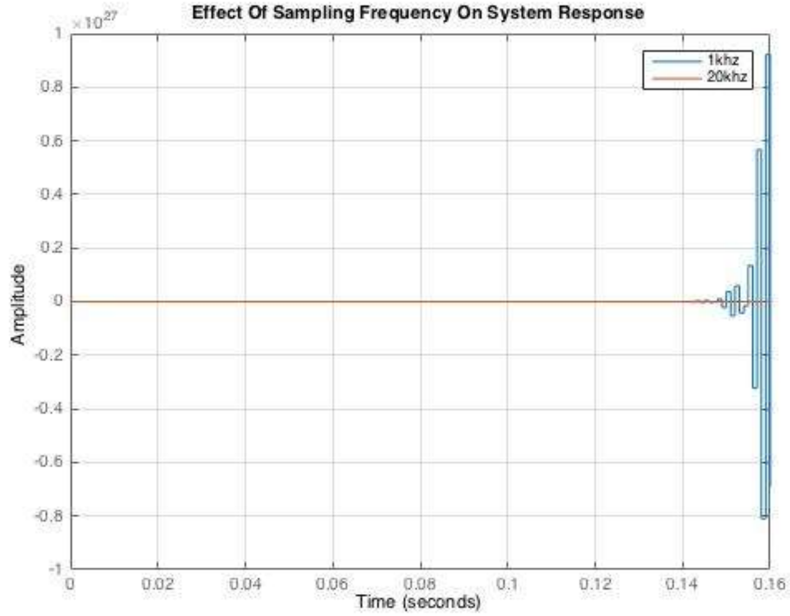


FIG 13: SAMPLING AT 1 AND 20 KHz.

When the sampling frequency is very less of the order of 1khz the system runs into oscillations and becomes unstable as shown above.

FIG 14: SAMPLING RESPONSE IN SIMULINK

The same is implemented in Simulink for three different frequencies namely 150 KHz,20 KHz and 10 KHz. From the Plot is evident that at very high frequency of 150 KHz the response has less overshoot ,settles faster and has zero steady state error.

SUMMARY:

Thus a Digital Controller has been designed meeting the required Time Domain and Frequency Domain Specifications. Sensitivity transfer function , unit step response of the system and also the effect of the sampling frequencies on the system response is discussed in detail.

REFERENCE:

[1] G. F. Franklin, J. D. Powell, and M. L. Workman, Digital Control of Dynamic Systems (3rd ed.), Addison-Wesley Longman, 1998.

[2] K. J. Astrom and B. Wittenmark, Computer-Controlled Systems:
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