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by James Summers

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Executive Summary

This report investigates the key concepts of different types of electrical, electronic and control systems. With the focus being on Transients, High and Low pass filters, Frequency responses, Open loop control and PID control. The different systems were then investigated using theoretical knowledge and simulation software and results were tabulated and analysed. The findings were then drawn up in a final conclusion.

Introduction & Aims and Objectives

The aim of this assignment is to investigate the behaviour of various electrical, electronic and control systems. These investigations will involve conducting theoretical calculations to provide a prediction of the circuits performance, before being modelled on simulation software and analysed with theoretical knowledge to reinforce the findings.



Task 1 – Transient Analysis of a First Order RL Electrical Circuit

A first order RL circuit was written in code and simulated with Matlab and was calculated theoretically with randomly selected circuit values for inductance and resistance. The uniquely selected values are 0.07H and 170Ω. The results were then analysed.

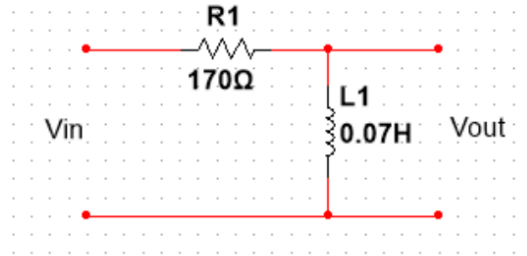


Figure 1 - RL Circuit

The Laplace Model

The Laplace model for the circuit was then written. The transfer function was written in terms of the time constant.

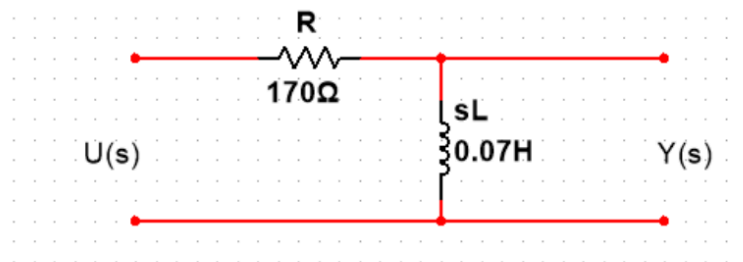


Figure 2 - RL Circuit Laplace form

1. Potential Divider

$$Y(s) = \frac{sL}{sL + R} \times U(s)$$

2. Apply the step input

$$U(s) = \frac{1}{s}$$

Therefore

$$Y(s) = \frac{sL}{sL + R} \times \frac{1}{s}$$

$$\frac{sL}{s(sL + R)}$$

The top and bottom get divided by L

$$\frac{L}{sL + R}$$

$$\frac{1}{s + A}$$

Where A = R/L

$$\frac{1}{s + \frac{R}{L}}$$

Inverse Laplace

$$I^{-1} \left\{ \frac{1}{s + \frac{R}{L}} \right\}$$

$$Y(t) = e^{-at}$$

Where $\tau = L/R$

$$e^{-\frac{Rt}{L}}$$



Calculating τ



$$\frac{0.07H}{170\Omega} = 0.41ms$$

3. Transfer Function in terms of Tau

$$\frac{Y(s)}{U(s)} = \frac{sL}{sL + R}$$



$$\frac{s \frac{L}{R}}{s \frac{L}{R} + 1}$$

$$\tau = L/R$$

$$\frac{\tau s}{\tau s + 1}$$

Matlab

A Matlab program was used to simulate the circuit to be able to compare the theoretical values with the simulated results (Figure 3).

```
Example 1 RC.m  Example Decay.m  Practise.m  +
1      s=tf('s');
2      system = (0.41*10^-3)*s/((0.41*10^-3)*s+1);
3      step(system);
4
```

Figure 3 - RL Circuit Matlab Code

The code from Matlab was then simulated to get the transient graph for the RL circuit (Figure 4).

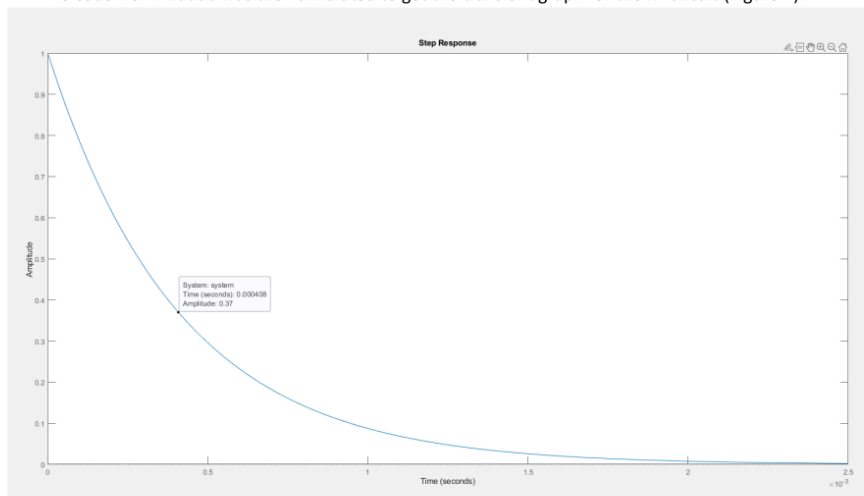


Figure 4 - Transient Response Decay RL Circuit

A results table was then created to compare the calculated and simulated values.

Table 1 - Task 1 Results

Time	Calculated	Simulated	Error
τ	0.410ms	0.408ms	0.002ms

Analysis

The results show very little error between the simulated and calculated values. This small error is due to the cursor selecting whole numbers on the Matlab software. The response of the circuit is an exponential decay, which is to be expected for a first order RL circuit. The time constant for a decay circuit is 0.368/36.8% of the full circuit current, which is derived from the discharge equation shown below. This point is shown on the Matlab graph proving the theoretical workings out are correct.

$$e^{-t/\tau} = 0.368$$



Task 2 – Transient Analysis of a First Order RC Electrical Circuit

A first order RC circuit was written in code and simulated with Matlab and was calculated theoretically with randomly selected circuit values for inductance and resistance. The randomly selected values are 10uF and 150Ω. The results were then analysed.

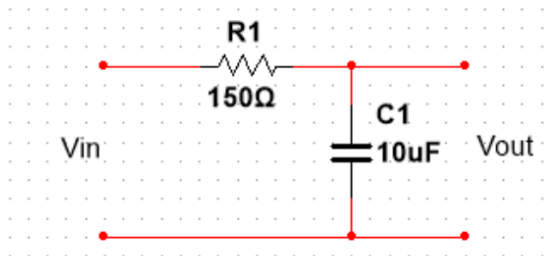


Figure 5 - RC Circuit

The Laplace Model

The Laplace model for the circuit was then written. The transfer function was written in terms of the time constant.

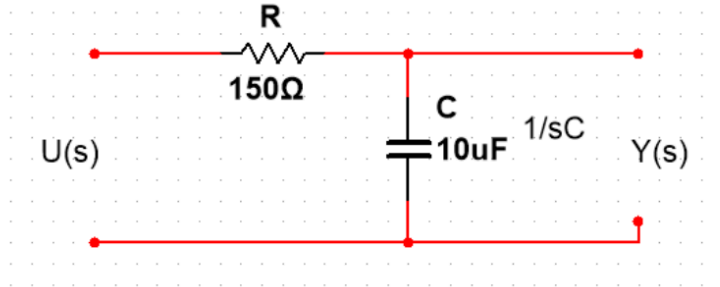


Figure 6 - RC Circuit Laplace form

1. Potential Divider

$$Y(s) = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} \times U(s)$$

2. Apply the step input

$$U(s) = \frac{1}{s}$$

Therefore

$$Y(s) = \frac{1}{RCs + 1} \times \frac{1}{s}$$

$$\frac{1}{s(RCs + 1)} = \frac{1}{s(s + a)}$$

Inverse Laplace

$$I^{-1} \left\{ \frac{1}{s(s + a)} \right\} = 1 - e^{-at}$$

$$Y(t) = e^{-at}$$

Where $\tau = RC$

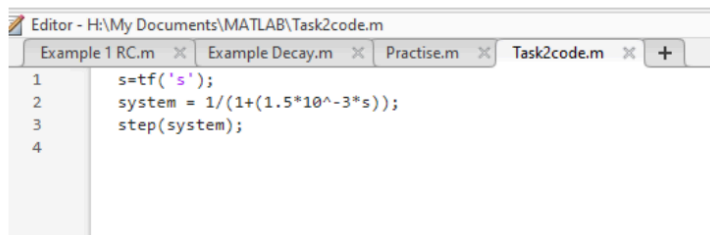
$$1 - e^{-\frac{t}{RC}}$$

Calculating τ

$$150 \times 10 \times 10^{-6} = 1.5 \text{ ms}$$

Matlab

A Matlab program was used to simulate the circuit to be able to compare the theoretical values with the simulated results (Figure 7).



```

Editor - H:\My Documents\MATLAB\Task2code.m
Example 1 RC.m  Example Decay.m  Practise.m  Task2code.m  +
1      s=tf('s');
2      system = 1/(1+(1.5*10^-3*s));
3      step(system);
4

```

Figure 7 – RC Circuit Matlab Code

The code from Matlab was then simulated to get the transient graph for the RC circuit (Figure 8).

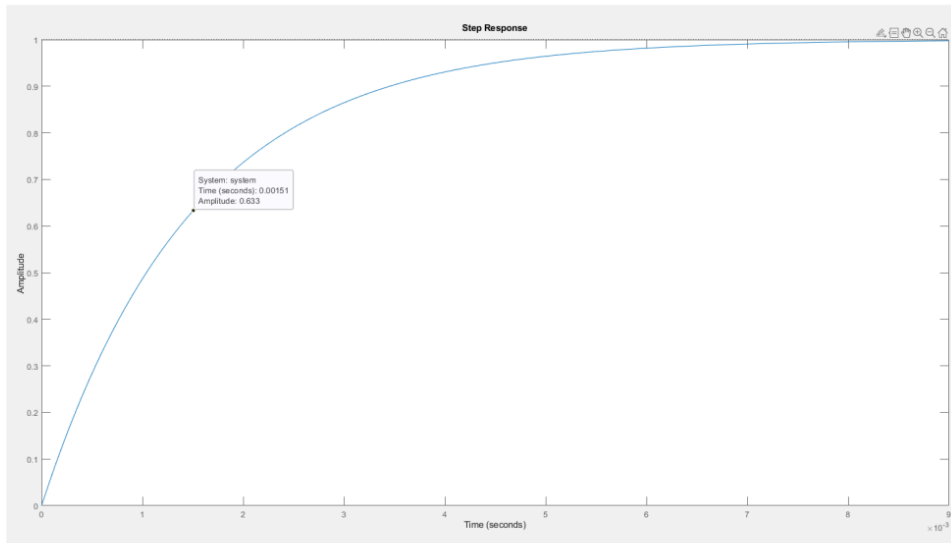


Figure 8 - Transient Response Exponential Growth RC Circuit

A results table was then created to compare the calculated and simulated values.

Table 2 - Task 2 Results

Time	Calculated	Simulated	Error
τ	1.5ms	1.51ms	0.01ms

Analysis

The results show very little error between the calculated and simulated results. The data obtained follows the correct trend for a first order RC circuit, as the circuit is meant to exponentially grow. The time constant for a circuit with exponential growth is 0.632/63.2% of the full charge. Taking a measurement at that point on the graph has proved the results to be correct.



$$1 - e^{-\frac{t}{\tau}} = 0.632$$

Task 3 – Frequency Performance Analysis of a First Order RL Electrical Circuit

The RL circuit in Task 1 (Figure 1) was reanalysed to look at the frequency response of the circuit. The same circuit values of 170Ω and 0.07H were reused and the circuit was simulated and calculated theoretically.

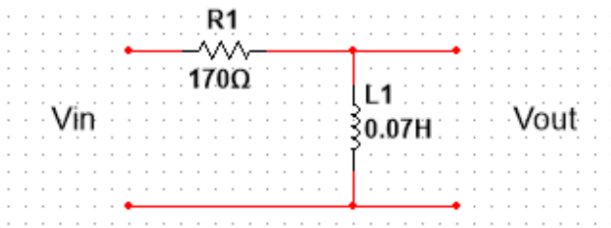


Figure 9 - RL Circuit (Task 1)

The Laplace Model

The Laplace model for the circuit was then created and written in the Laplace domain.

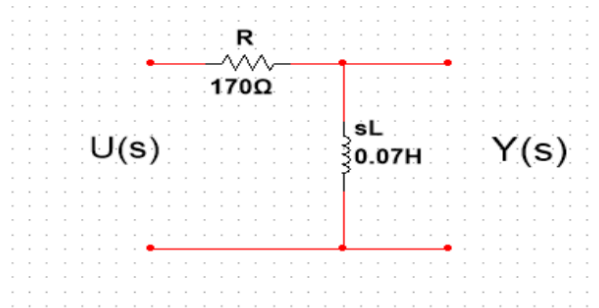


Figure 10 - RL Circuit Laplace form (Task 1)

$$\text{Cut-off frequency} = \omega c = \frac{R}{L} = \frac{170}{0.07} = 2428.57 \text{ Rads/s}$$



$$\text{Laplace formula} = H(s) = \frac{1}{\frac{1}{\omega c} + 1} = \frac{s}{s + \omega c} = \frac{1}{s + 2428.57}$$

Matlab

A Matlab program was used to simulate the circuit to be able to compare the theoretical values with the simulated results (Figure 11).

```
>> Task3
>> s = tf('s');
system = s/(s+2428.57);
bode(system);
grid on
```

Figure 11 - RL Circuit Matlab Code

The Matlab code was then simulated to a frequency response and phase response graph (Figure 12).

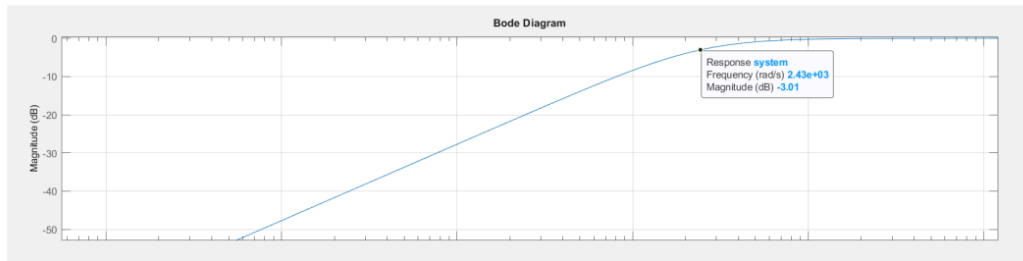


Figure 12 - RL Circuit Response Cut Off Frequency at -3dB

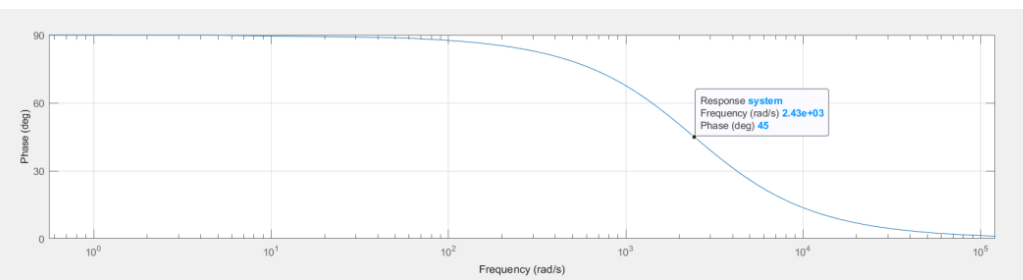


Figure 13 - RL Circuit Response Phase Shift

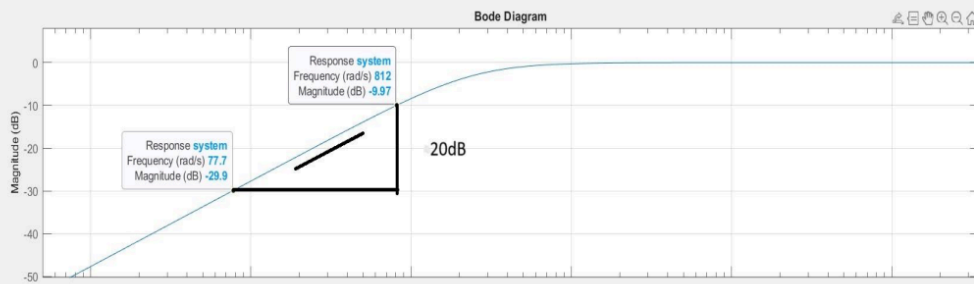


Figure 14 - RL Response Roll Off -20dB

A results table was then created to display and compare the results between the calculated and simulated values.

Table 3 - Task 3 Results

Measurements	Calculated	Measured
ω_c (Rads/s)	2428.57	2430.00
Phase (°)	45	45
Roll off (dB/dec)	-20	-20

Analysis

Due to the configuration of the circuit, it is possible to tell that the circuit would be high pass filter, which means it would only allow high frequencies to pass after the -3dB point. The phase shift at the natural frequency is 45 degrees and the roll off is 20dB. The results obtained show virtually no error between the calculated and measured values, proving the results to be correct.

Task 4 – Frequency Performance Analysis of a First Order RC Electrical Circuit

The RC circuit in Task 2 (Figure 15) was reanalysed to look at the frequency response of the circuit. The same circuit values of 10uF and 150Ω were reused and the circuit was simulated and calculated theoretically.

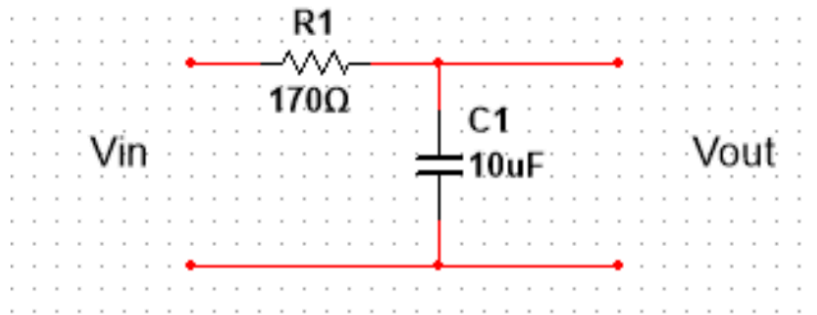


Figure 15 - RC Circuit (Task 2)

The Laplace Model

The Laplace model for the circuit was then created and written in the Laplace domain.

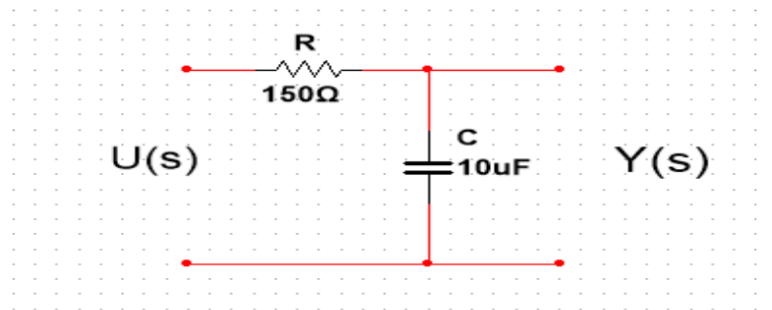


Figure 16 - RC Circuit Laplace form (Task 2)

$$\text{Cut-off frequency} = \omega c = \frac{1}{RC} = \frac{1}{150 \times 10 \times 10^{-6}} = 666.66 \text{ Rads/S}$$

$$\text{Laplace formula} = H(s) = \frac{1}{\omega c + 1} = \frac{\frac{1}{\omega c}}{\frac{1}{\omega c} + \omega c} = \frac{\omega c}{s + \omega c} = \frac{666.66}{s + 666.66}$$

Matlab

A Matlab program was used to simulate the circuit to be able to compare the theoretical values with the simulated results (Figure 17).

```

Command window

>> Task4
fx >> s=tf('s');
system= 666.66/((s)+666.66);
bode(system)
grid on;

```

Figure 17 - RC Circuit Matlab Code

The Matlab code was then simulated to a frequency response and phase response graph (Figures 18-20).

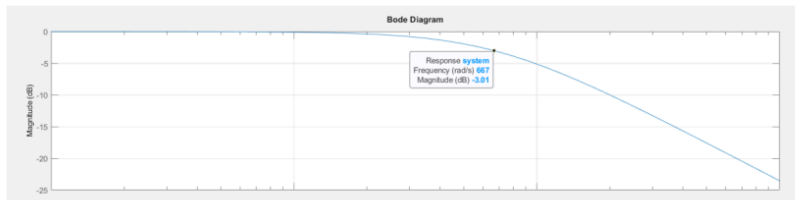


Figure 18 -- RC Response Cut off Frequency at -3dB

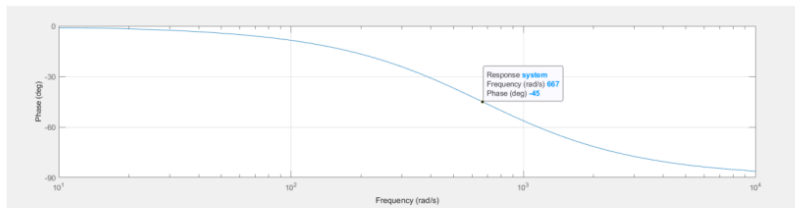


Figure 19 - RC Response Phase Shift

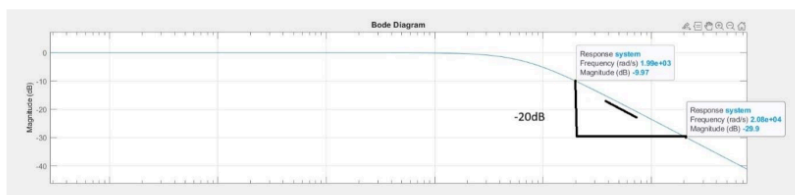


Figure 20 - RC Response Roll Off -20dB

A results table was then created to display the results between calculated and simulated values.

Table 4 - Task 4 Results

Measurements	Calculated	Measured
ω_c (Rads/s)	666.66	667
Phase (°)	45	45
Roll off (dB/dec)	-20	-20

Analysis

Due to the configuration of the circuit, it is possible to tell that the circuit would be a first order low pass filter, as it only has one reactive component, which means it would only allow low frequencies to pass after the -3dB point. The circuit has a phase shift of 45 degrees and a roll off slope of -20dB. The results obtained show virtually no error between the calculated and measured values, proving the results to be correct.



Task 5 – Transient Performance Analysis of a Second Order Series Electrical Circuit

The RLC circuit (Figure 21) was analysed again to look at the effect the resistance value has on the circuit and how it affects the damping factor. The 4 types of damping are: Under Damped, Over Damped, Critically Damped and No Damping. The component values selected are: $L=0.11\text{H}$, $C=60\mu\text{F}$ and $R=30\Omega$.

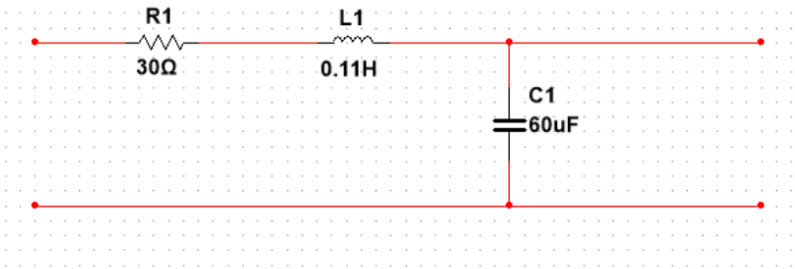


Figure 21 - RLC Circuit

The Laplace Model

The Laplace model for the circuit was then created and written in the Laplace domain.

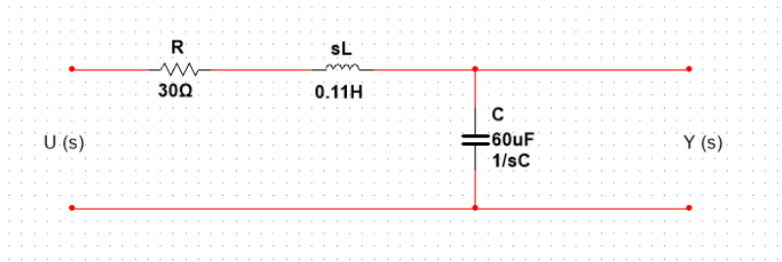


Figure 22 - RLC Circuit Laplace Form

1. Potential Divider Rule

$$Y(s) = \frac{\frac{1}{sC}}{R + sL + \frac{1}{sC}} \quad \text{10}$$

2. Multiply Top and Bottom by s/L

$$\frac{Y(s)}{X(s)} = \frac{\frac{1}{sC} \times sL}{R \times \frac{s}{L} + sL \times \frac{s}{L} + \frac{1}{sC} \times s/L}$$

$$H(s) = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2}$$

K = Gain = 1

Wn = Natural Frequency = $\frac{1}{\sqrt{LC}}$

ζ = Damping Coefficient = $\frac{R}{2} \sqrt{\frac{C}{L}}$

11

Calculations

The following equations were used to calculate the natural frequency and damping coefficient. The natural frequency remains the same for all the circuits.

$$\text{Natural frequency} = \omega_n = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.11 \times 60 \times 10^{-6}}} = 389.25 \text{ Rads/s}$$

$$\zeta = \text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}}$$

Under Damped

An underdamped circuit is when the damping coefficient is less than 1, this causes the circuit to oscillate and have overshoot before reaching its steady state.

$$\text{Damping Coefficient} = \zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{30}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 0.350$$

$$H(s) = \frac{K \omega_n^2}{s^2 + 2 \zeta \omega_n s + \omega_n^2} = \frac{1 \times 389.25^2}{s^2 + (2 \times 0.350 \times 389.25) s + 389.25^2}$$

Over Damped

An overdamped circuit is when the damping coefficient is greater than 1, this causes the circuit to slowly rise to its steady state.

$$\text{Damping Coefficient} = \zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{150}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 1.751$$

$$H(s) = \frac{K \omega_n^2}{s^2 + 2 \zeta \omega_n s + \omega_n^2} = \frac{1 \times 389.25^2}{s^2 + (2 \times 1.751 \times 389.25) s + 389.25^2}$$

Critically Damped

A Critically Damped circuit is when the damping coefficient is equal to 1, the circuit rises quickly to its steady state with no oscillation. In order to calculate the damping factor, the equation must be transposed to calculate the resistor value required.

$$R = \frac{2 \zeta}{\sqrt{\frac{C}{L}}} = \frac{2 \times 1}{\sqrt{\frac{60 \times 10^{-6}}{0.11}}} = 85.63488386$$

$$\text{Damping Coefficient} = \zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{85.63488386}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 1$$

No Damping

To attain a circuit with no damping, the circuit must have a very low resistance. A value of 0.0000001 was used for this simulation.

$$\text{Damping Coefficient} = \zeta = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{0.000001}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 1.167748416 \times 10^{-9}$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 389.25^2}{s^2 + ((2 \times 1.167748416 \times 10^{-9} \times 389.25) \times s) + 389.25^2}$$

Matlab

The systems were then simulated on Matlab and the responses are shown in Figures 23 to 30.

Underdamped

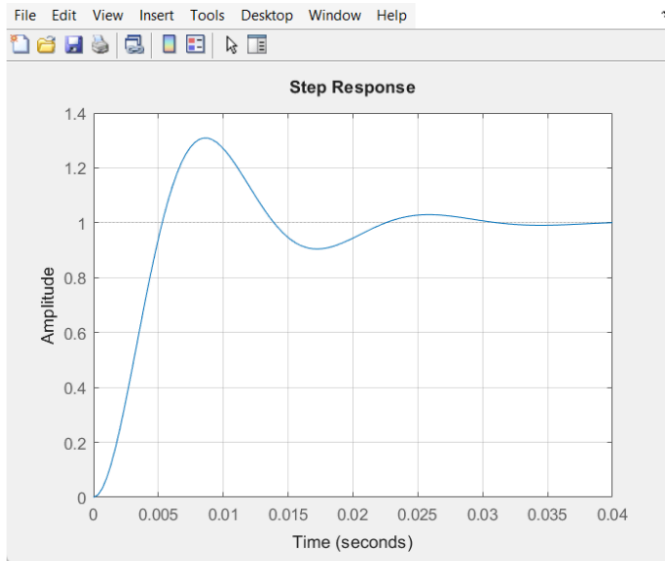


Figure 23 - Underdamped Response

```

1      s=tf('s');
2      system=389.25^2/(s^2+(2*0.35*389.25)*s+389.25^2);
3      step(system);
4      grid on;

```

Figure 24 - Underdamped Response Matlab Code

Overdamped

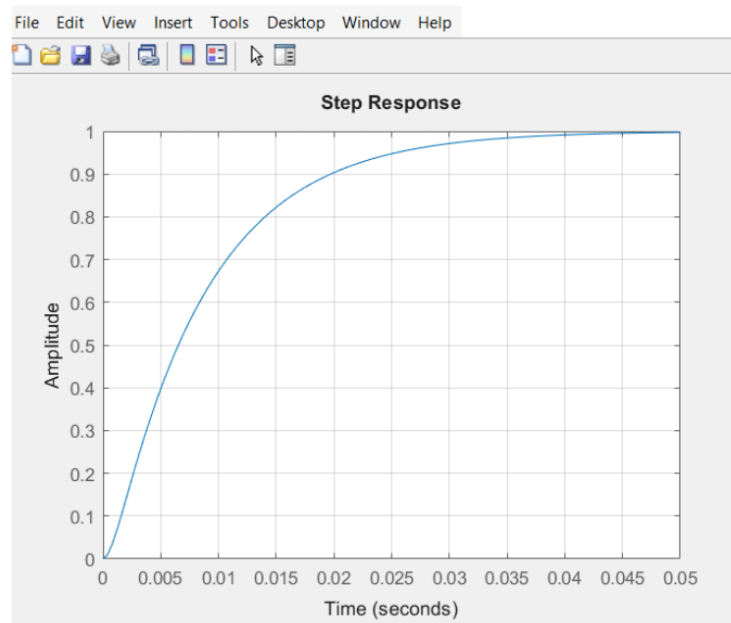


Figure 25 - Over Damped Response

```
Task3.m Task4.m Task5.m +
1      s=tf('s');
2      system=389.25^2/(s^2+(2*1.751*389.25)*s+389.25^2);
3      step(system);
4      grid on;
```

Figure 26 - Overdamped Response Matlab Code

Critically Damped

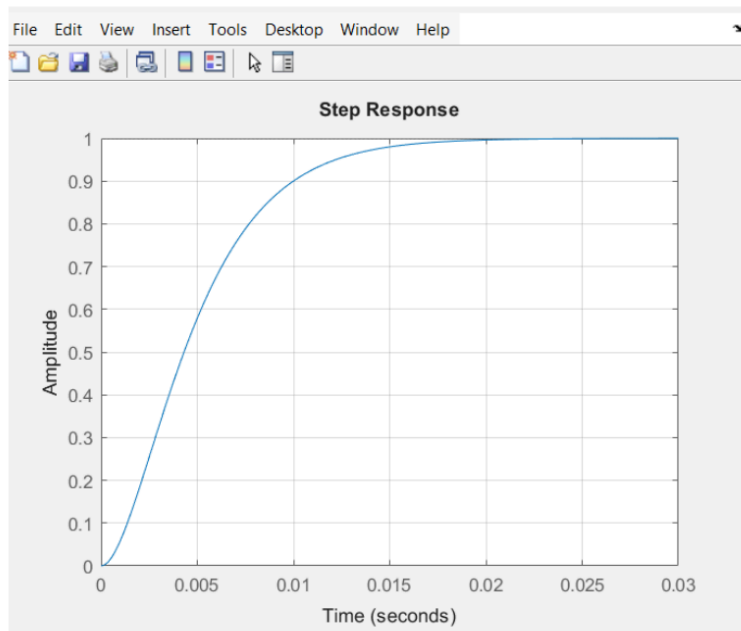


Figure 27 - Critically Damped Response

```
Editor - C:\Users\jambe\OneDrive\Documents\MATLAB\Task5.m
Task3.m Task4.m Task5.m +
1      s=tf('s');
2      system=389.25^2/(s^2+(2*1*389.25)*s+389.25^2);
3      step(system);
4      grid on;
```

Figure 28 - Critically Damped Response Matlab Code

No Damping

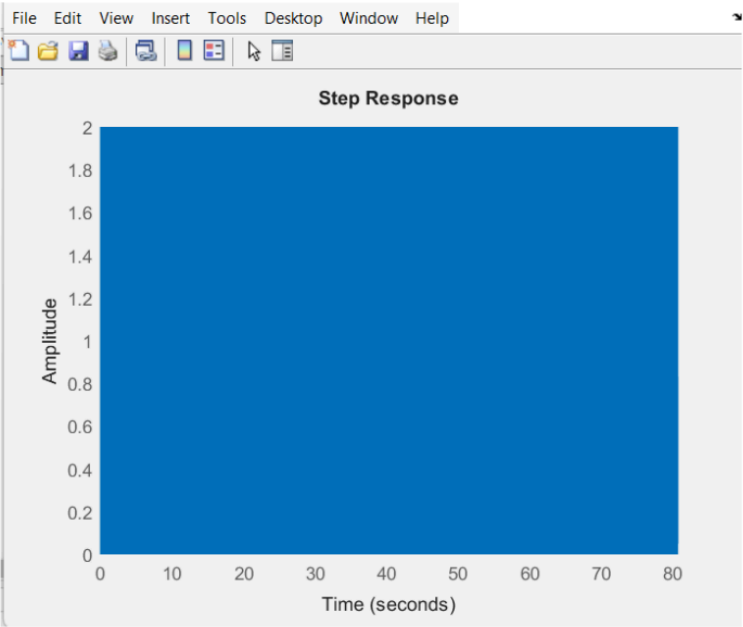


Figure 29 - No Damping Response

```
Editor - C:\Users\jamber\OneDrive\Documents\MATLAB\Task5.m
Task3.m Task4.m Task5.m
1      s=tf('s');
2      system=389.25^2/(s^2+(2*1.167748416*10^-9*389.25)*s+389.25^2);
3      step(system);
4      grid on;
```

Figure 30 - No Damping Response Matlab Code

Table 5 - Task 5 Results

Resistor Value (Ω)	Damping Coefficient (ζ)	Circuit Effect
30	0.350 ($\zeta < 1$)	Underdamped
150	1.751 ($\zeta > 1$)	Overdamped
85.63488386	1 ($\zeta = 1$)	Critically Damped
0.0000001	1.16	No Damping

Analysis

The simulations show that the resistor value directly effects the damping coefficient of the circuit. The results show that as the value of resistance is increased, the damping coefficient increases, which means that the circuit might not reach the t_{13} red value or could take longer than the optimum time to reach it. The results also show that decreasing the resistance values, decreases the stability of the response.

Task 6 – Frequency Performance Analysis of a Second Order Series Electrical Circuit

The circuit in figure 31 was reanalysed to look at the frequency performance parameters, such as cut off frequency.

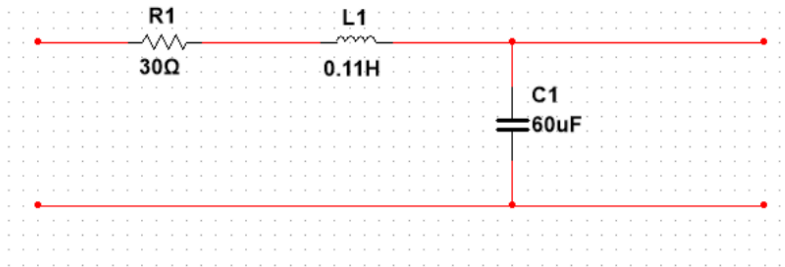


Figure 31 - RLC Circuit (Task 6)

The Laplace Model

The Laplace model for the circuit was then created and written in the Laplace domain.

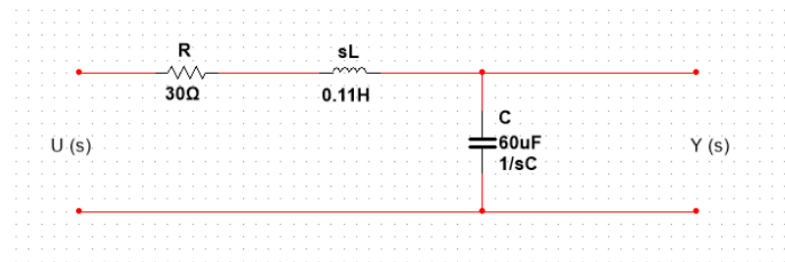


Figure 32 - RLC Circuit (Task 6) Laplace form

1. Potential Divider Rule

$$Y(s) = \frac{\frac{1}{sC}}{R + sL + \frac{1}{sC}}$$

2. Multiply Top and Bottom by s/L

$$\frac{Y(s)}{X(s)} = \frac{\frac{1}{sC} \times sL}{R \times \frac{s}{L} + sL \times \frac{s}{L} + \frac{1}{sC} \times s/L}$$

$$H(s) = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2}$$

$$K = \text{Gain} = 1$$

$$W_m = \text{Frequency for maximum amplitude} = \sqrt{\left(\frac{1}{LC} - \frac{1}{2} \left(\frac{R}{L}\right)^2\right)}$$

$$W_n = \text{Natural Frequency} = \frac{1}{\sqrt{LC}}$$

$$\zeta = \text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}}$$

$$Q = \text{Gain} = \frac{1}{R} \sqrt{\frac{L}{C}}$$



Calculations

The following equations were used to calculate the natural frequency and damping coefficient. The natural frequency remains the same for all the circuits. A range of values were selected, including an Over Damped, Critically Damped and three Under Damped.

$$\text{Natural frequency} = W_n = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.11 \times 60 \times 10^{-6}}} = 389.25 \text{ Rads/s}$$

$$\text{Frequency for Maximum Amplitude} = W_m = \sqrt{\frac{1}{LC} - \frac{1}{2} \left(\frac{R}{L}\right)^2} =$$

$$\sqrt{\frac{1}{0.11 \times 60 \times 10^{-6}} - \frac{1}{2} \left(\frac{0.000001}{0.11}\right)^2} = 389.24 \text{ Rads/s}$$

Under Damped

Resistance Value = 10 Ω

$$\text{Gain } (G) = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{1}{10} \sqrt{\frac{0.11}{60 \times 10^{-6}}} = 4.28$$

$$\text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{10}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 0.11$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 389.25^2}{s^2 + ((2 \times 0.11 \times 389.25) \times s) + 389.25^2}$$

Resistance Value = 20 Ω

$$\text{Gain } (G) = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{1}{20} \sqrt{\frac{0.11}{60 \times 10^{-6}}} = 2.14$$

$$\text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{20}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 0.23$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 389.25^2}{s^2 + ((2 \times 0.23 \times 389.25) \times s) + 389.25^2}$$

Resistance Value = 40 Ω

$$\text{Gain } (G) = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{1}{40} \sqrt{\frac{0.11}{60 \times 10^{-6}}} = 1.07$$

$$\text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{40}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 0.46$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 389.25^2}{s^2 + ((2 \times 0.46 \times 389.25) \times s) + 389.25^2}$$

Over Damped

Resistance Value = 150 Ω

$$\text{Gain } (G) = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{1}{150} \sqrt{\frac{0.11}{60 \times 10^{-6}}} = 0.285$$

$$\text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{150}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 1.751$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 389.25^2}{s^2 + ((2 \times 1.751 \times 389.25) \times s) + 389.25^2}$$

Critically Damped

Resistance Value = 85.63488386Ω

$$\text{Gain } (G) = \frac{1}{R} \sqrt{\frac{L}{C}} = \frac{1}{85.63488386} \sqrt{\frac{0.11}{60 \times 10^{-6}}} = 0.5$$

$$\text{Damping Coefficient} = \frac{R}{2} \sqrt{\frac{C}{L}} = \frac{85.63488386}{2} \sqrt{\frac{60 \times 10^{-6}}{0.11}} = 1$$

$$H(s) = \frac{K W n^2}{s^2 + 2 \zeta W n s + W n^2} = \frac{1 \times 389.25^2}{s^2 + ((2 \times 1 \times 389.25) \times s) + 389.25^2}$$

Matlab

The systems were then simulated on Matlab. The code and responses are shown in Figures 33 to 36.

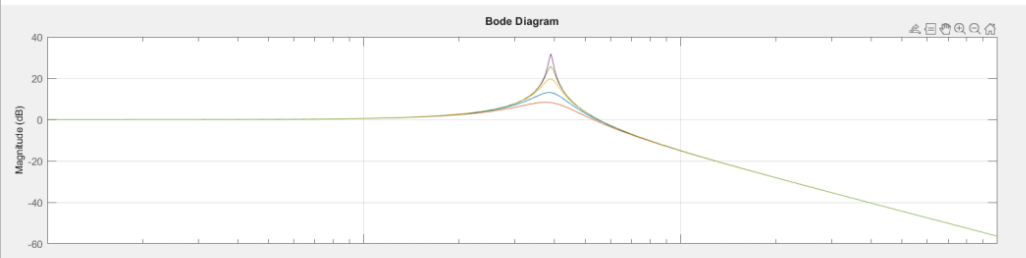


Figure 33 - Bode Diagram Response

16

```

1
2     s=tf('s');
3     system1 = 151515/(s^2 + 85.63488386*s +151515);
4     bode(system1);
5     grid on
6     hold on
7
8     s=tf('s');
9     system2 = 151515/(s^2 + 150*s +151515);
10    bode(system2);
11    s=tf('s');
12    system3 = 151515/(s^2 + 40*s +151515);
13    bode(system3);
14    s=tf('s');
15    system4 = 151515/(s^2 + 10*s +151515);
16    bode(system4);
17    s=tf('s');
18    system5 = 151515/(s^2 + 20*s +151515);
19    bode(system5);
20    s=tf('s');
21    grid on
22

```

Figure 34 - RLC Circuit (Task 6) Matlab Code

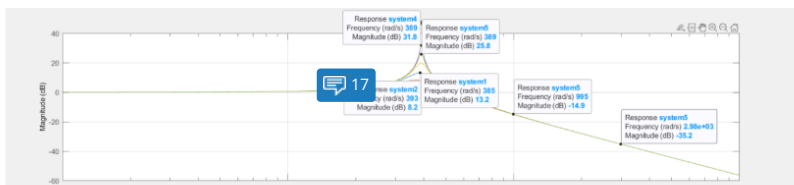


Figure 35 - RLC Response Cut off frequency

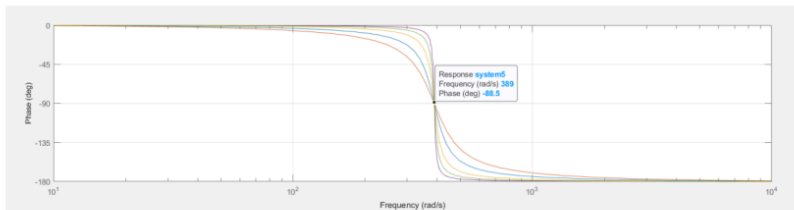


Figure 36 - RLC Response Phase shift

Analysis

The simulations show that the resistor value directly effects the damping coefficient of the circuit. The results show that as the value of resistance is increased, the damping coefficient increases, whilst also reducing the circuit gain. This means the circuit might not reach the desired value or take longer than the optimum time to reach it. On the other hand, decreasing the resistance values, decreases the stability of the response. At the resonant frequency the phase angle is -90 degrees.

Task 7 - Frequency Performance Analysis of a First Order Electronic System

The low pass filter in figure 37 was created on Multisim. This looked at how the capacitance value effects the cut off frequency and phase shift. The component values selected are as per the brief, with a selected capacitor value of $C = 320\text{nF}$.

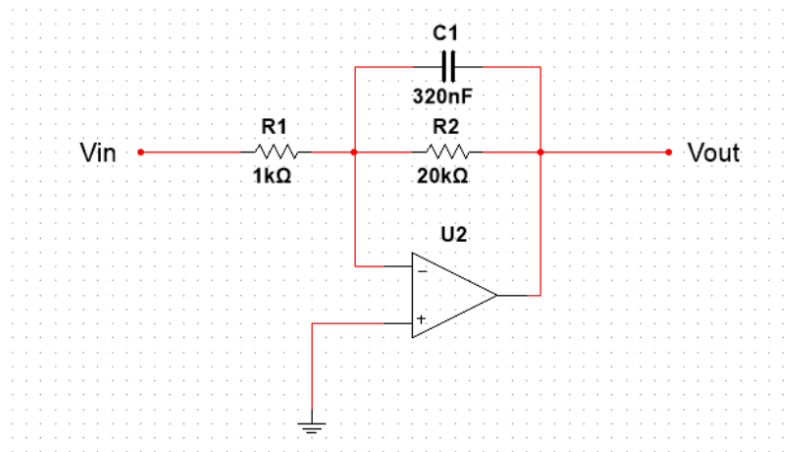


Figure 37 - Low Pass Filter Circuit

The Laplace Model

The Laplace model for the circuit was then created and written in the Laplace domain.

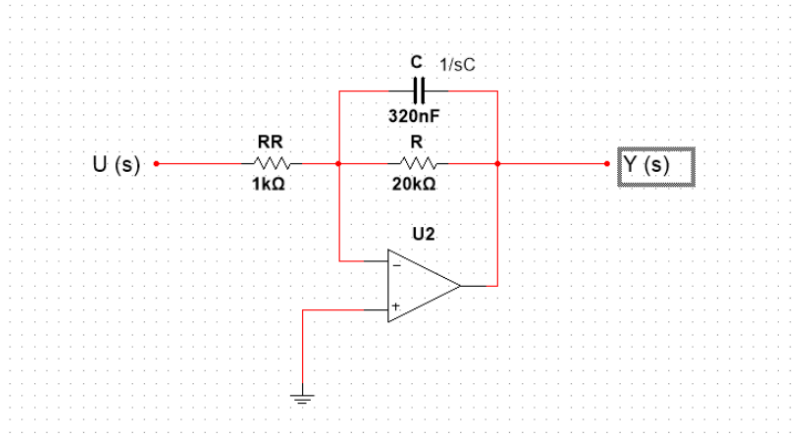


Figure 38 - Low Pass Filter Circuit Laplace form

$$\text{Gain (K)} = \frac{R2}{R1} = \frac{20000}{1000} = 20$$

$$\text{Cut off frequency (Wc)} = \frac{1}{CR2} = \frac{1}{320 \times 10^{-9} \times 20000} = 156.25 \text{ Rads/s}$$

$$\text{Transfer function } H(s) = -k \left[\frac{Wc}{s + Wc} \right] = -20 \left[\frac{156.25}{s + 156.25} \right]$$

Matlab

A Matlab program was used to simulate the circuit to be able to compare the theoretical values with the simulated results.

```
Task7.m x Task8.m x Task4.m x Task6.m x Task6.asv x +
1 s=tf('s');
2 system1 = -20*(156.25/(s+156.25));
3 bode(system1);
4 grid on
5 hold on
```

Figure 39 - Low Pass Filter Circuit Matlab Code

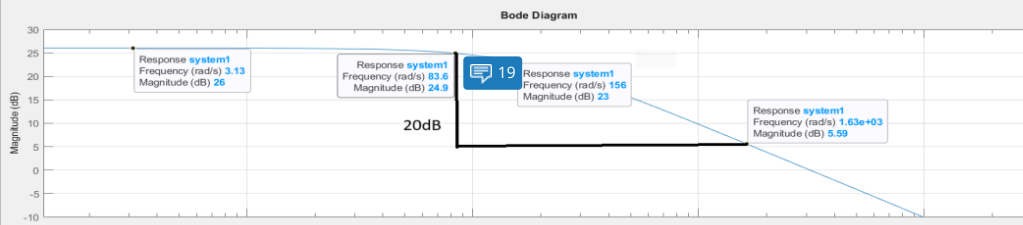


Figure 40 - Low Pass Filter Circuit Response Cut off Frequency and Roll off

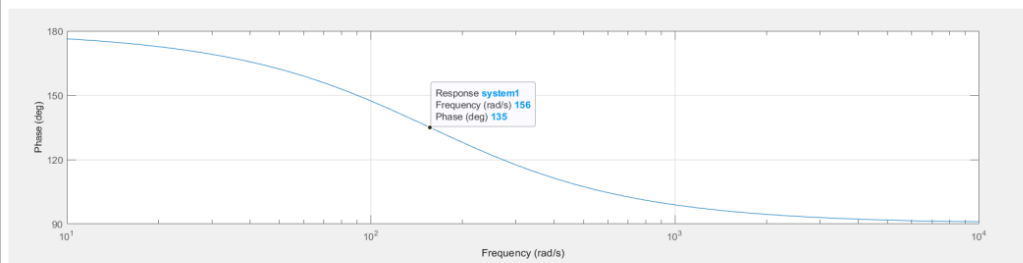


Figure 41 - Low Pass Filter Circuit Response Phase Shift

Analysis

The results gathered prove that the calculated and simulated values are consistent with each other. Figure 40 shows the cut off frequency of the circuit and the roll off of 20dB, the DC gain of the inverting amplifier can also be proved using the equation shown below. As the circuit is an inverting amplifier it will have a phase shift of $-45 + 180$ degrees = 135 degrees (Figure 41).

$$20 \log(20) = 26.02$$



Task 8 – Frequency Performance Analysis of a First Order Electronic System

The high pass filter (figure 42) was created on Multisim. This investigated how the capacitance value effects the cut off frequency and phase shift. The component values selected are as per the brief, with a selected capacitor value of $C = 32\text{nF}$.

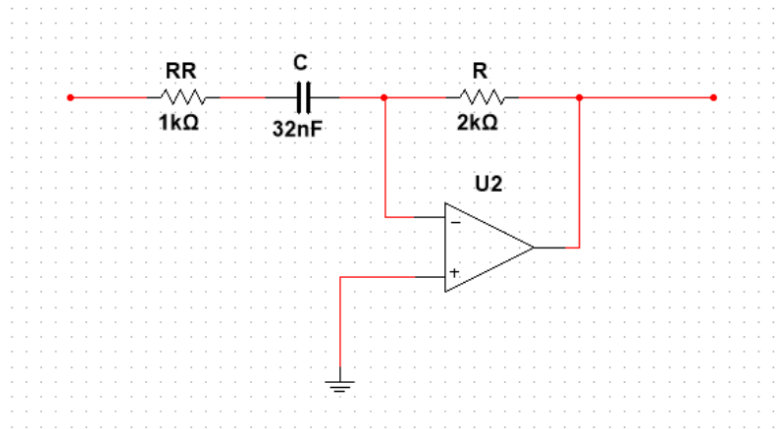


Figure 42 - High Pass Filter Circuit

The Laplace Model

The Laplace model for the circuit was then created and written in the Laplace domain.

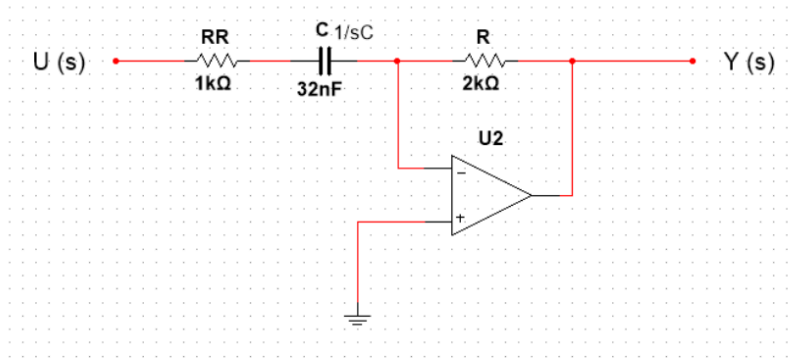


Figure 43 - High Pass Filter Circuit Laplace form

$$\text{Gain}(K) = \frac{R2}{R1} = \frac{2000}{1000} = 2$$

$$\text{Cut off frequency}(W_c) = \frac{1}{CR1} = \frac{1}{32 \times 10^{-9} \times 1000} = 31250 \text{ Rads/s}$$

$$\text{Transfer function } H(s) = -k \left[\frac{s}{s + W_c} \right] = -2 \left(\frac{s}{s + 31250} \right)$$

Matlab

A Matlab program was used to simulate the circuit to be able to compare the theoretical values with the simulated.

```

Task7.m x Task8.m x Task4.m x Task6.m x Task6.asv x +
1      s=tf('s');
2      system1 = -2*(s/(s+31250));
3      bode(system1);
4      grid on
5      hold on

```

Figure 44 - High Pass Filter Circuit Matlab Code

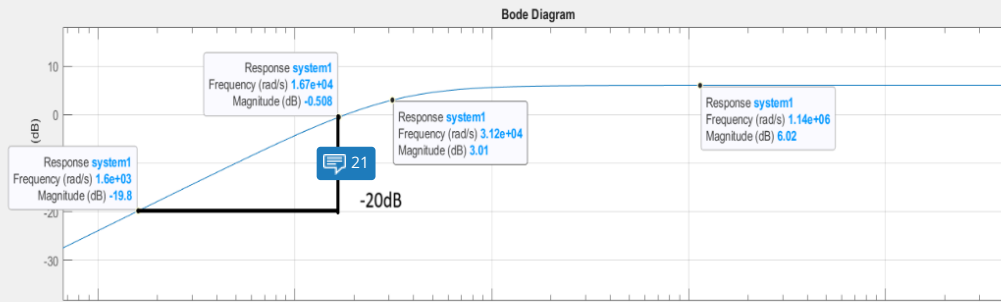


Figure 46 - High Pass Filter Circuit Response Cut off Frequency and Roll off

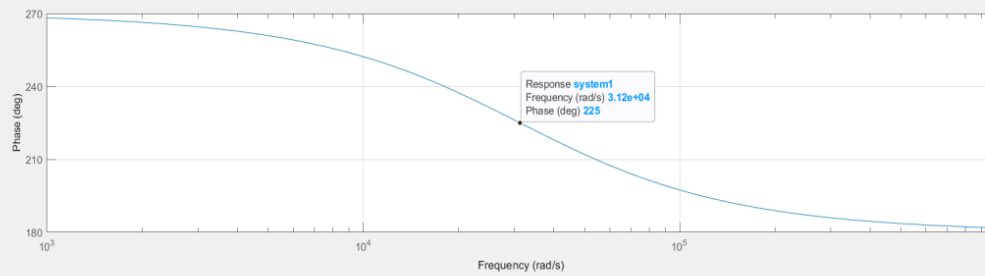


Figure 45 - High Pass Filter Circuit Response Phase shift

Analysis

The collected results show that the calculated and simulated values are consistent with each other, Figure 46 shows the cut off frequency of the circuit and the roll off of 20dB, the DC gain of the inverting amplifier can also be proved using the equation shown below. As the circuit is a high pass filter it will have a phase shift of $45 + 180$ degrees = 225 degrees (Figure 45).

$$20 \log(2) = 6.02$$

22

Task 9 – First Order Control System Analysis

The first order control system (Figure 47) was constructed on Simulink, and the open loop performance was determined. The circuit was then modified to determine the K value for stability within the circuit.

Open Loop Response

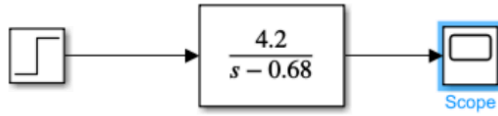


Figure 47 - Open Loop Circuit Diagram

The system was then simulated, and the open loop response is shown in figure 48.

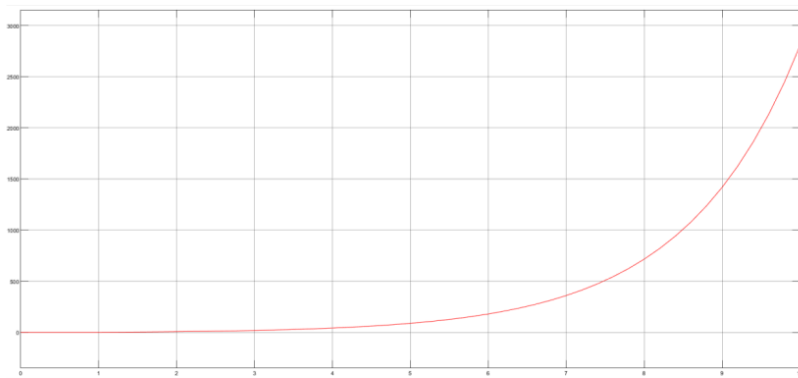


Figure 48 - Open Loop Circuit Response

To check the stability of the system, Matlab code was written to display an Argand (Pole/Zero) map (Figure 49).

```

1 num=[4.2];
2 den=[1 -0.68];
3 [zz,pp,kk]=tf2zp(num,den);
4 pzmap(pp,zz)

```

Figure 49 - Pole Zero Map Code

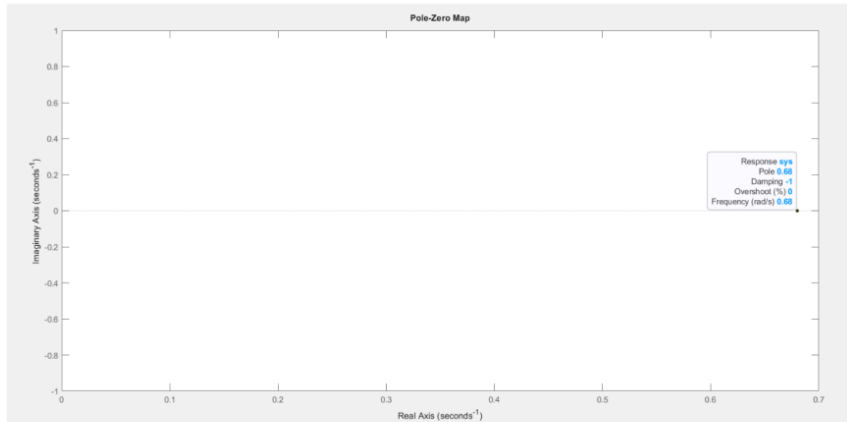


Figure 50 - Pole Zero Map Response

From the pole zero map the pole is (0.68). This shows that the system will be unstable due to being in the positive plain. (Figure 50) The pole can be calculated shown below.

$$\text{Pole at } s - 0.68 = 0$$

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$$0 + 0.68 = s$$

Closed Loop Response

To improve the stability of the system, the circuit was changed to closed loop control. This involved introducing negative feedback into the circuit. This channels a portion of the systems output back into the input to help maintain equilibrium.

The open loop system was then modified and negative feedback was introduced, a gain of 1 was added and the system was simulated.

The Laplace Model

A block diagram for the circuit was created allowing the Laplace formula to be derived. (Figures 51 and 52)

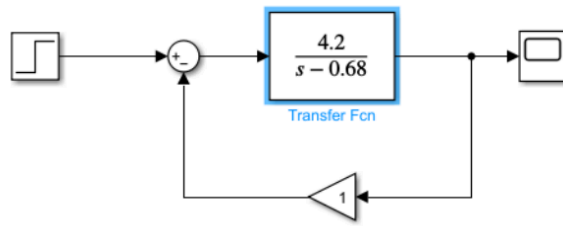


Figure 51 - Closed Loop Circuit Diagram

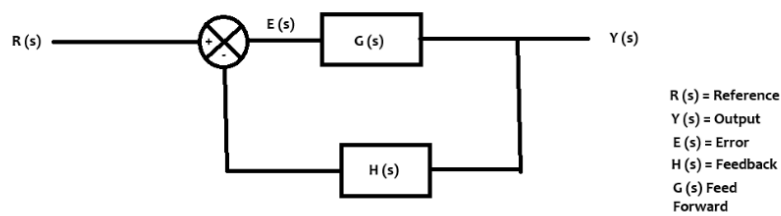


Figure 52 - Closed Loop Circuit Diagram Laplace form

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$$\frac{G(s)}{1 + G(s)H(s)}$$

$$\frac{\frac{4.2}{(s - 0.68)}}{1 + \frac{4.2k}{(s - 0.68)}}$$

Multiply top and bottom by $(s - 0.68)$

$$\frac{4.2}{s - 0.68 + 4.2k}$$

$$\frac{4.2}{s + 3.52}$$

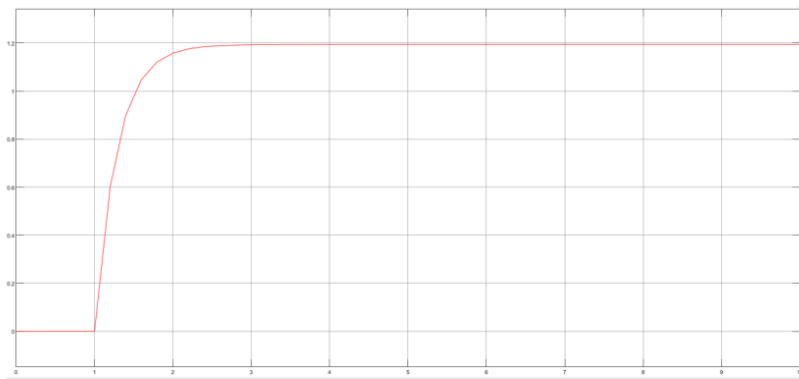


Figure 53 - Closed Loop Circuit Response

The response showed that the stability of the system had improved as there were no oscillations and a fast rise to equilibrium. Matlab code (Figure 54) was then used to create an Argand diagram 25

```

1 num=[4.2];
2 den=[1 +3.52];
3 [zz,pp,kk]=tf2zp(num,den);
4 pzmap(pp,zz)

```

Figure 54 - Argand Diagram Matlab Code

Due to it being a positive number, the system should be stable as the pole would be in the negative plain.

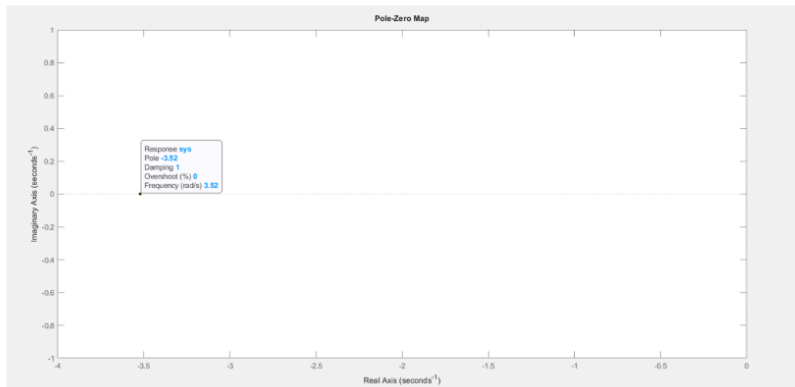


Figure 55 - Argand Diagram

Manipulating the Formula for Minimum K value

The transfer function was then manipulated to find out the minimum value for K to achieve a stable system. (Figure 56)

$$\frac{G(s)}{1 + G(s)H(s)}$$

$$\frac{\frac{4.2}{(s - 0.68)}}{1 + \frac{4.2}{(s - 0.68)}k} = \frac{4.2}{s - 0.68 + 4.2k}$$

$$s = 0.68 + 4.2k = 0$$

$$s = 0.68 - 4.2k$$

$$0.68 - (4.2 \times 0.16) = 8 \times 10^{-3}$$

26

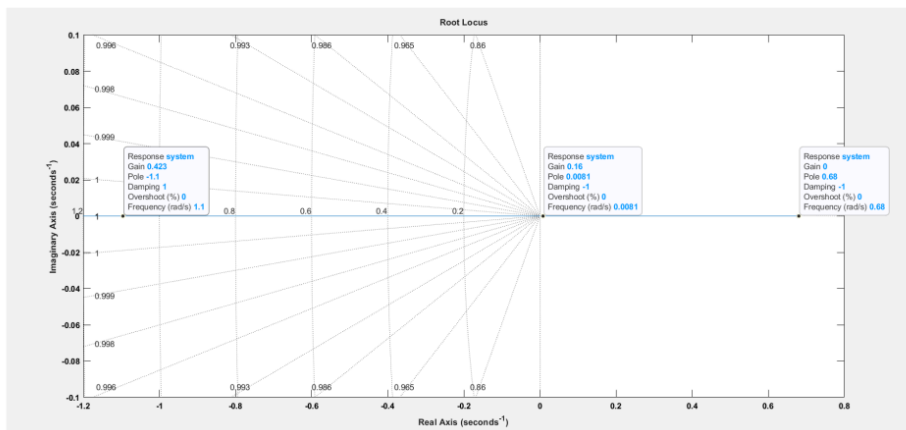


Figure 56 - Root Locus Response

The root locus plot highlights that the lowest gain value to achieve a pole of zero is 0.16.



Adjusting Gain to Investigate Stability

The gain was then varied to highlight how it changes the behaviour of the system.

$K = 3$

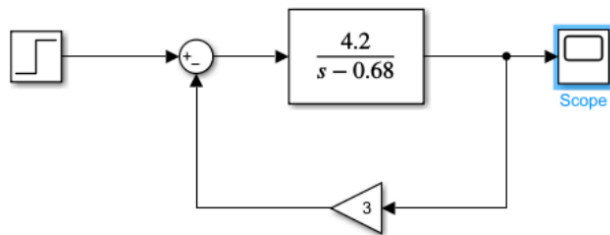


Figure 57 - Closed Loop Circuit Diagram $K = 3$

$$s = 0.68 - 4.2k = 0.68 - 4.2 \times (3) = -11.92$$

This would indicate a stable system as the pole is in the negative plain.

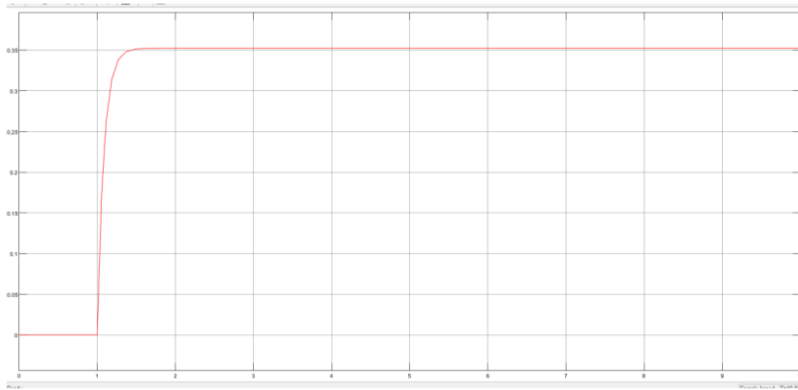


Figure 58 - $K = 3$ Response

$K = 0.5$

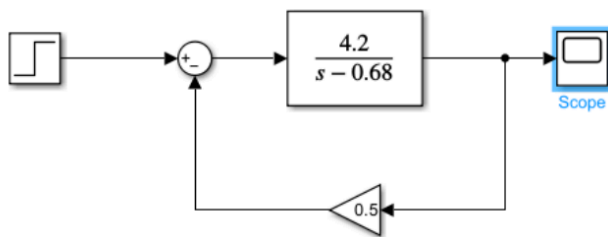


Figure 59 - Closed Loop Circuit Diagram $K = 0.5$

$$s = 0.68 - 4.2k = 0.68 - 4.2 \times (0.5) = -1.42$$

This would indicate a stable system as the pole is in the negative plain.

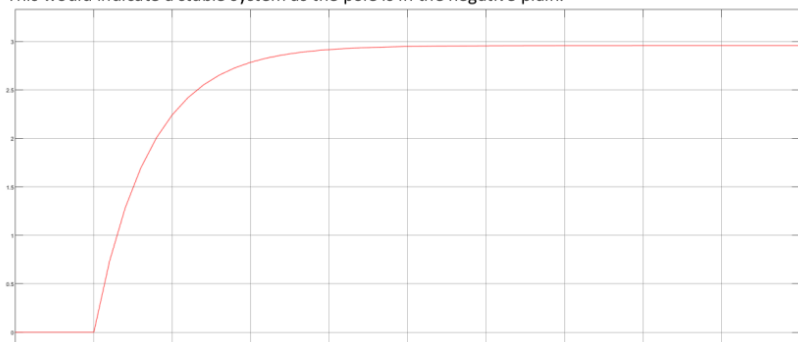


Figure 60 - $K = 0.5$ Response

K = 0.0006

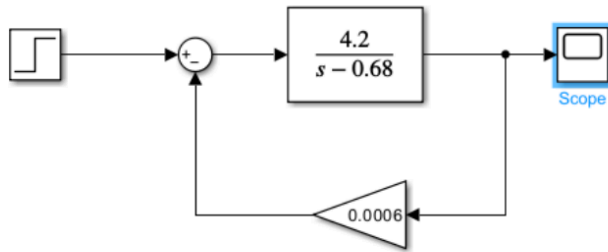


Figure 61 - Closed Loop Response Circuit Diagram K = 0.0006

$$s = 0.68 - 4.2k = 0.68 - 4.2 \times (0.0006) = 0.677$$

This would indicate an unstable system as the pole is in the positive plain.

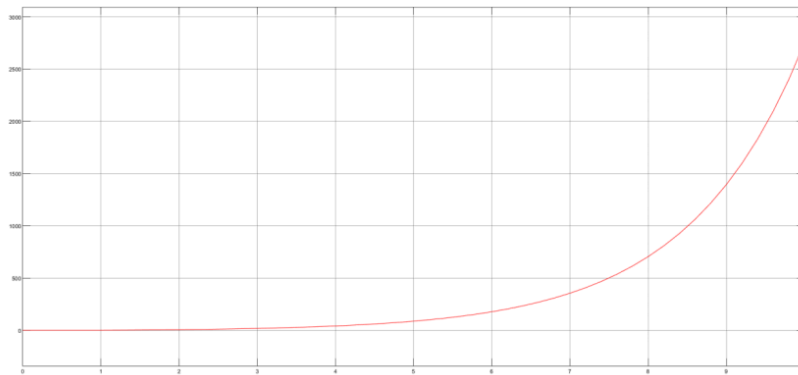


Figure 62 - K = 0.0006 Response

Table 6 - Task 9 Closed Loop Response Results

Gain (K)	Pole	Calculated Stability	Measured Stability
3	-11.92	Stable	Stable
0.5	-1.42	Stable	Stable
0.0006	0.677	Unstable	Unstable

Analysis

The investigation shows that when the circuit is open loop it lacks stability as the circuit is in the positive plain on a pole zero map, the introduction of negative feedback increases the stability as a portion of the output is feedback into the input signal reducing the error. The circuit then ended up in the negative plain indicating it was stable. The gain value was then adjusted to study its impact on

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the stability. The findings show that the smaller the circuit gain the more unstable it becomes, this is proven by the calculated and simulated results shown in figures 58,60 and 62.

Task 10 – DC Motor Model Analysis

The model shown in Figure 64 is a mathematical representation of a DC motor including the electrical and mechanical transfer function, with the disturbance set to zero initially. A motor model was then built and simulated using Simulink. The model required a series of calculations to be built.

30

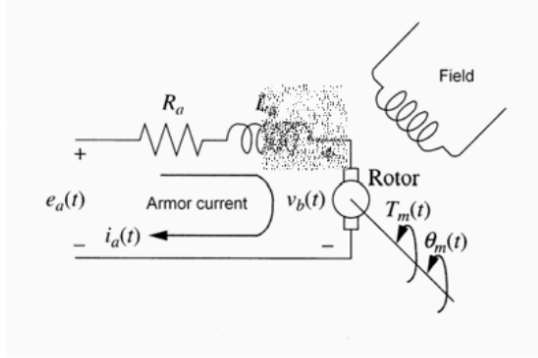


Figure 63 - Schematic Diagram DC Motor (researchgate,2008)

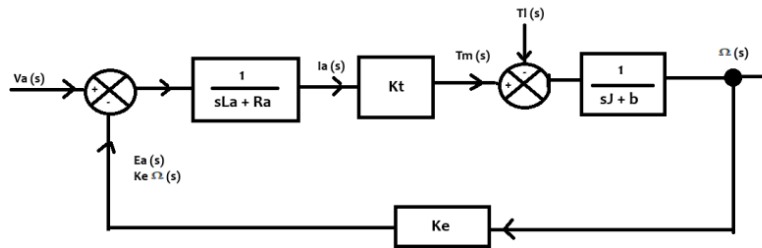


Figure 64 - DC Motor Diagram Laplace form

The transfer function for the system reduces to:

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$$H(s) = \frac{K W_n^2}{s^2 + 2 \zeta W_n s + W_n^2}$$

K = DC gain

ω_n = Natural Frequency

ζ = Damping Coefficient

The transfer function with all the motor parameters inserted.

$$H(s) = \frac{357.14}{s^2 + 7.51s + 9.01}$$

Calculations

Natural Frequency

$$\text{Natural Frequency } (\omega_n) = \sqrt{\frac{Ra \cdot b}{La \cdot J} + \frac{Kt \cdot Ke}{La \cdot J}}$$

$$\text{Natural Frequency } (\omega_n) = \sqrt{\frac{1.5 \times 3.68 \times 10^{-6}}{0.2 \times 0.0035} + \frac{0.025 \times 0.025}{0.2 \times 0.00035}} = 3.01 \text{ Rads/s}$$

Gain

$$\text{Gain } (K) = \frac{Kt}{Ra + KtKe}$$

$$\text{Gain } (K) = \frac{0.025}{1.5 \times 3.68 \times 10^{-6} + 0.025 \times 0.025} = 39.65$$

Damping Factor

$$\zeta = \frac{\frac{b}{J} + \frac{Ra}{La}}{2\omega_n}$$

$$\zeta = \frac{\left(\frac{3.68 \times 10^{-6}}{0.00035} + \frac{1.5}{0.2}\right)}{2 \times 3.01} = 1.252$$

Stall Torque

$$\text{Stall torque} = \frac{Kt \cdot Va}{Ra} = \frac{0.025 \times 14}{1.5} = 0.233 \text{ N/m}$$

Friction less no load speed

$$\text{Friction Less No Load Speed } \Omega_{NL} = \frac{Va}{Ke} = \frac{14}{0.025} = 560 \text{ Rads/s}$$

Pole Zero Map

There are no poles in the numerator, therefore only the denominator needs to be formatted as a quadratic equation.

$$H(s) = \frac{357.14}{s^2 + 7.51s + 9.01}$$

$$s^2 + 7.51s + 9.01 = 0$$

$$s = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$A = 1$$

$$B = 7.51$$

$$C = 9.01$$

$$s = \frac{-(7.51) \pm \sqrt{(7.51)^2 - 4 \times 1 \times 9.01}}{2 \times 1}$$

$$+ = -1.5$$

$$- = -6.01$$

This would indicate the system is stable due to the poles being in the negative plain.

Simulations

The stability of the system was then investigated using a pole zero diagram, this was calculated using the quadratic formula and then was simulated using Matlab.

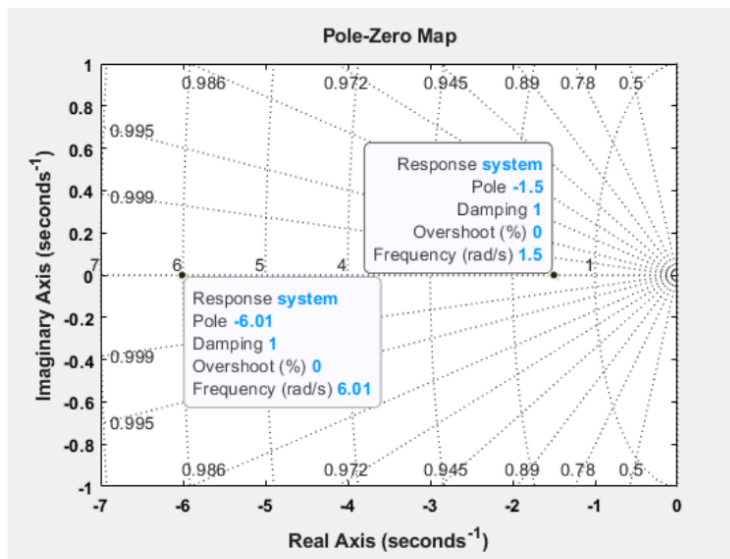


Figure 65 - Pole Zero Diagram

A model for the motor was then constructed using Simulink and was simulated.

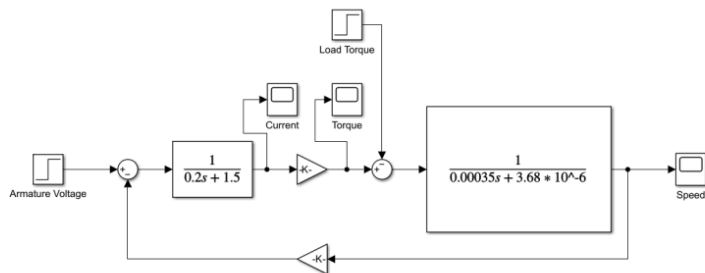


Figure 66 - Simulink Model DC Motor

32

The Motor was firstly simulated over a 20 second period with an input armature voltage of 14Vdc with no disturbances, figures 67 and 68 show the no load speed and the torque. Figures 69 and 70 show the theoretical stall talk being added to the model and again showing the speed and torque of the motor.

33



Figure 67 - DC Motor No Load Speed Response

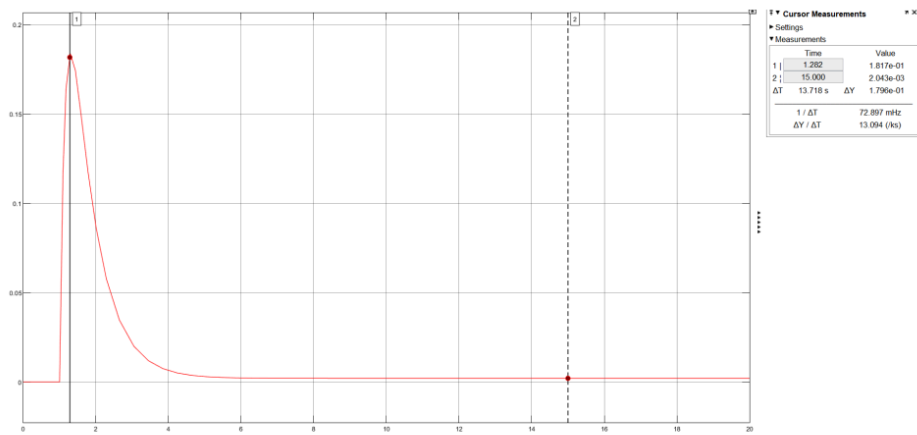


Figure 68 - DC Motor No Load Speed Response (Torque)

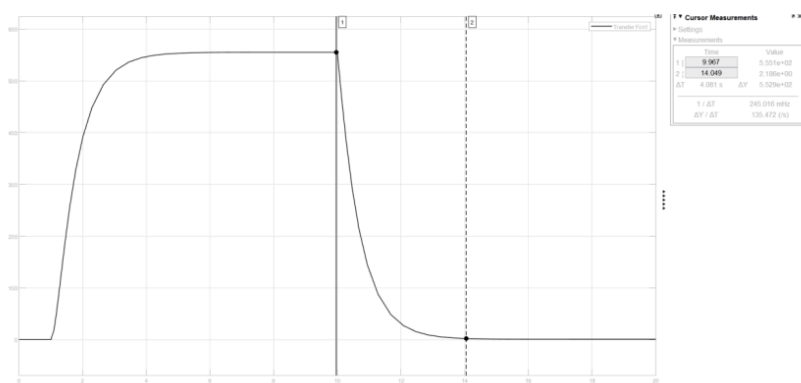


Figure 69 - DC Motor Stall Torque Applied (Speed Response)

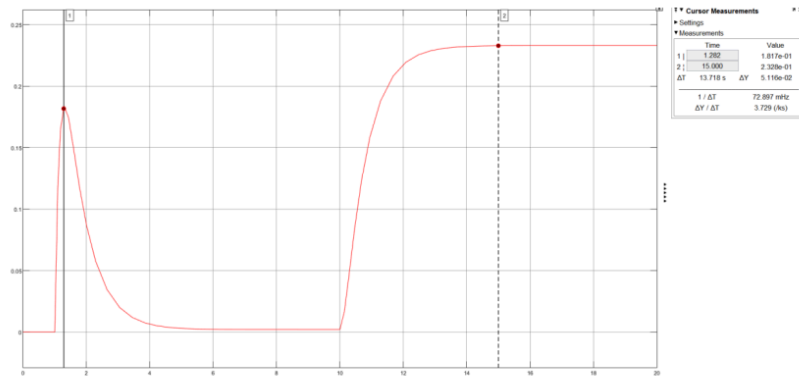


Figure 70 - DC Motor Stall Torque Applied (Torque)

The model was again modified, this time a disturbance of 0.04Nm after 10 seconds. The speed and current were then measured and compared with the theoretical values (Figures 71 and 72).

$$\text{Loaded speed } \Omega L = \frac{V_a - \frac{K_e T_l}{K_t}}{\frac{R_a b}{K_t} + K_e} = \frac{14 - \left(\frac{1.5 \times 0.04}{0.025} \right)}{\left(\frac{1.5 \times 3.68 \times 10^{-6}}{0.025} \right) + 0.025} = 459.93 \text{ Rads/s}$$

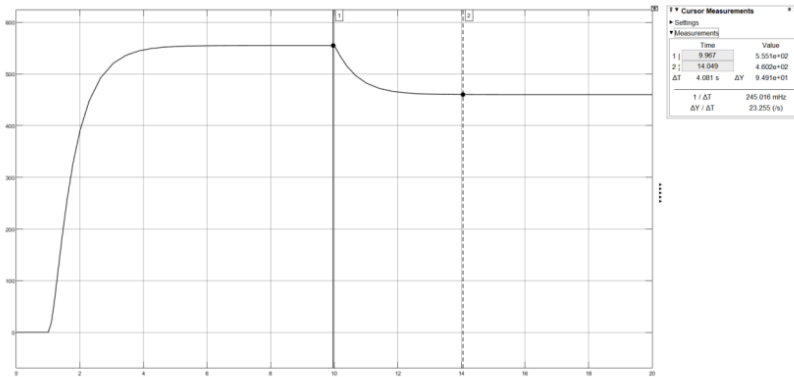


Figure 71 - DC Motor Loaded Speed Response

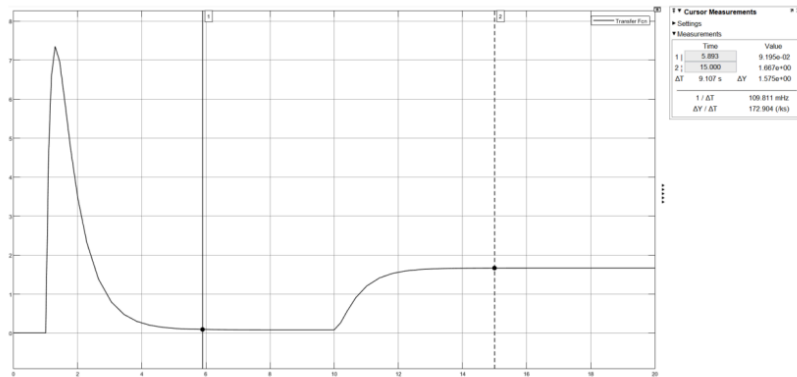


Figure 72 - DC Motor Loaded Speed Response (Current)

Table 7 - Task 10 Results

Rads/s	Calculated	Simulated	Error
No Load Speed	560	555.1	4.9
Loaded Speed	459.93	460	0.07



Analysis

The simulations show that initially when the motor is run with no load, it reaches the set speed with friction. The current graph also follows the correct pattern as there is an inrush current when the motor is started which flattens off when the motor is up to its set speed. When the motor stall torque is introduced after 10 seconds the motor begins to stall, looking at the torque graphs shows a sharp increase indicating that the motor is underload and trying not to stall. The stall torque was then removed and a disturbance (load) was introduced after 10 seconds, the motor firstly reaches its set speed before dropping slightly due to load on it. The current graph mirrors this as there an initial inrush when the motor is started before settling, the load is introduced and the current rises again trying to raise the motor speed.



Task 11 - Proportional Speed Control System

The motor model used in Task 10 was then modified to introduce proportional control (KP). The disturbance value was decreased to 0.03Nm and the model was split into separate sub systems for simplicity (Figure 73), they were then fed into a 3-input scope to look at the waveforms. The three sub systems show how increasing and decreasing KP affects the response of the circuit.

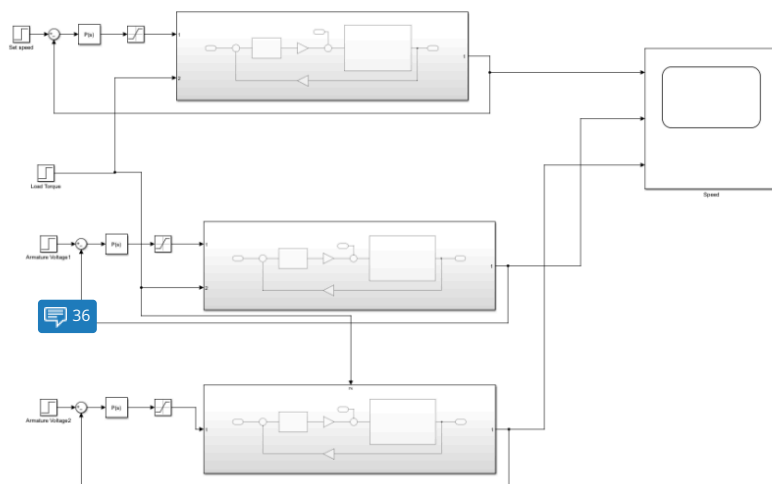


Figure 73 - Simulink 3 Subsystems

One of the subcircuits was tuned using Simulink to provide the optimum value for KP.

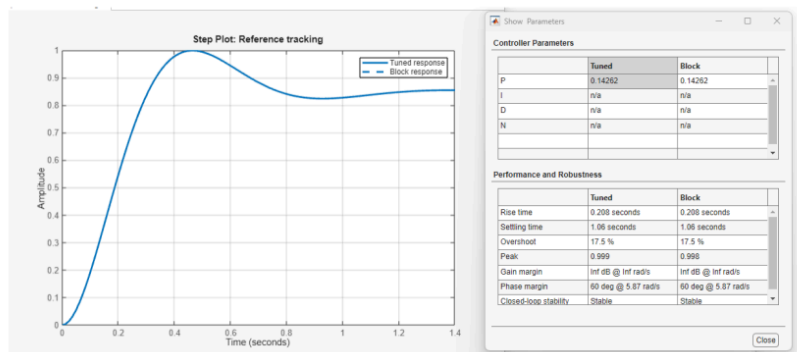


Figure 74 - Tuned KP Value

A pair of values above and below optimum value were then simulated to show what effects increasing and decreasing KP does to the response.

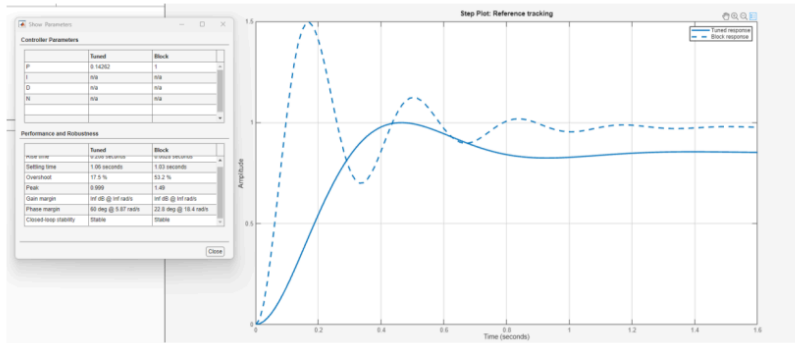


Figure 75 - High Value for KP

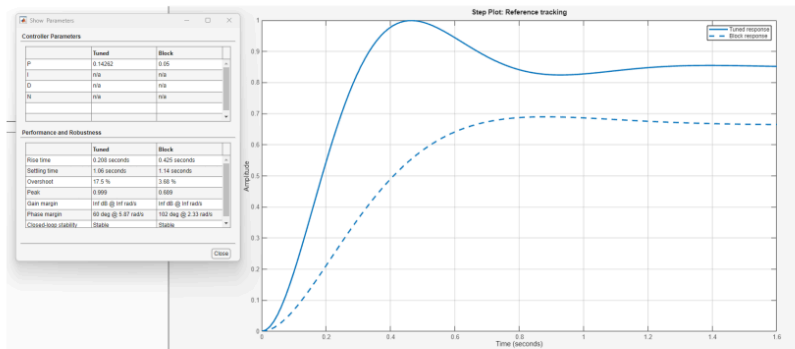


Figure 76 - Low Value for KP

The KP values were then measured on the 3 input scope, one being above the optimum value and one below. It is possible to see that increasing the value of KP led to a faster response time to the error, whilst also reducing steady state error. However, if the value of KP is too high it can cause larger overshoot and instability.

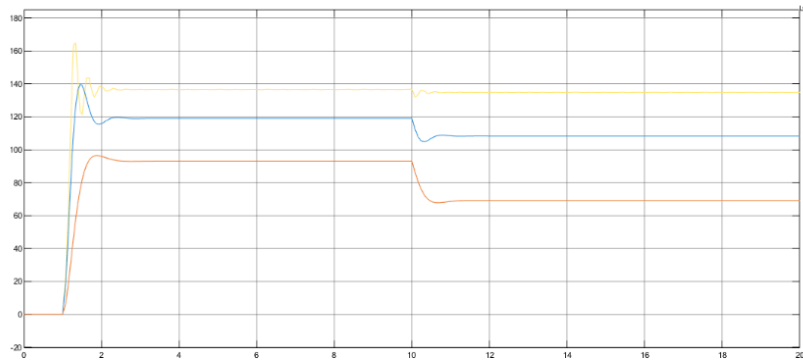


Figure 77 - 3 Input Scope for Different KP Values

Table 8 - Task 11 KP Results

KP Value	Steady State Error	Overshoot (%)	Rise Time (s)	Settling Time (s)
1 (High)	-2	53.2	0.028	1.03
0.14262 (Tuned)	-20	17.5	0.208	1.06
0.01 (Low)	-45	3.68	0.425	1.14

Analysis

The simulations show that introducing proportional control has helped increase stability in the circuit compared to the open loop response used in previous tasks. As previously mentioned, increasing the value of KP leads to a faster response time to mitigate the error whilst also reducing steady state error. However, if the value of KP is too high, it can cause larger overshoot and instability.

Task 12 - Proportional-Integral Speed Control System

The motor model used in Task 11 was then modified to introduce proportional-integral control (KI). The 3 inputs were then fed into a 3-input scope to measure the waveforms. The three sub systems show how increasing and decreasing KI affects the response of the circuit.

One of the subcircuits was firstly tuned to show the optimum response, the value for KP was kept constant while varying the KI value. (Figure 78)

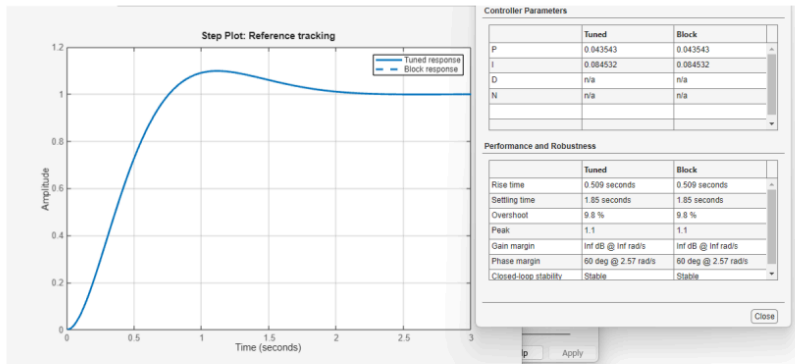


Figure 78 - Tuned Value for KI

A pair of values above and below the optimum value were then simulated to show how KI effects the response.

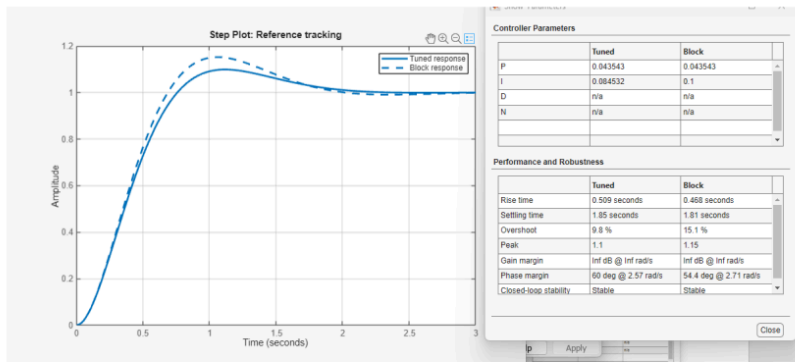


Figure 79 - High Value for KI

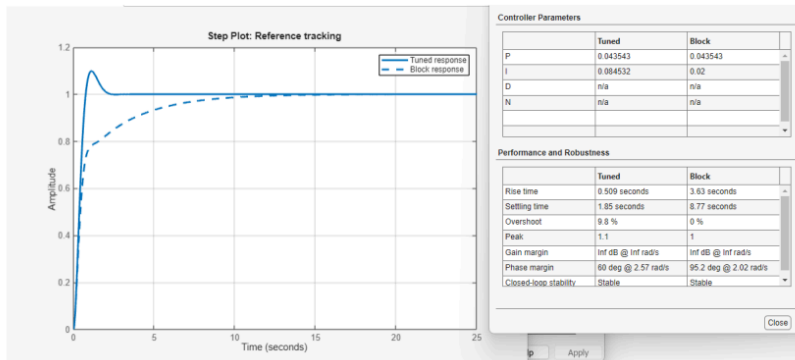


Figure 80 - Low Value for KI

The KI values were then measured on the 3-input scope, one being above the optimum value and one below. It is possible to see that increasing the value of KI led to a slower response time. It helps reduce the value of steady state error.

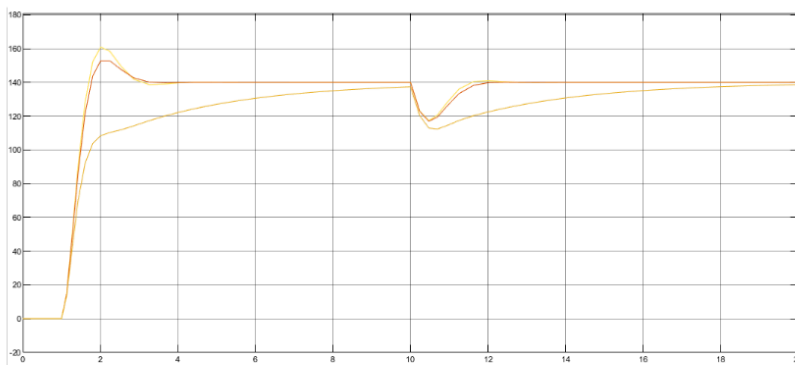


Figure 81 - 3 Input Scope of Different KI Values

Table 9 - Task 12 Results KI Values

KP Value	Steady State Error	Overshoot (%)	Settling Time (s)	Rise Time (s)
0.1 (High)	0	15.1	1.03	0.468
0.084532 (Tuned)	0	9.8	1.06	0.509
0.02 (Low)	-4	0	1.14	3.63

Analysis

The simulations show that introducing integral control has helped increase stability in the circuit compared to the open loop response used in previous tasks. Integral control continually calculates the error overtime and tries to erase the error that is calculated. Which is ideal for systems with constant disturbances or persistent errors. As previously mentioned, increasing the value of KI slows the reponse down to mitigate the error, whilst also reducing steady state error. If the value of KI becomes high (integral windup), it can cause the systems rising time to increase.



Task 13 - Proportional-Integral-Derivative Speed Control System

The motor model used in Task 12 was then modified to introduce proportional-integral-derivative control (PID). The three inputs were then fed into a 3-input scope to measure the waveforms. The three sub systems show how increasing and decreasing KD affects the response of the circuit.

One of the subcircuits was firstly tuned to show the optimum response, the value for KP and KI were kept constant while varying the KD value (Figure 82).

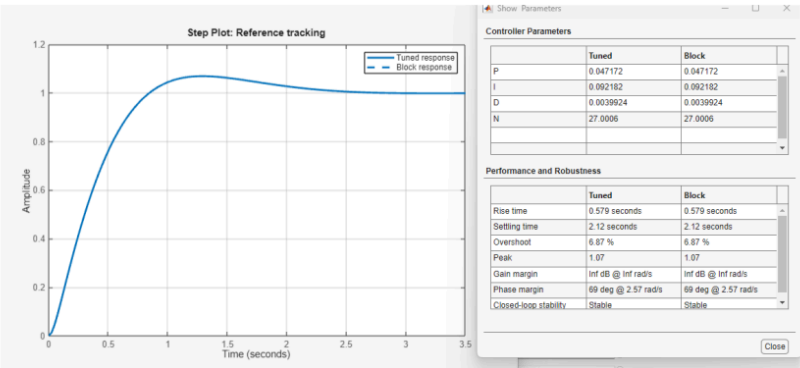


Figure 82 - Tuned Values for KD

A pair of values above and below the optimum value were then simulated to show how KD effects the response.

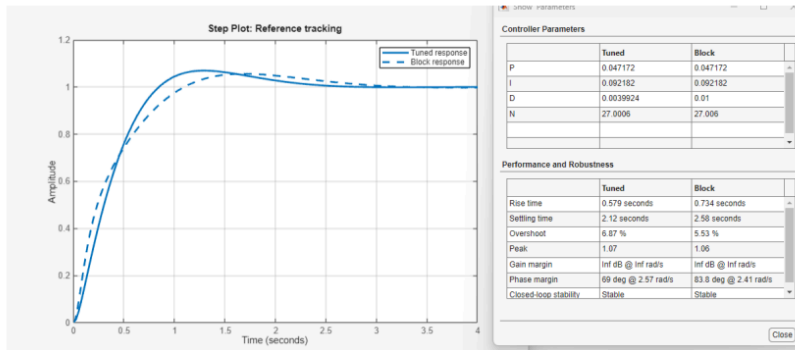


Figure 83 - High Value for KD

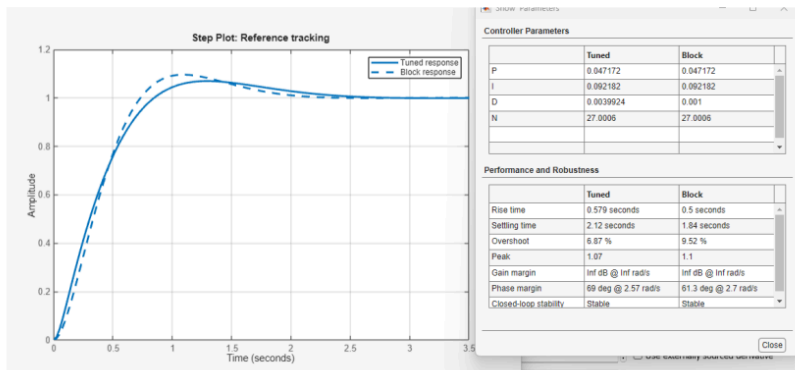


Figure 84 - Low Value for KD

The KD values were then measured on the 3-input scope, one being above the optimum value and one below. It is possible to see that increasing the value of KD leads to a faster settling time. It also provides a smoother response curve.

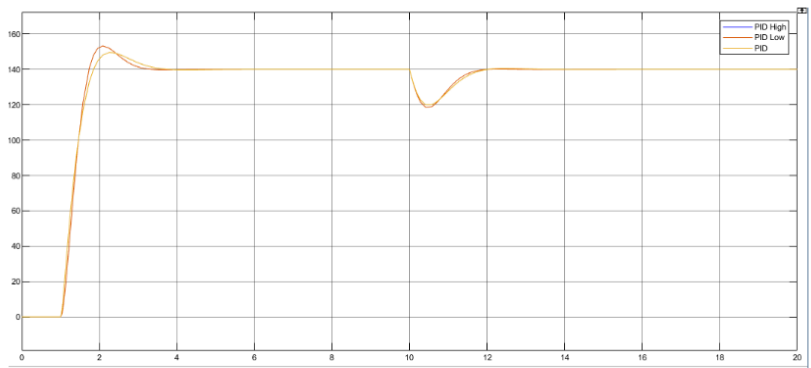


Figure 85 - 3 Input Scope of Different KD Values

Table 10 - Task 13 Results KD Values

KD Value	Steady State Error	Overshoot (%)	Settling Time (s)	Rise Time (s)
0.01 (High)	0	5.53	1.03	0.734
0.0039924 (Tuned)	0	6.87	1.06	0.579
0.001 (Low)	0	9.52	1.14	0.5

Analysis

The simulations show that introducing derivative control has helped increase stability in the circuit compared to the PI and P responses in previous tasks. Derivative control reduces overshoot by looking at the rate of change of the error, and slowing down the rate of change as it comes close to the setpoint. This also helps with oscillations as the system doesn't rapidly shoot over the setpoint and require a settling period. Derivative control has a predictive action that anticipates the error, as if the error starts growing rapidly the derivative control starts increasing.



Task 14 - Controller Comparisons

The motor model used in Task 13 was then modified to investigate the different effects of having a P, PI and a PID control system. The three inputs were then fed into a 3-input scope to measure the waveforms.

The 3 subsystems were firstly tuned to investigate the response statistics.

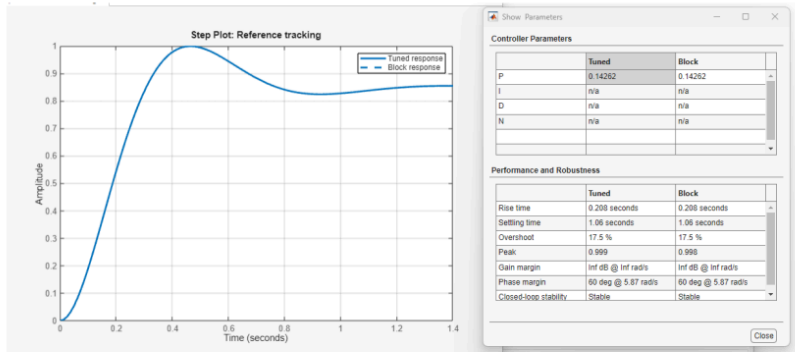


Figure 86 - Tuned KP Value

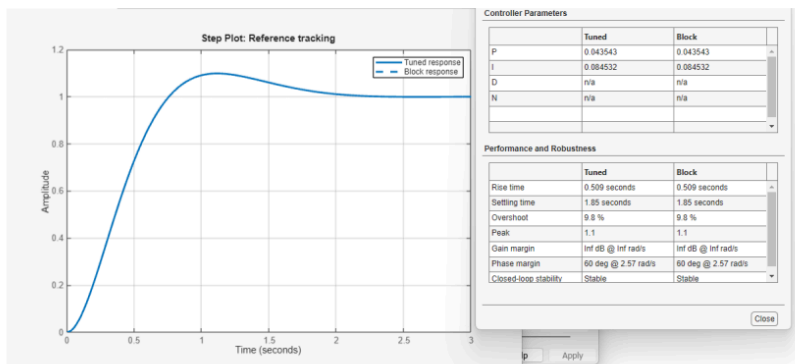


Figure 87 - Tuned KI Value

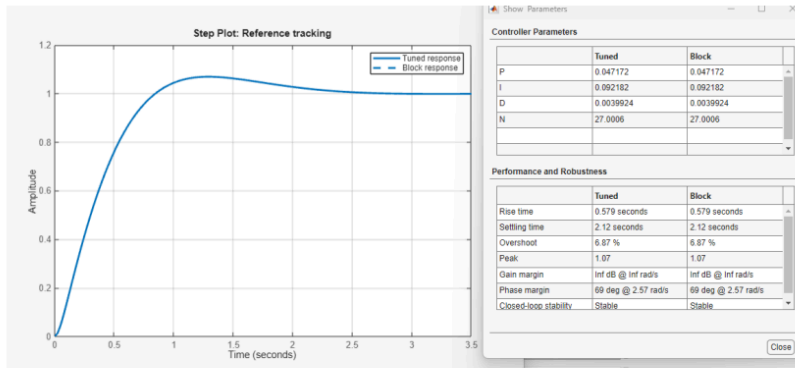


Figure 88 - Tuned KD Value

The 3 subsystems were then fed into a 3-input scope and waveforms were analysed.

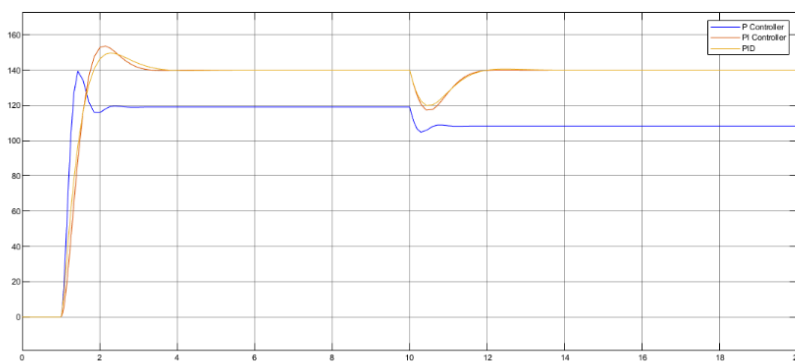


Figure 89 - 3 Input Scope of Different Types of Controller

Table 11 - Task 14 Results of Different Controller Response Statistics

P Value	PI Value	PID Value	Steady State Error	Overshoot (%)	Rise Time (s)	Settling Time (s)
0.14262 (P Tuned)			-20	17.5	0.208	1.06
0.043543	0.084532 (PI Tuned)		0	9.8	0.509	1.85
0.047172	0.092182	0.0039924 (PID Tuned)	0	6.87	0.579	2.12

Analysis

From the results shown in Table 11 and Figure 89 PID control can be seen to be far superior to P or PI control, this is due to the decreased overshoot percentage and having no steady state error. Whilst the rise time and settling time are marginally higher, this is due to the more controlled response that derivative control provides. As previously mentioned, derivative control reduces overshoot by looking at the rate of change of the error, and slowing down the rate of change as it comes close to the setpoint. The P control doesn't have a high enough gain to reach the setpoint speed of 140 Rads/s providing the highest steady state error of -20. The  42 is better than just the P control with a lower overshoot percentage and no steady state error, though it takes slightly longer to react to disturbance compared to PID.

Task 15 - Overall Conclusions and Recommendations

Electrical Conclusion

Task 1-6 investigated transient and frequency responses of first order electrical circuits. The transient responses showed exponential growth and decay due to their component configuration, and the time constants were investigated. In a decay circuit the time constant can be found at 36.8% of the full charge, meanwhile in a charge circuit the time constant can be found at 63.2%. Tasks 3-6 investigated frequency responses of first order circuits, analysing the cut off frequency and roll off. The investigation also included looking how the resistance value effects the damping coefficient within the system. With the results showing that as the resistance increased the damping increased.

Electronic Conclusion

Tasks 7 and 8 investigate frequency responses of first order electronic systems. The systems were found to be high and low pass filters due to their configuration and parameters such as cut off frequency, roll off and phase shift were analysed. The High pass filter showed that signals above the 3dB point were allowed to pass through, whilst the Low pass filter allowed signals below this.

Control

Tasks 9-14 involve an investigation into different methods of control, firstly investigating open loop control, the findings showed that the system lacked stability due to having no form of feedback. The system was modified to introduce feedback and the minimum value to make the system stable was found. A DC motor model was then made using a selection of values used from the brief, simulated using Simulink to show the effects of introducing the stall torque and different disturbances. The findings were shown in graphical form and analysed. The motor model was then modified to introduce different control methods starting with P before modifying for PI, then PID. The findings showed that PID was the best control method due to it having the least overshoot and no steady state error.



Recommendations

A recommendation would be to further investigate each of the 3 sections, which could be done by investigating the circuits in higher orders or varying the component values to achieve different responses.

References

Researchgate (2008) Schematic Diagram of the DC motor. Available at:

https://www.researchgate.net/figure/Schematic-diagram-of-the-DC-motor_fig1_4324391

(Accessed: 12 March 2025)

2320629

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

74/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8



Comment 1

This should appear immediately after the title page.



Comment 2

Brief but good.

PAGE 9

PAGE 10



Comment 3

Good, but provide the full equation.



Comment 4

Define time constant

PAGE 11

PAGE 12



Comment 5

At what value of t?



Comment 6

Good work but be aware of the comments for task 1, they apply to this task also.



Comment 7

Source?



Comment 8

Lacks depth.



Comment 9

Your work is correct but it lacks depth, derivations, and critical evaluation.



Comment 10

Missing X(s)



Comment 11

Source?



Comment 12

Your work is correct.



Comment 13

Ok, what else can be deemed from the results?



Comment 14

Define terms, derive or give source of equations.



Comment 15

This would be a good place to explain the locus of w_m to w_o



Comment 16

Excellent work and results.



Comment 17

You could have used the zoom tool to show the locus.



Comment 18

Too brief and lacks reference to magnification and resonance.



Comment 19

You cannot measure roll off at this point, needs to be on the linear part of the response.



Comment 20

Largely descriptive, what about the purpose of the op-amp vs the passive filter?



Comment 21

Better measurement technique.



Comment 22

See comment for previous task analysis.



Comment 23

Explain what is meant by a pole.



Comment 24

Good work here.



Comment 25

Oscillations are not the issue.



Comment 26

You are supposed to be finding a minimum k value that makes s negative.



Comment 27

Good.



Comment 28

Sp/WW



Comment 29

Ok, worth defining poles and zeroes to give context.



Comment 30

Correct image but a shame the quality is low.



Comment 31

Show the derivation from the individual TFs, this is standard form.



Comment 32

Good work.



Comment 33

SP/WW

PAGE 50

PAGE 51

PAGE 52



Comment 34

Results correctly gathered.



Comment 35

State the describing equations including the motor constants.

PAGE 53



Comment 36

Explain the additional blocks.

PAGE 54

PAGE 55



Comment 37

A good set of results and the method clearly explained.



Comment 38

A better word could be chosen e.g. accuracy.

PAGE 56

PAGE 57

PAGE 58



Comment 39

Good work here, to aid your analysis refer to the mathematical describing equations of PID.

PAGE 59

PAGE 60



Comment 40

See previous comment.

PAGE 61

PAGE 62



Comment 41

A logical and clear approach.

PAGE 63



Comment 42

Your analysis is mainly descriptive, but the approach is logical. For higher grade relate findings to theory, include the equation for the individual gains and the summation.



Comment 43

Fair observations, but again mostly descriptive, lacks depth, relate to theory.

PAGE 64

GRADING FORM: NEW CSG-RUBRIC

JAMES SUMMERS

74

1. ENGAGEMENT WITH LITERATURE



NA

0

2. KNOWLEDGE AND UNDERSTANDING



Reasonably extensive knowledge demonstrated via good explanations, correctly gathered results and logical approach. See comments for improvement opportunities. 23/30

23

3. COGNITIVE AND INTELLECTUAL



Analysis accurately describes the findings in each task and there are very few mistakes/omissions. For a higher mark relate the analysis to theory and use describing mathematical equations to explain the trends. 20/30

20

4. PRACTICAL APPLICATION



Excellent application of methods both mathematical and simulation techniques show good results and a logical and clear approach. Some further derivations could have been applied in some areas, see comments. 25/30

25

5. TRANSFERABLE SKILLS



Written communication is confident and suitable, the report flows and there are few minor errors as marked. 6/10

6