

# ENB301: Practical Report

Lachlan Nicholson (n8866864) Declan Gilmour (n8871566)

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## 1 Executive Summary:

This report provides the documentation and analysis of three closely associated practical experiments; the open loop system, the closed loop motor control system, and the effects of varying the systems gain and input signal frequency. The methods of analysis conducted within this document include thorough mathematical estimations and computational simulations. The results of the previously mentioned experiments, beyond showing clearly the benefits and application of closed loop control systems, conclusively show that the input frequency does not effect the overshoot or settling time of the closed loop system, but the gain is proportional these properties. Moreover, the difference in theoretical calculations and practical applications due to un-modeled system interactions was shown in depth.

Still not really done

subject matter

methods

findings

conclusions

recommendations

limitations

## 2 Aim:

### 1-2 sentences on the report purpose

The purpose of this report is to demonstrate sound knowledge and understanding of basic control systems; more specifically, closed loop feedback systems. This report entails (beyond other things) the procedures followed during the practical lab, the associated results or observational data, and the answers to all questions posed during the lab.

## 3 Introduction:

0.5-1 page overview of the lab

## 4 Procedure:

brief summary of prac procedure as described in this document (0.5-1page for each part (bcd))

This section consists of individual summaries of the procedures required in each section, accomplished during the practical labs. Briefly cover what each part of prac is to accomplish.

## 4.1 Experiment B

Experiment B utilizes experimentally measured time response data to calculate approximate values for  $K_m$  and  $\alpha$ . The pre-lab preparation for this section of the practical required familiarization with all aspects of the oscilloscopes and their functions (triggers, scales, saving data); moreover, it was suggested that the user should also be familiar with the construction process outlined within the coming procedures. In an attempt to better show the procedures of this particular experiment, the required tasks will be separated into two categories; the setup, and the analysis. Both of the aforementioned sections will be displayed in numbered point formation to show clearly the extent of each step.

### SETUP:

1. The dual power supply was setup in independent mode, with 5.0 V and 2.0 V respectively. (measured using a multimeter to ensure accuracy)
2. Next, the 5V supply was connected across the potentiometer (outer wires), whilst using a multimeter to measure the wiper voltage (middle wire). Moreover, turning the flywheel clockwise increased the wiper voltage; however, if the inverse was true, the 5V and 0V wires would have been swapped.
3. After having adjusted the flywheel to the center position, and after connecting the 0V rail to one side of the motor; the circuit was briefly connected using the 2V supply. The polarity of the two connections were then adjusted to ensure the motor moves in a clockwise direction when voltage is applied.
4. The flywheel was returned to the central location whilst the wiper voltage of the potentiometer and the positive terminal of the motor were measured using the digital CRO. The trigger was set to 0.5 V and a USB inserted.
5. After briefly completing the motor circuit, the CRO was triggered and recorded the response of the potentiometer and input voltage. The channel gain was inspected to ensure it had been set correctly and all important regions of the response can be seen, then the data was saved to the USB.
6. The previous step was repeated multiple times to ensure viable data had been collected.

### ANALYSIS:

1. After the experimental data had been saved to a USB and transferred to a computer, it was then plotted in matlab.
2. The experimental data was also plotted against the systems estimated transfer function  $y_1(t)$ .
3. Using a robust self constructed function to estimate the system parameters according the experimental data, approximate values for  $K_m$  and  $\alpha$  were obtained.
4. The system transfer function  $y_1(t)$  was then adjusted, and another diagram constructed to compare the experimental and calculated systems response.
5. Lastly, using the second order model for the motor and the previously calculated  $\alpha$  value;  $K_m$  and  $\beta$  were approximated.

## 4.2 Experiment C

Section C utilized the open loop response of the motor that had been measured and approximated in the previous procedures to achieve a closed loop control system for the position of the motor (voltage across the potentiometer). The pre-lab component of experiment C required the extensive analysis of a provided circuit diagram; breaking the system down into functional elements of the control system, calculating individual transfer functions for these elements, and constructing an overall transfer function for the system ( $G_c(s)$ ). As mentioned previously, the procedures followed in this experiment will also be separated into the setup or preparation, and the analysis.

The pre-lab aspect of this experiment required the operator to be familiar with typical breadboard design strategies, the pin-out of the op-amp used within the experiment, common resistor code colours, and the use of noise mitigation capacitors.

Refer to figure 19 for the complete closed loop motor control system schematic used in the following procedures.

### SETUP:

1. The function generator was setup to output a 0.1 Hz square wave an amplitude of 0.5 V.
2. The aforementioned circuit was constructed, but the motor was only connected after taking multiple measurements to ensure the circuit was operating as expected.
3. With the motor connected, the response of the system was captured and saved by the digital CRO; this step was repeated multiple times to ensure accuracy.
4. The gain was then adjusted to produce a 5% overshoot, the resistor values used and the systems response were recorded.

### ANALYSIS:

1. The collected data was imported into matlab, and compared against the predicted model derived previously in **part A and B**.
2. After which, the experimentally found gain required to produce an overshoot of 5% was compared against the predicted gain value.
3. Lastly, a discussion took place surrounding the use of alternate methods to derive the open and/or closed loop response for the system using the same equipment.

### 4.3 Experiment D

The final experiment, using the same circuit constructed in the previous experiment, examined the response of the system to different input frequencies, the impact of gain on the systems response, and the implementation of a new method to approximate the open and/or closed loop response.

#### ANALYSIS:

1. The closed loop response of the system was estimated **using the method outlined in the previous procedures**
2. The  $K_m$  and  $\alpha$  values were then compared to **the method outlined in worksheet**
3. Using the same circuit constructed in the previous procedure (system gain set at the experimentally found gain required to produce a 5% OS) the overshoot was measured and recorded, for input frequencies of 0.5Hz, 0.75Hz, 1Hz, 1.25Hz and 1.5Hz.
4. Additionally, the systems response for each frequency was also recorded and saved in-case of future need.
5. The impact of altering the gain was then examined, as the response of the system was recorded twice more; using a new gain value each time.
6. The closed loop system was then simulated in Simulink, using the model parameters determined in the previous experiment. A group discussion was raised over the quality of the model, the results of which can be found in section [7.2.3](#).
7. Another group discussion was began, as a proposal for a **PI/PD/PID** controller that would achieve a faster response was formed and simulated. Refer to the previously mentioned section for the in depth proposal.

## 5 Results:

summary of what you observed in parts B,C,D (less than 2 pages per part), noting detailed answers are to be provided in the appendix.

### 5.1 Part B

calculate predicted  $K_m$  and  $\alpha$  values. correct polarity of the motor above B5

## 5.2 Part C

As mentioned previously, the goal of experiment C was to construct a closed loop control system (feedback) for the position of the motor (voltage across the potentiometer); making use of the estimated open loop response variables found in part B ( $K_m$  and  $\alpha$ ).

The pre-experimental aspect of this section required the breakdown and analysis of the circuit diagram captured in figure 19, the full method and calculations has been provided in section 7.2.2; the in depth analysis resulted in an estimated overall transfer function for the system.

$$G_c(s) = \frac{\frac{R_f}{R_1} K_m}{s^2 + s\alpha + \frac{R_f}{R_1} K_m}$$
$$G_c(s) = \frac{1075.8}{s^2 + 38.61s + 1075.8}$$

After constructing the circuit shown in figure 19 and asserting the correct polarity of the motor, the response of the system was captured and saved by the digital CRO. The closed loop response of this system was measured 3 times, and the graphical representation of this data has been included below.

### FIGURES

WHAT WE CAN SEE FROM THIS (AS VOLTAGE GOES UP, THIS GOES UP), and here is the closed loop response with experimentally found gain required to produce an overshoot of 5%.

### FIGURES

WHAT WE CAN SEE FROM THIS

compare models  
compare gains  
new method

closed loop control system for the position of the motor overall TF estimated gain for 5% OS practical gain for 5% OS comparisons C8

### 5.3 Part D

Experiment D explored the effect of input frequency on the closed loop system response, as well as examining the effect of increasing or decreasing the systems gain. **and bode**

#### D1/C8

After measuring and recording the systems response and percentage overshoot for five different input frequencies; the following table was constructed (refer to section 7.2.3 for calculations responsible for the construction of this table).

Input Frequency (Hz)	Overshoot (%)
0.5	6.1
0.75	5.7
1	6.1
1.25	6.5
1.5	5.8

Both the above table, and the systems response (figure 26) show clearly that increasing the frequency has no effect on overshoot, settling time, or steady state error. However, after the frequency exceeds a certain limit ( $1/f < Ts$ ) the system does not have enough time to reach a steady state value. Moreover, if the frequency of the input were to continue increasing, eventually the operation amplifier will begin attenuating the output voltage.

The reason the frequency has no effect on these values, as explained in section 7.2.3, is that the circuit contains no energy storing devices (such as capacitors or inductors), and as such- **frequency should not affect any circuit properties**. Additionally, the approximated transfer function of this system is independent of the input frequency, or more simply;

$$G_c(s) = \frac{\frac{R_f}{R_1} K_m}{s^2 + s\alpha + \frac{R_f}{R_1} K_m}$$

and recall,

$$W_n = \sqrt{b} = \sqrt{K_m * \frac{R_f}{R_1}}$$

$$\zeta = \frac{a}{2b} = \frac{a}{2 * W_n} = \frac{\alpha}{2 * \sqrt{K_m * \frac{R_f}{R_1}}}$$

and

$$\%OS = e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}} * 100$$

$$T_s = \frac{4}{\zeta W_n}$$

Thus, as neither  $W_n$  or  $\zeta$  are dependent on frequency, both overshoot and settling time are also independent of frequency. This explains why besides the reduced time available for the signal to settle, no visible changes to these properties were observed as the frequency was increased.

The impact of the systems gain however, was much more noticeable. From figure 27, it can be seen that increasing the gain resulted in an increased overshoot and a decreased settling time. This has been proven more in depth in the associated answers section, but a summary of the findings can be found below.

From the previous equations, it can be seen that both  $\zeta$  and  $W_n$  rely on the gain ( $K = R_f/R_1$ ).

Furthermore, this means both the overshoot and settling time rely on the gain factor. **SUB IN TO FIND OS and Ts AND SHOW THEY RELY ON GAIN, PROP/invPROP WHY IS THIS USEFUL - prop controller?**

D4/D5



## **6 Discussion/Recommendations:**

**0.5-1page**

## 7 Appendices

### 7.1 Pre-lab:

#### 7.1.1 Lachlan Nicholson

1. Below is the requested functional diagram for the complete servo motor control system.

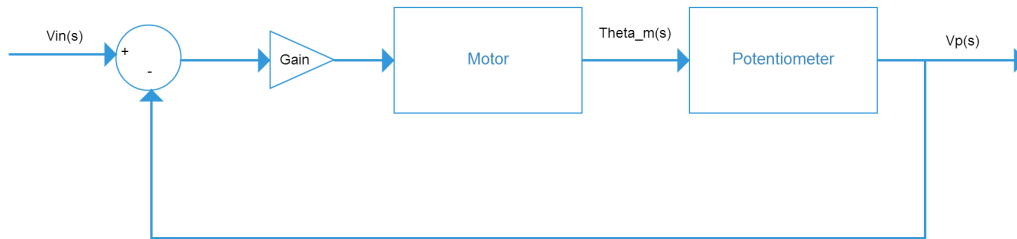


Figure 1: Functional Diagram of the control system

2. The updated functional diagram has been included below.

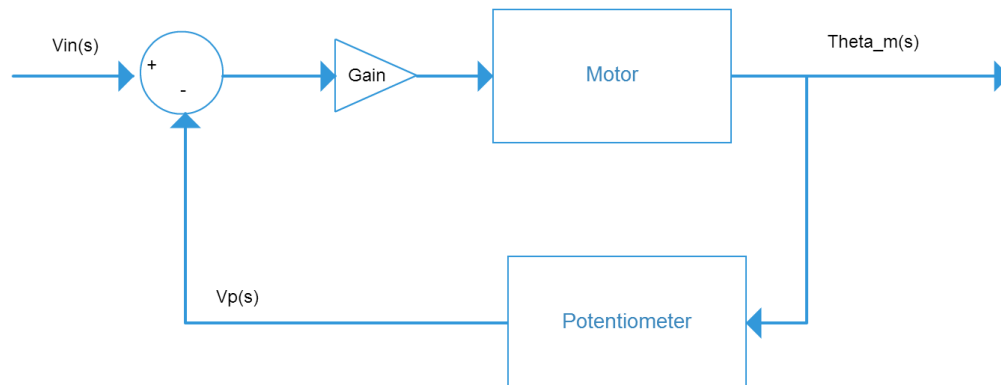


Figure 2: Updated Functional Diagram

3. The output of the requested matlab script has been included below, after which, the code itself has been provided.

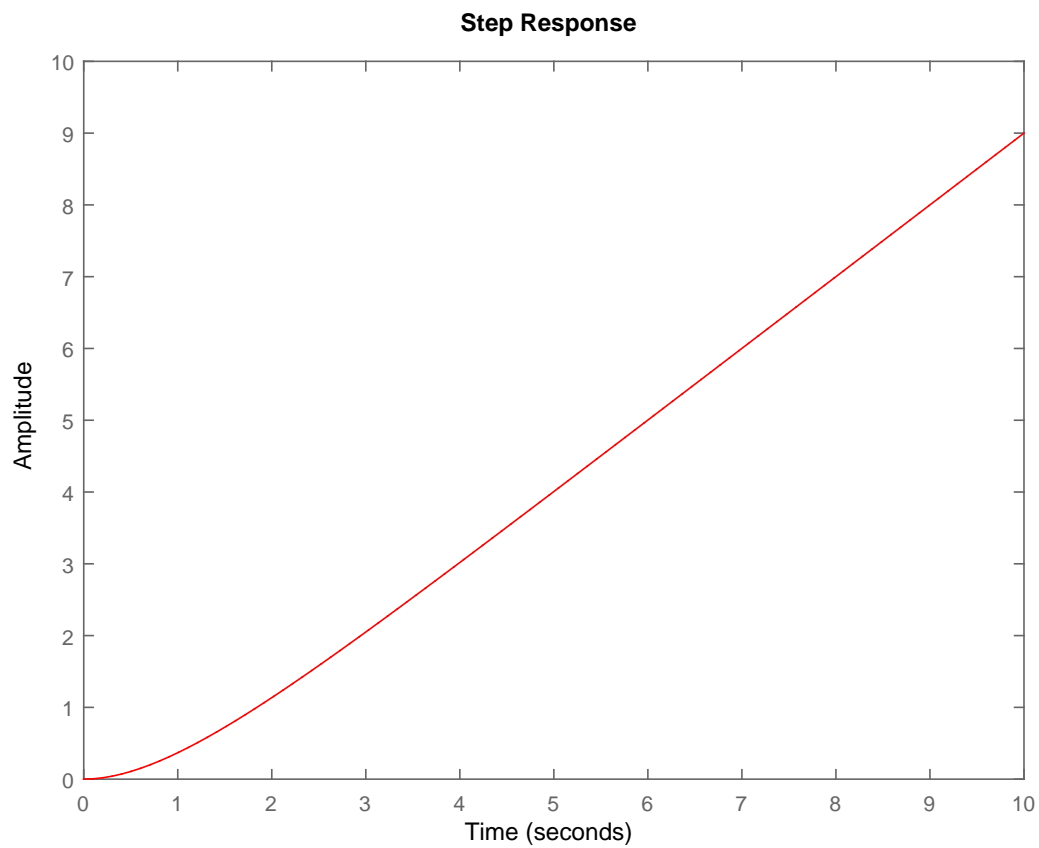


Figure 3: Simulated Response

```
1 %% A3
2 Alpha = 1;
3 K_m = 1;
4
5 t = linspace(0,10,100);
6 G_0 = tf([K_m],[1 Alpha 0]);
7 figure();
8 step(G_0, t, 'r')
9 print('-depsc','a3')
```

4. The given data describing the step response of an ideal servo model has been compared to the previously estimated system response.

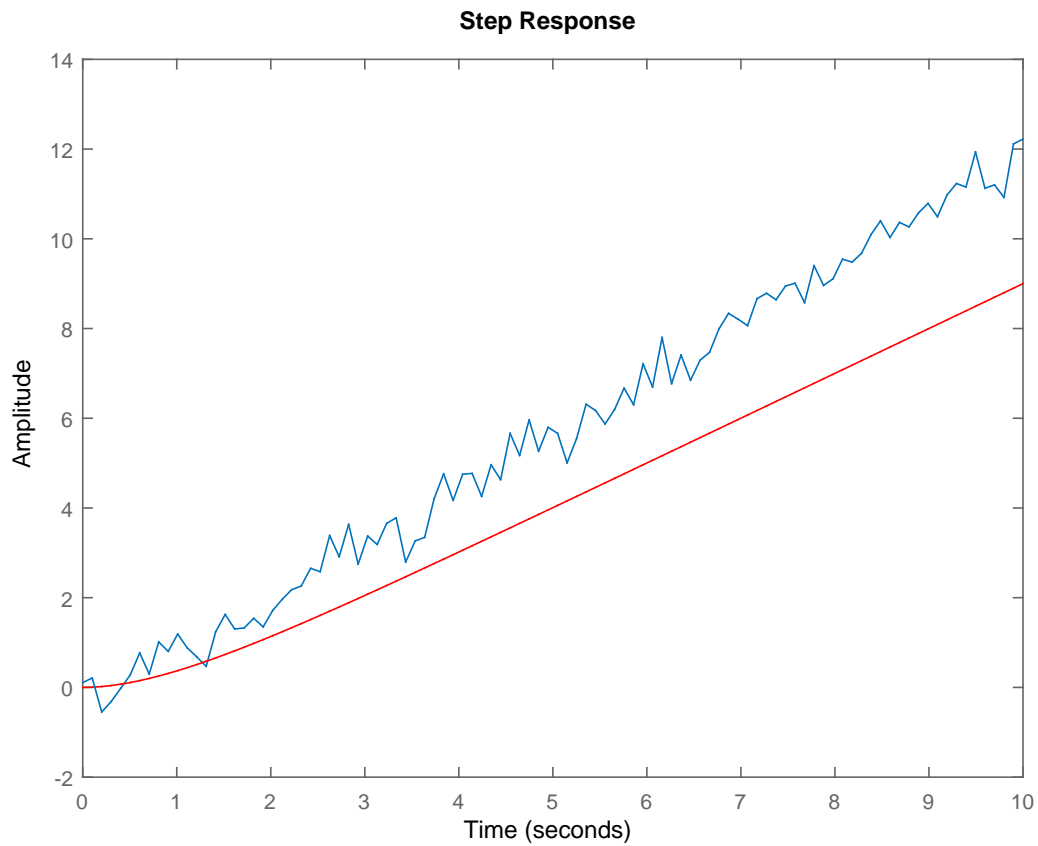


Figure 4: Given Data and Estimated Response

```
1 %% A4
2 Alpha = 1;
3 K_m = 1;
4 t = linspace(0,10,100);
5 G_0 = tf([K_m],[1 Alpha 0]);
6
7 load ENB301TestData_2015.mat
8 figure();
9 plot(t,y1);
10 hold;
11 step(G_0, t, 'r')
12 print('-depsc','a4')
```

5. steady/transient Q

6. After changing the values of  $K_m$  and  $\alpha$  in the previous matlab script, it was found that values of  $K_m = 1.3$  and  $\alpha = 1$  resulted in an output that matched the test data. Furthermore, a script was created specifically to automatically find the best estimates for values of  $K_m$  and  $\alpha$  within a given range. The results of both the manual and automatic estimations have been included below.

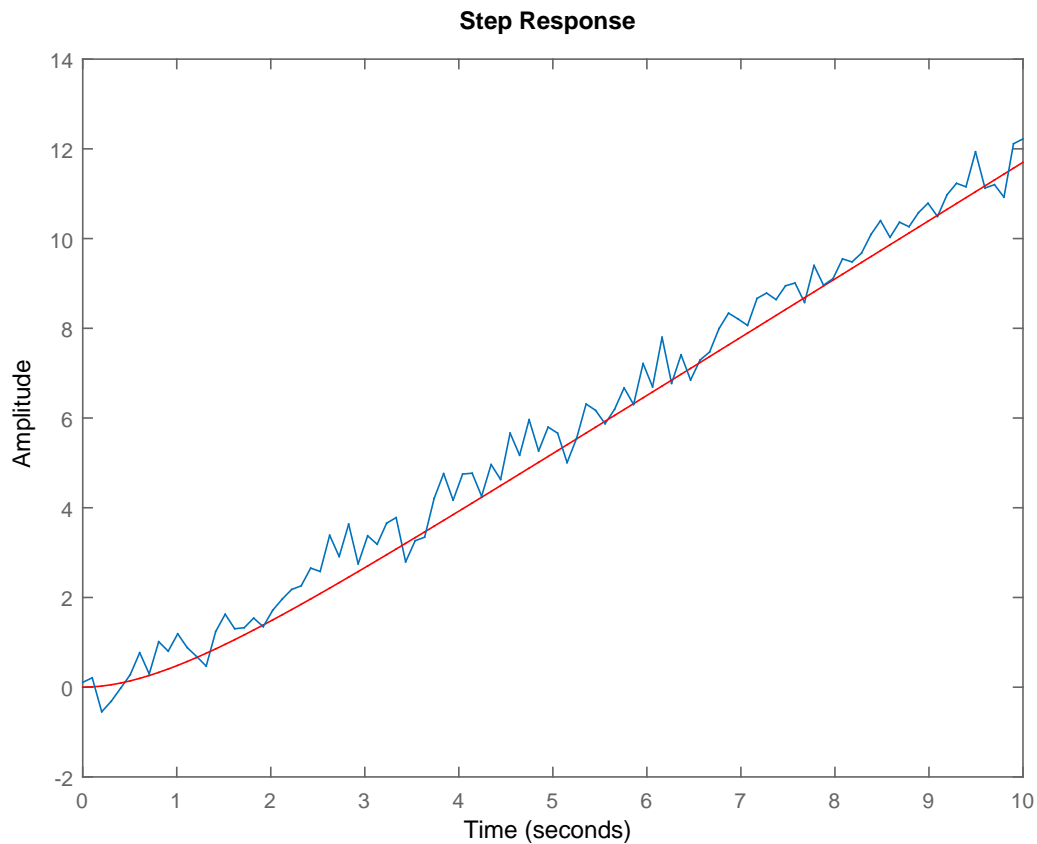


Figure 5: Manually Estimated System Values

```

1 %% A6
2 Alpha = 1; %0.5-1.5
3 K_m = 1.3; %1-2
4 G_0 = tf([K_m],[1 Alpha 0]);
5 figure();
6 plot(t,y1);
7 hold;
8 step(G_0, t, 'r');
9 print('-depsc','a6a')

```

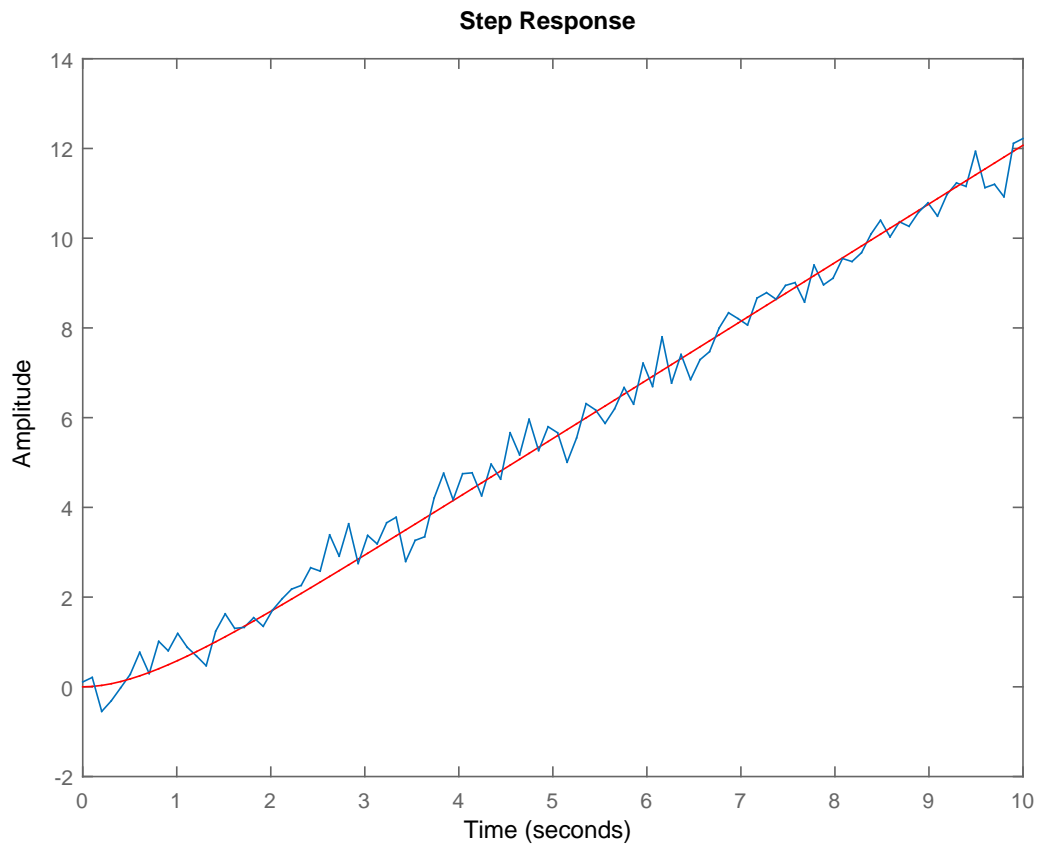


Figure 6: Inverting Amplifier System

```

1 %% Automated:
2 % loop values of alpha and k_m
3 % calculate RMS error each time
4 % pick values with the least error
5
6 y1_rms = rms(y1);
7 prevdiff = 10000;
8
9 for Alpha = 0.1:0.1:3
10     for K_m = 0.1:0.1:3
11         G_0 = tf([K_m],[1 Alpha 0]);
12         G_t = step(G_0, t, 'r');
13         G_t_rms = rms(G_t);
14         diff = y1_rms - G_t_rms;
15         if (abs(diff) < abs(prevdiff))
16             prevdiff = diff;
17             K_m_f = K_m;
18             Alpha_f = Alpha;
19         end
20     end
21 end
22
23 G_0 = tf([K_m_f],[1 Alpha_f 0]);
24 figure();
25 plot(t,y1);
26 hold;
27 step(G_0, t, 'r');
28 print('-depsc','a6b')
29
30 % Final values:
31 % Alpha_f = 1.3
32 % K_m_f = 1.7

```

7. Using matlabs random number generator, uncertainty was added to the output  $y_1(t)$ , and both the ideal and noisy response were plotted. **QUESTIONS**

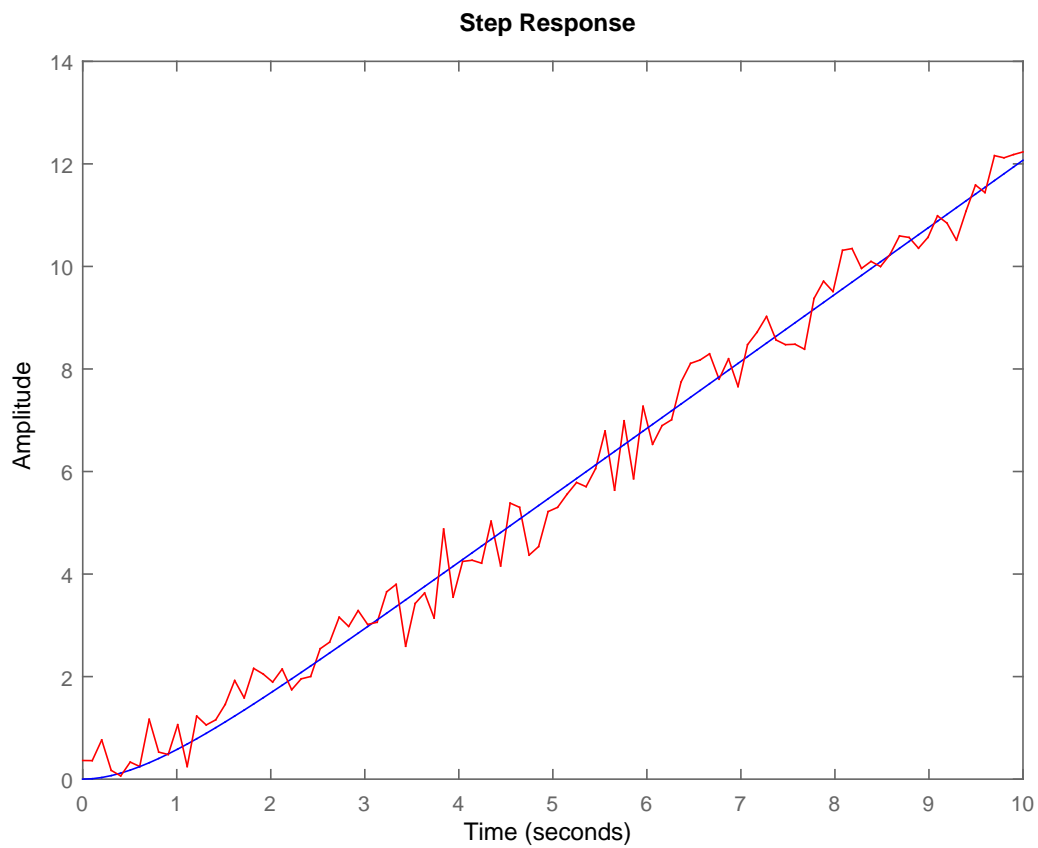


Figure 7: Estimated System Response + Uncertainty

```
1 %% A7
2 rand_power = 2;
3
4 y_1 = step(G_0, t, 'r');
5 y_n = y_1 + (rand_power/2)*rand(size(y_1,1),1) - ...
        (rand_power/2)*rand(size(y_1,1),1);
6
7 figure();
8 step(G_0, t, 'b');
9 hold;
10 plot(t,y_n,'r');
11 print('-depsc','a7')
```

### 7.1.2 Declan Gilmour

1. Model the complete servo motor control system using a functional diagram. Label all signals and assumptions made including measurement units.

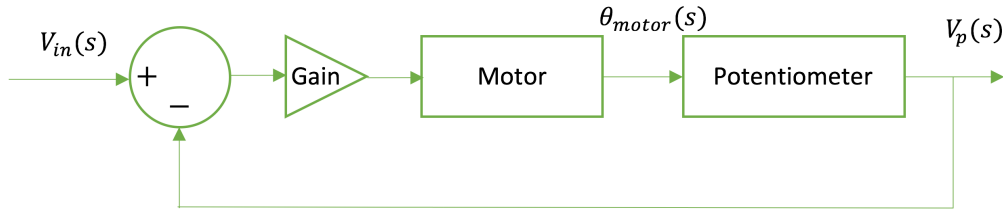


Figure 8: Servo Motor Functional Diagram

A voltage is fed into the motor with a magnitude gain. From here the voltage is converted into rotational movement  $\theta_{motor}(s)$  by the motor. This rotational movement alters the displacement of the potentiometer wiper. The potentiometer acts as a sensor to indicate arm displacement in the form of output voltage  $V_p(t)$ .

2. Update the servo motor functional diagram and make any necessary changes.

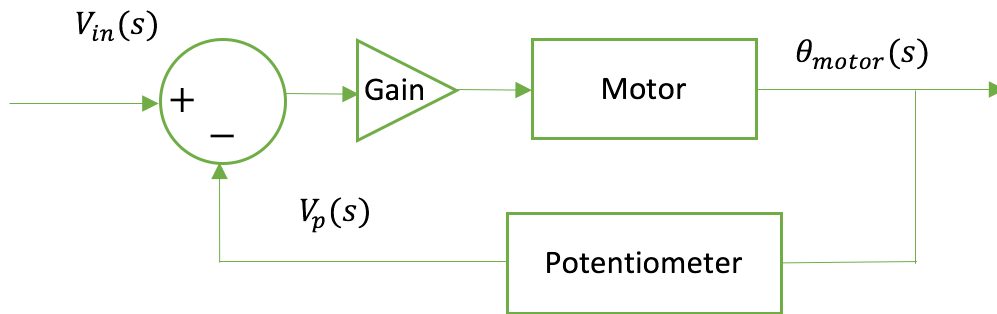


Figure 9: Updated Servo Motor Functional Diagram

To calculate the two servo motor system characteristics,  $\alpha$  and  $K_m$  the system response would need to be recorded to a step input. This open loop time response is measured in terms of how the voltage applied to the motor affects the voltage seen at the potentiometer.

The selection of optimum values of  $\alpha$  and  $K_m$ , would require the potentiometer voltage to be measured with respect of the input voltage. The modification of the Servo Motor Functional Diagram is needed, incorporating a feedback loop as shown.



### 3. Create code to simulate motor shaft angle for various values of $K_m$ and $\alpha$

Bellow is the Matlab code used to simulate the motor shaft angle.

```
1 %% A3 - Simulate motor shaft angle for values of km and alpha
2 alpha = 1;
3 km = 1;
4 t = linspace(0,10,100);
5
6 % Build transfer function
7 G = tf(km, [1 alpha 0]); % Set G(s) = km / (s + a)
8 G_0 = step(G,t); % Set G_0(s) = km / (s * (s + a))
9
10 % Plot motor set response
11 figure
12 plot(t,G_0,'r')
13 title('Simulated Step Response')
14 xlabel('t (sec)')
15 ylabel('Amplitude')
16 print('-depsc','A3')
17 close
```

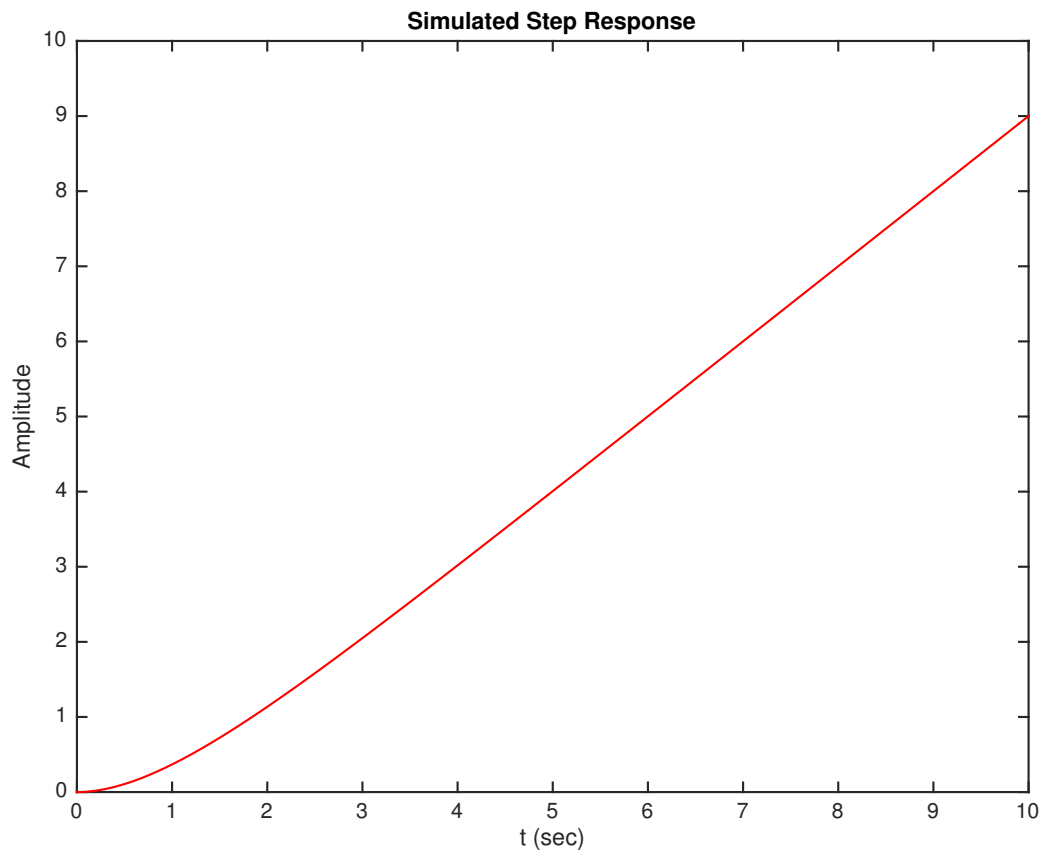


Figure 10: Updated Servo Motor Functional Diagram

4. Plot  $y_1(t)$  against the servo motor response in ENB301\_TestData and compare.

Bellow is the Matlab code used to generate the simulated step response against imported test data.

```
1 %% A4 - Plot motor unit step response data against simulated response
2 load ENB301TestData_2015.mat
3 alpha = 1;
4 km=1;
5 G = tf(km,[1 alpha 0]);
6 G_0 = step(G,t);
7
8 figure
9 hold on
10 plot(t,y1,'b')
11 plot(t,G_0,'r')
12 title('Simulated Step Response and Test Data')
13 xlabel('t (sec)')
14 ylabel('Amplitude')
15 legend('y1(t): Simulated Step Response','Test Data')
16 hold off
17 print('-depsc','A4')
18 close
```

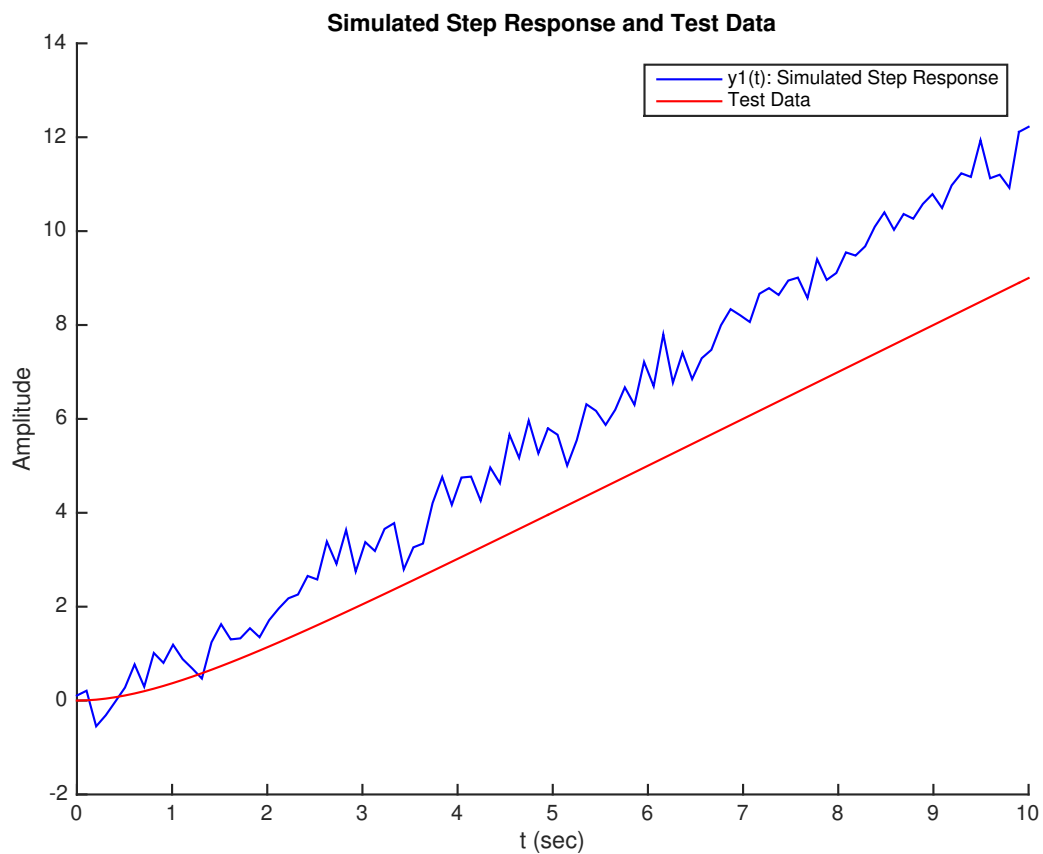


Figure 11: Updated Servo Motor Functional Diagram

5. What is the steady state response and transient response predominantly determined by?

6. Change the values of  $K_m$  and  $\alpha$  for to match the simulated response with the test data.

The estimated  $K_m$  value is 2.3838 and  $\alpha$  1.8990. Bellow is the Matlab Code to estimate km and alpha variables.

```
1 %% A6 - Estimate km and alpha variables
2 load ENB301TestData_2015
3 output = zeros(3,100*100);
4 error = 0;
5 ii = 1;
6 for km = linspace(0,4,100)
7     for alpha = linspace(0,4,100)
8         G = tf(km, [1 alpha 0]);
9         G_0 = step(G,t);
10
11         % Calculate mean square error
12         for jj = 1 : length(t)
13             error = error + (G_0(jj) - y1(jj))^2;
14         end
15
16         output(:,ii) = [km;alpha;error];
17         ii = ii + 1;
18         error = 0;
19     end
20 end
21
22 [~,index] = min(output(3,:));
23 km = output(1,index); % Output variable
24 alpha = output(2,index); % Output variable
25
26 % Build transfer function
27 G = tf(km, [1 alpha 0]); % Set optimal G(s) = km / (s + a)
28 G_0 = step(G,t); % Set optimal G_0(s) = km / (s * (s + a))
29
30 % Plot step function G_0(s)
31 figure
32 hold on
33 plot(t,G_0,'-b');
34 plot(t,y1,'-r');
35 title('Estimated Step Response of Test Data')
36 xlabel('t (sec)')
37 ylabel('Amplitude')
38 legend('Estimated Step Response', 'Test Data');
39 hold off;
40 print('-depsc','A6')
41 close
42
43 % Output km and alpha
44 disp(km) %2.3838
45 disp(alpha) %1.8990
```

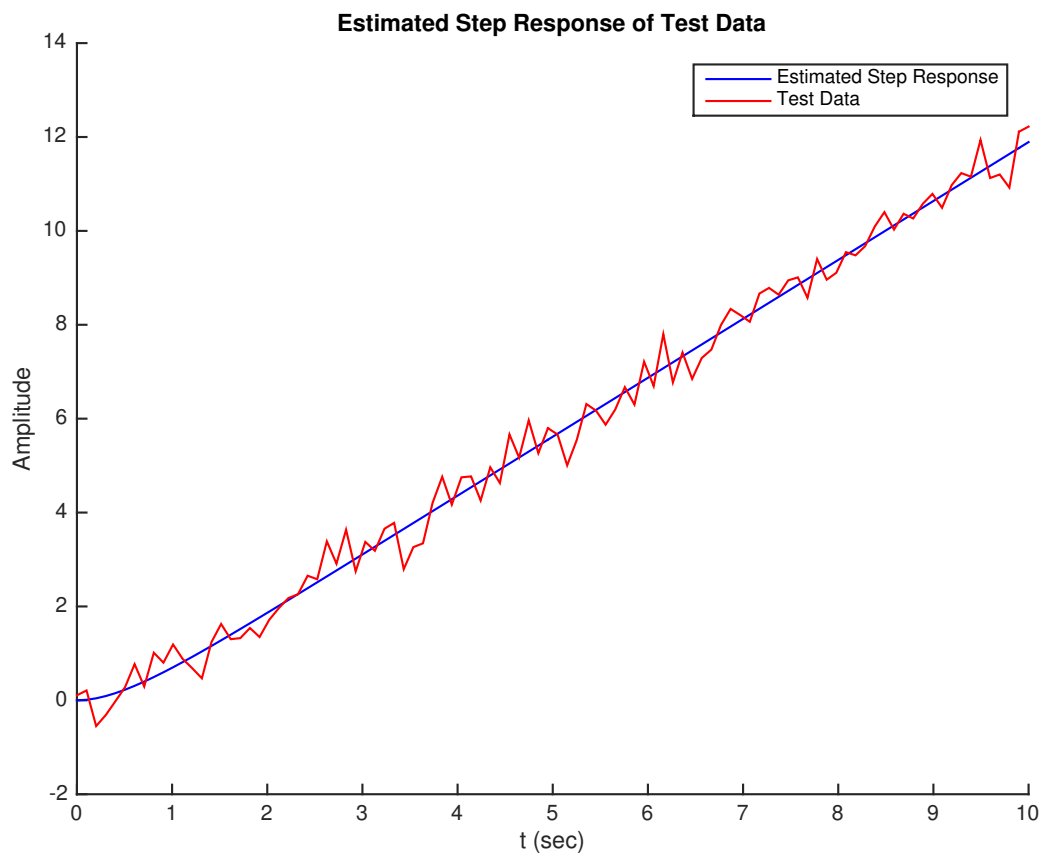


Figure 12: Estimated  $K_m$  and  $\alpha$  values

7. **Plot the step response from original signal and a step response from a noisy signal.**  
 Bellow is the Matlab Code to plot a step response from both original and noisy signals.  $K_m = 2.4242$  and  $\alpha = 1.9394$ .

```

1  %load ENB301TestData_2015
2  % Generate noise
3  % Standard: sigma = 5, Decreased: signma = 0.2, Increased: sigma = 20
4  sigma = 5; %noise standard deviation
5  noise = sigma*randn(size(G_0)); %noise vector
6
7  % Create noisy signal
8  yn = y1 + noise;
9
10 output = zeros(3,100*100);
11 error = 0;
12 ii = 1;
13 for km = linspace(0,4,100)
14     for alpha = linspace(0,4,100)
15         G = tf(km, [1 alpha 0]);
16         G_0 = step(G,t);
17
18         % Calculate mean square error
19         for jj = 1 : length(t)
20             error = error + (G_0(jj) - yn(jj))^2;
21         end
22
23         output(:,ii) = [km;alpha;error];
24         ii = ii + 1;
25         error = 0;
26     end
27 end
28
29 [~,index] = min(output(3,:));
30 km = output(1,index); % Output variable
31 alpha = output(2,index); % Output variable
32
33 % Build transfer function
34 G_noisy = tf(km, [1 alpha 0]); % Set optimal G(s) = km / (s + a)
35 G_0_noisy = step(G_noisy,t); % Set optimal G_0(s) = km / (s * (s + a))
36
37 % Output km and alpha
38 disp(km) %2.4242
39 disp(alpha) %1.9394
40
41 % Plot noisy signal vs noisy test data
42 figure(2)
43 hold on
44 plot(t,G_0_noisy, '-r');
45 plot(t,G_0, '-b');
46 title('Estimated Step Response of Noisy Test Data')
47 xlabel('t (sec)')
48 ylabel('Amplitude')
49 legend('Noisy Step Response', 'Original Step Response');
50 hold off
51 print('-depsc','A7')
52 close

```

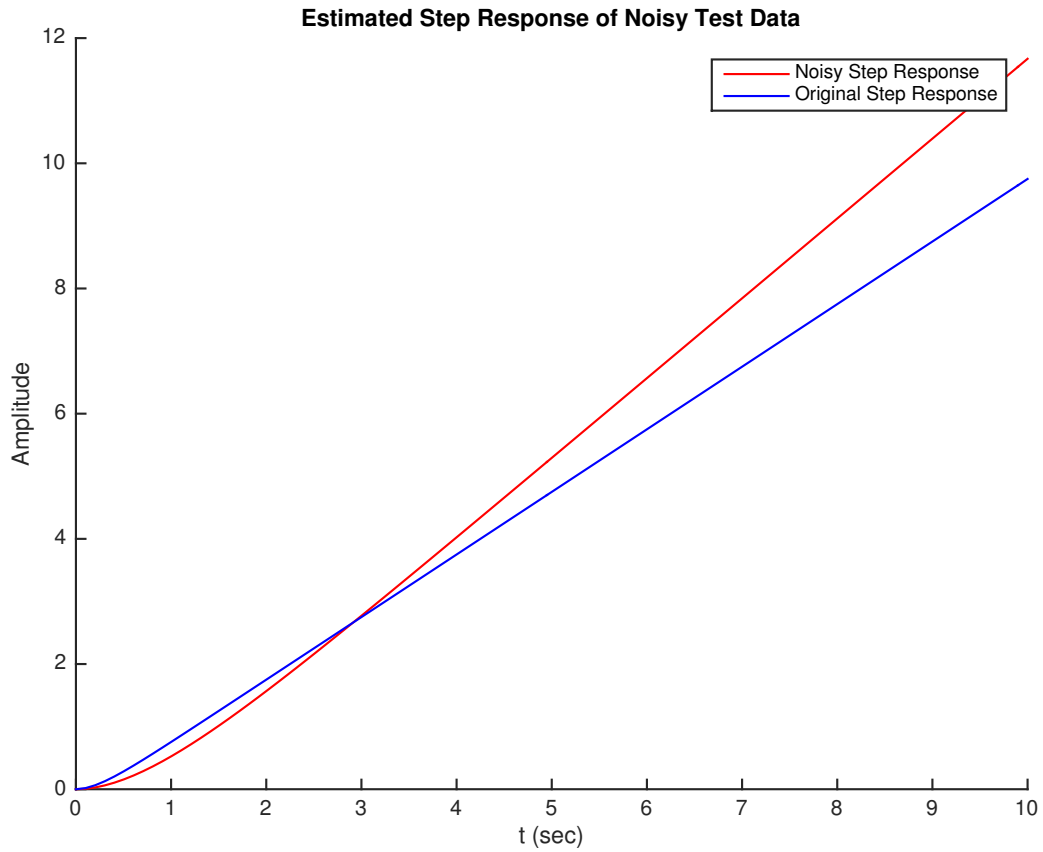


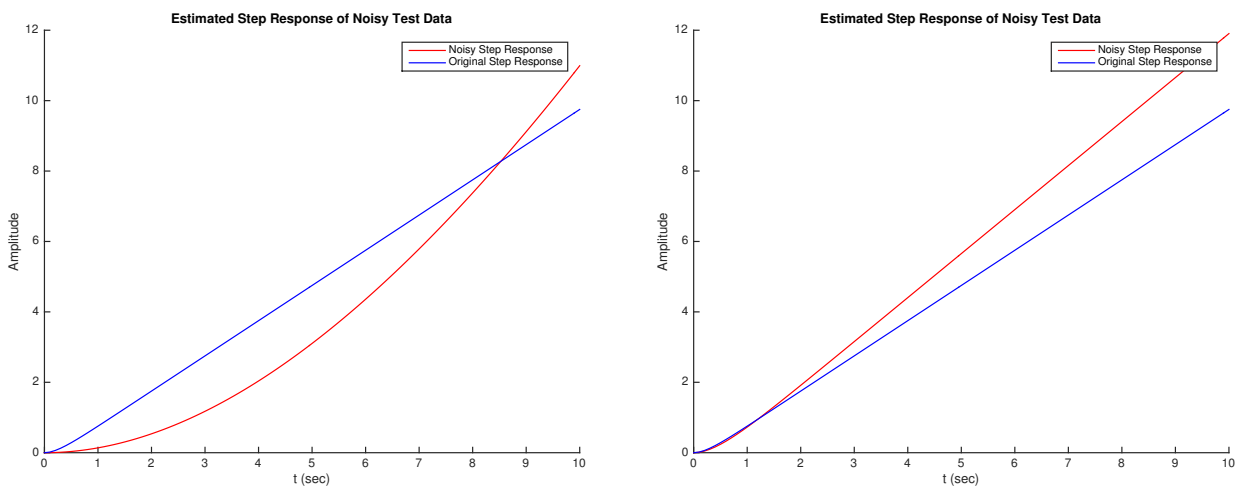
Figure 13: Original Step Response and Noisy Step Response

For this noisy step response,  $K_m = 1.4949$  and  $\alpha = 1.1717$ . When the noise decreases,  $K_m$  and  $\alpha$  decreases in magnitude. When the noise increases,  $K_m$  and  $\alpha$  increases in magnitude. The transient response of the system appears to increase as the noise of the system increases.

### Is this Realistic?

#### Where are the source of uncertainty or noise in a real system?

Sources of uncertainty or noise in a system can include: control error, electrical noise, external factors such as weather and human error.



(a) Increased Noise:  $K_m = 0.2828$  and  $\alpha = 0.0808$

(b) Decreased Noise:  $K_m = 2.6263$  and  $\alpha = 2.1010$

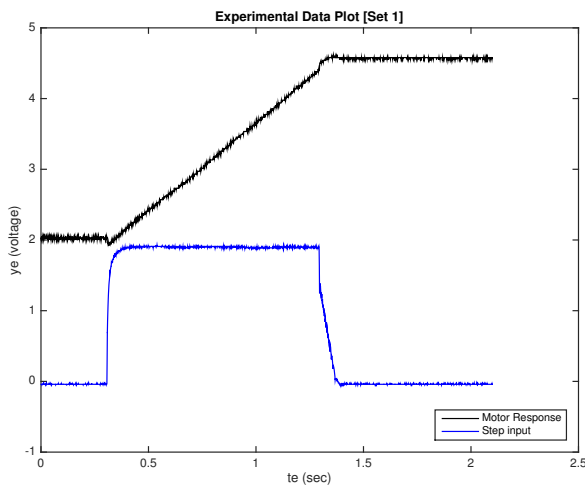
Figure 14: Increased and Decreased noisy Step Response

## 7.2 Answers:

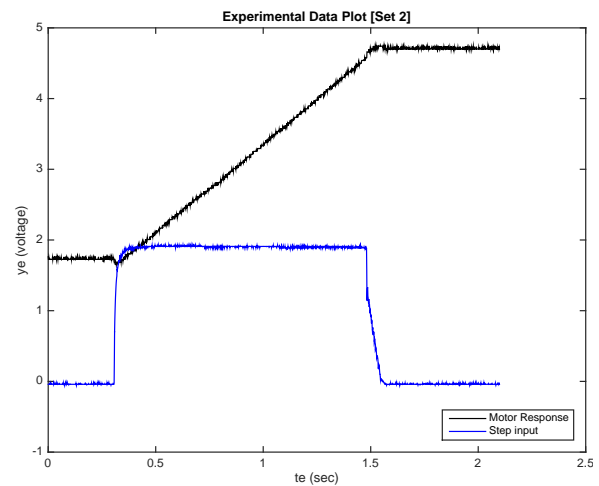
### 7.2.1 Part B

1. Read experimental data file(s) and store in vectors  $y_e(t)$  and  $t_e$ . Plot the experimental results in black.

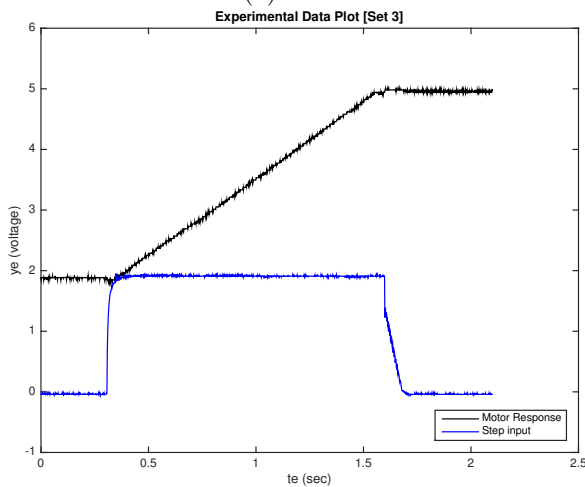
```
1 %% B1
2 % Load experimental data and plot in black
3 data = csvread('PartB.Test1.csv',2,0); % Read in test 1
4 te_1 = data(1:end,1); % Store te variable
5 te_1 = te_1 + abs(te_1(1)); % Move te variable to start at zero
6 ye_1 = data(1:end,2); % Store ye variable
7 ye_1step = data(1:end,3); % Store ye step input variable
8
9 figure
10 plot(te_1, ye_1, 'k', te_1, ye_1step, 'b') % Plot ye in black and ye in blue
11 title('Experimental Data Plot [Set 1]')
12 xlabel('te (sec)')
13 ylabel('ye (voltage)')
14 print('-depsc', strcat('figures', filesep, 'B1.dataset1')); % Store figure
15 close
```



(a) Data Set 1



(b) Data Set 2



(c) Data Set 3

Figure 15: Open Loop response



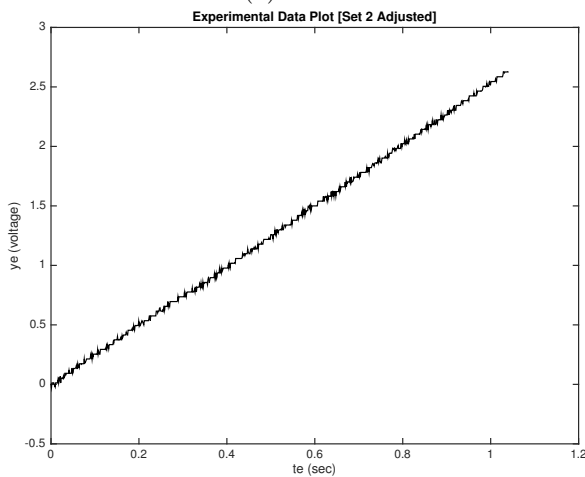
2. Modify the MATLAB script created in the pre-labs to simultaneously plot both the experimental data and  $y_1(t)$ . No real idea what to put here...
3. Derive a figure of merit for the estimation compared with experimental results.  
Mean Square error calculation:  $error = (G_0 - y_e)^2$   
Root Mean Square error calculation:  $error = \sqrt[2]{(G_0 - y_e)^2}$
4. Improve estimates using the plots and figure of merit calculations. Derive the two parameters for the servo motor function  $G(s) = \frac{K_m}{(S+\alpha)(S+\beta)}$ .



(a) Data Set 1



(b) Data Set 2



(c) Data Set 3

Figure 16: Servo Motor Response Modified:  $k_m$  and  $\alpha$

```

1 % Plot experimental data ye against systems estimated tf y1
2 [te_1new, ye_1new] = timing_fix(te_1, ye_1);
3 [te_2new, ye_2new] = timing_fix(te_2, ye_2);
4 [te_3new, ye_3new] = timing_fix(te_3, ye_3);
5
6 figure
7 plot(te_1new, ye_1new, 'k')
8 title('Experimental Data Plot [Set 1 Adjusted]')
9 xlabel('te (sec)')
10 ylabel('ye (voltage)')
11 print('-depsc', strcat('figures', filesep, 'B2_dataset1'));
12 close
13
14 figure
15 plot(te_1new, ye_1new, 'k')

```

```

16 title('Experimental Data Plot [Set 1 Adjusted]')
17 xlabel('te (sec)')
18 ylabel('ye (voltage)')
19 print('-depsec',strcat('figures',filesep,'B2-dataset1'));
20 close

```

```

1 % Prepare experimental data for alpha and km parameter calculations
2 [te_1trim, ye_1trim] = trimForCalculation(te_1new, ye_1new, mf1);
3 [te_2trim, ye_2trim] = trimForCalculation(te_2new, ye_2new, mf1);
4 [te_3trim, ye_3trim] = trimForCalculation(te_3new, ye_3new, mf1);
5
6 km_num = 500; % number of km values used
7 km_max = 500; % max km value used
8 alpha_num = 500; % number of alpha values used
9 alpha_max = 500; % max alpha value used

```

```

1 % Preallocate size for speed
2 output_ms = zeros(3, km_num*alpha_num);
3 output_rms = zeros(3, km_num*alpha_num);
4 km_ms = zeros(1, 3);
5 alpha_ms = zeros(1, 3);
6 km_rms = zeros(1, 3);
7 alpha_rms = zeros(1, 3);
8
9 for iteration = 1 : 3
10
11     % Set te and ye based on iteration
12     if (iteration == 1)
13         te = te_1trim;
14         ye = ye_1trim;
15     elseif (iteration == 2)
16         te = te_2trim;
17         ye = ye_2trim;
18     else
19         te = te_3trim;
20         ye = ye_3trim;
21     end
22
23     % Set cycle variables
24     error_ms = 0;
25     error_rms = 0;
26     ii = 1;
27     count = 0;
28
29     for km = linspace(0, km_max, km_num) % Cycle km values
30         for alpha = linspace(0, alpha_max, alpha_num) % Cycle alpha values
31             G = tf(km, [1 alpha 0]);
32             G_0 = step(G, te);
33
34             % Calculate error
35             for jj = 1 : length(te)
36                 % Calculate mean square error
37                 error_ms = error_ms + (G_0(jj) - ye(jj))^2;
38
39                 % Calculate root mean square error
40                 error_rms = error_rms + rms(G_0(jj) - ye(jj));
41             end
42
43             % Store km, alpha and the error taken to calculate
44             output_ms(:, ii) = [km; alpha; error_ms];
45             output_rms(:, ii) = [km; alpha; error_rms];
46
47             % Reset cycle variables
48             ii = ii + 1;

```

```

49         error_ms = 0;
50         error_rms = 0;
51     end
52
53     % Output km iterations
54     %count = count + 1;
55     %fprintf('%d %s %d\n',count,'/',km_num);
56 end
57
58 % Calculate km and alpha values for mean square error calculation
59 [~,index] = min(output_ms(3,:));
60 km_ms(iteration) = output_ms(1,index); % Output variable
61 alpha_ms(iteration) = output_ms(2,index); % Output variable
62
63 % Calculate km and alpha values for root mean square error calculation
64 [~,index] = min(output_rms(3,:));
65 km_rms(iteration) = output_rms(1,index); % Output variable
66 alpha_rms(iteration) = output_rms(2,index); % Output variable
67 end
68 km_mean = (mean(km_ms) + mean(km_rms)) / 2;
69 alpha_mean = (mean(alpha_ms) + mean(alpha_rms)) / 2;

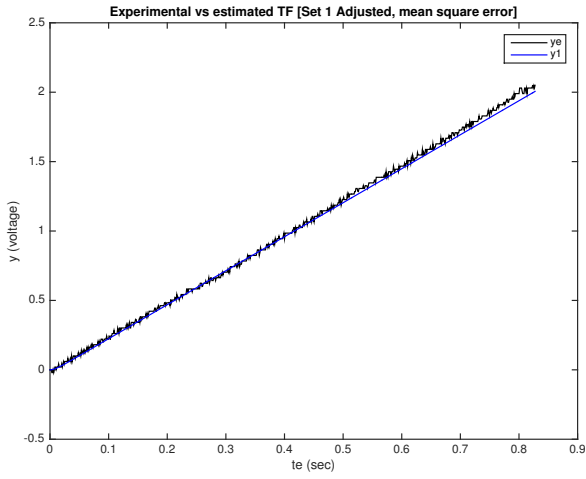
```

```

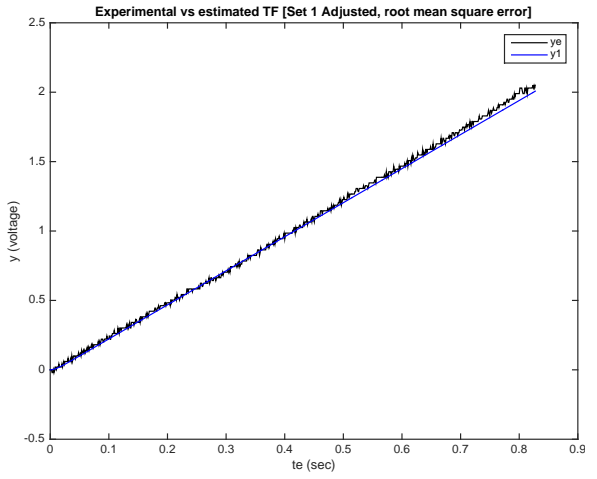
1 % Plot y1 against ye
2 % Data Set 1
3 G = tf(km_ms(1), [1 alpha_ms(1) 0]);
4 y1_ms = step(G,te_lnew);
5 figure
6 plot(te_lnew,medfilt1(ye_lnew,1),'k',te_lnew,medfilt1(y1_ms,1),'b')
7 title('Experimental vs estimated TF [Set 1 Adjusted, mean square error]')
8 xlabel('te (sec)')
9 ylabel('y (voltage)')
10 legend('ye','y1')
11 print('-depsc',strcat('figures',filesep,'y1-dataset1_ms'));
12 close

```

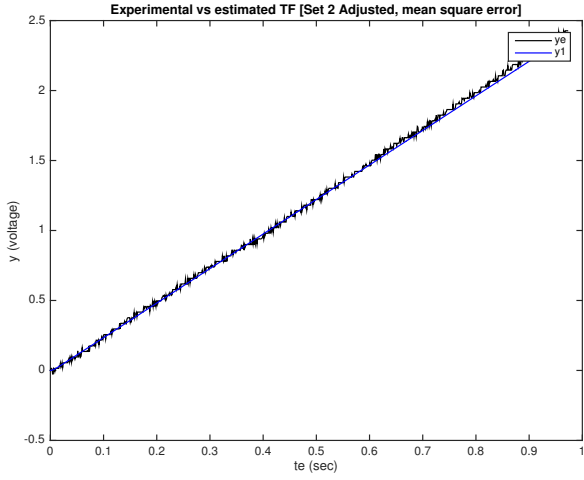
The average constants found are as follows:  $\alpha = 170.3407$   $k_m = 422.0107$



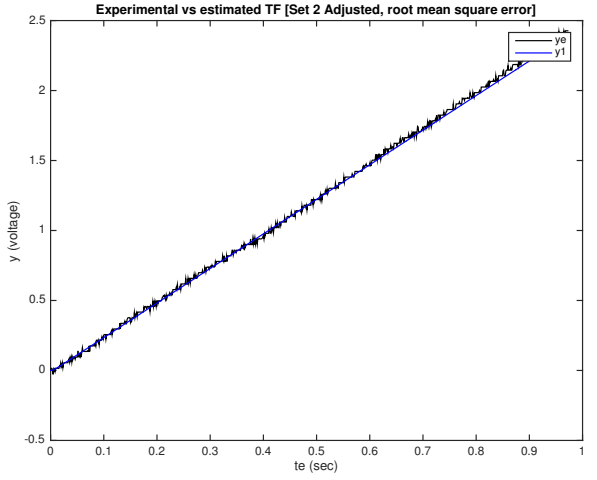
(a) Data Set 1 (ms)



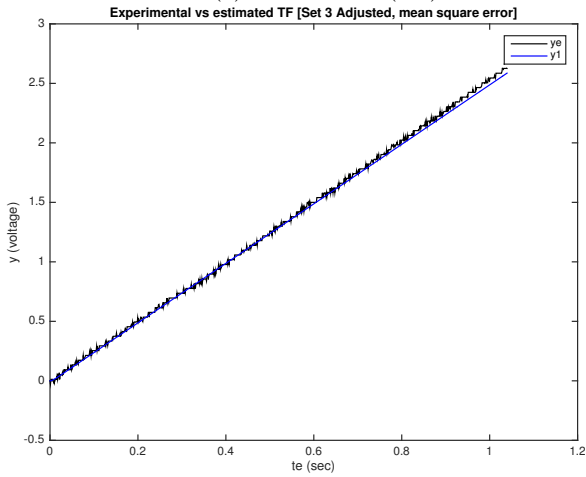
(b) Data Set 1 (rms)



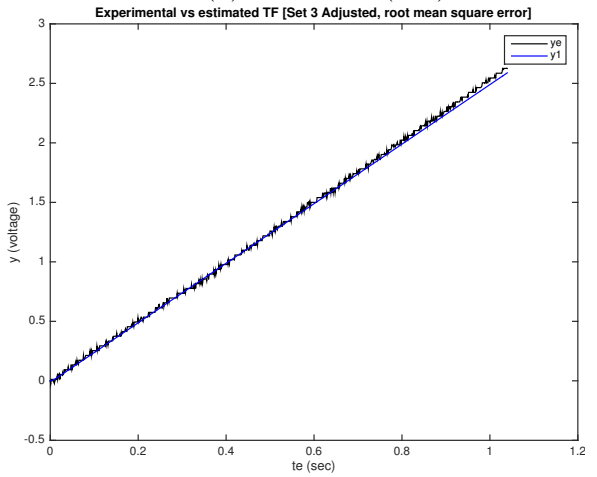
(c) Data Set 2 (ms)



(d) Data Set 2 (rms)



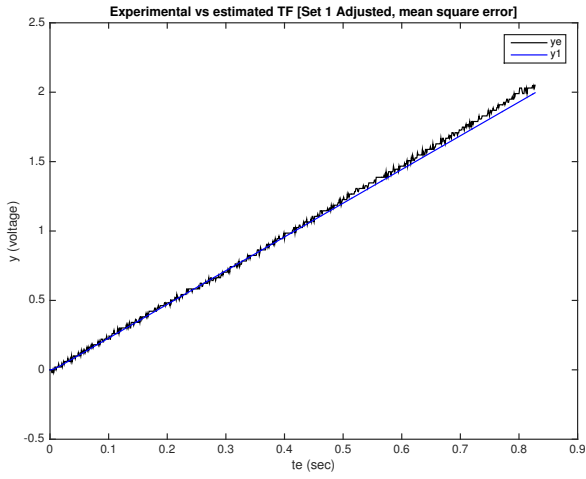
(e) Data Set 3 (ms)



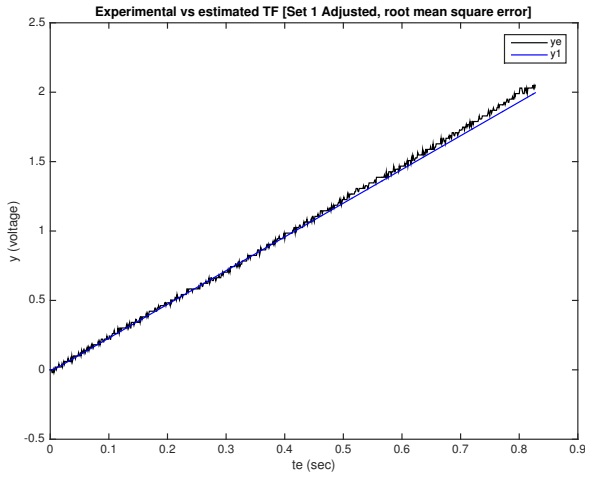
(f) Data Set 3 (rms)

Figure 17: Servo Motor Response Modeled

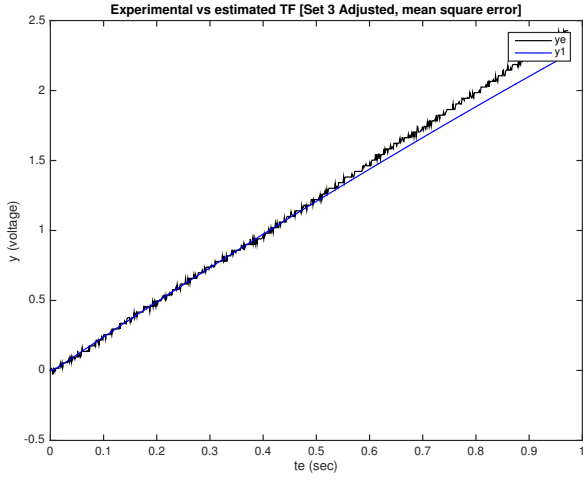
5. The mechanical constant  $\alpha$  was found to be  $\alpha = \alpha_{mean}$ . Using the second order equation  $G(s) = \frac{K_m}{(s+\alpha)}$  new values of gain constant  $k_m$  and electrical constant  $\beta$ . Values were found for  $y_1(t) \approx y_2(t)$ . The average constants found are as follows:  $\beta = 0.0646$   $k_m = 426.6867$



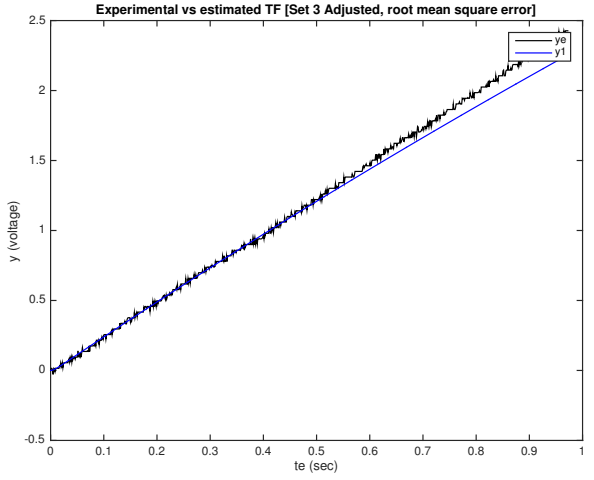
(a) Data Set 1 (ms)



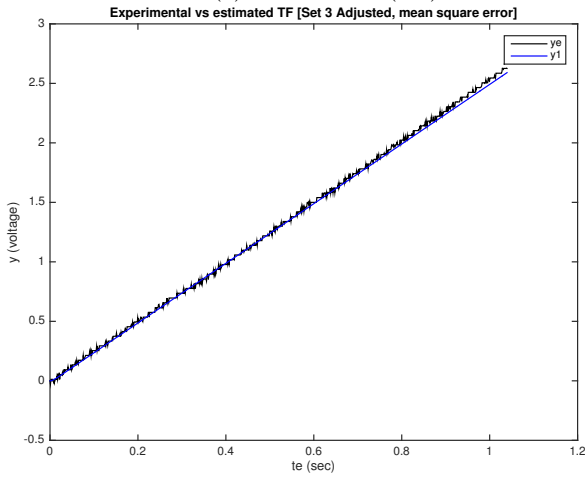
(b) Data Set 1 (rms)



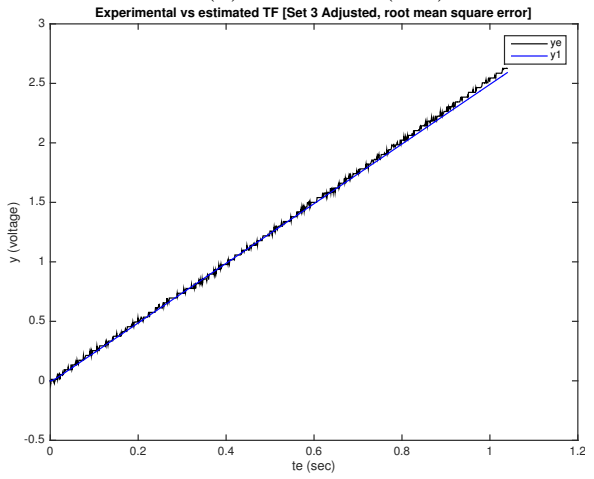
(c) Data Set 2 (ms)



(d) Data Set 2 (rms)



(e) Data Set 3 (ms)



(f) Data Set 3 (rms)

Figure 18: Servo Motor Response Modeled:  $k_m$  and  $\beta$

```

1 km_num = 500;      % number of km values used
2 km_max = 500;      % max km value used
3 beta_num = 50;      % number of alpha values used
4 beta_max = 1;      % max alpha value used
5
6 % Preallocate size for speed
7 output_ms = zeros(3,km_num*beta_num);
8 output_rms = zeros(3,km_num*beta_num);
9 km2_ms = zeros(1,3);
10 beta_ms = zeros(1,3);
11 km2_rms = zeros(1,3);
12 beta_rms = zeros(1,3);
13
14 for iteration = 1:3
15     if(iteration == 1)
16         te = te_1trim;
17         ye = ye_1trim;
18     elseif(iteration==2)
19         te = te_2trim;
20         ye = ye_2trim;
21     else
22         te = te_3trim;
23         ye = ye_3trim;
24     end
25
26     % Set cycle variables
27     error_ms = 0;
28     error_rms = 0;
29     ii = 1;
30     count = 0;
31
32     for km = linspace(0,km_max,km_num) % Cycle km values
33         for beta = linspace(0,beta_max,beta_num) % Cycle alpha values
34             G = tf(km, [1 (alpha_mean+beta) (alpha_mean*beta)]);
35             G_0 = step(G,te);
36
37             % Calculate error
38             for jj = 1 : length(te)
39                 % Calculate mean square error
40                 error_ms = error_ms + (G_0(jj) - ye(jj))^2;
41
42                 % Calculate root mean square error
43                 error_rms = error_rms + rms(G_0(jj) - ye(jj));
44             end
45
46             % Store km, alpha and the error taken to calculate
47             output_ms(:,ii) = [km;beta;error_ms];
48             output_rms(:,ii) = [km;beta;error_rms];
49
50             % Reset cycle variables
51             ii = ii + 1;
52             error_ms = 0;
53             error_rms = 0;
54         end
55
56         % Output km iterations
57         count = count + 1;
58         fprintf('%d %s %d\n',count,'/',km_num);
59     end
60
61     % Calculate km and alpha values for mean square error calculation
62     [~,index] = min(output_ms(3,:));
63     km2_ms(iteration) = output_ms(1,index); % Output variable
64     beta_ms(iteration) = output_ms(2,index); % Output variable
65
66     % Calculate km and alpha values for root mean square error calculation

```

```

67     [~,index] = min(output_rms(3,:));
68     km2_rms(iteration) = output_rms(1,index); % Output variable
69     beta_rms(iteration) = output_rms(2,index); % Output variable
70 end
71
72 km_mean2 = (mean(km_ms) + mean(km2_rms)) / 2;
73 beta_mean = (mean(beta_ms) + mean(beta_rms)) / 2;

```

```

1 % Plot y2 against ye
2 % Data Set 1
3 G = tf(km2_ms(1), [1 (alpha_mean+beta_ms(1)) (alpha_mean*beta_ms(1))]);
4 y2_ms = step(G,te_1new);
5 figure
6 plot(te_1new,medfilt1(ye_1new,1),'k',te_1new,medfilt1(y2_ms,1),'b')
7 title('Experimental vs estimated TF [Set 1 Adjusted, mean square error]')
8 xlabel('te (sec)')
9 ylabel('y (voltage)')
10 legend('ye','y1')
11 print('-depsc',strcat('figures',filesep,'y2_dataset1.ms'));
12 close

```

### 7.2.2 Part C

1. Re-draw figure 19 and place boxes around the set of components that correspond to each functional element of the control system.



Figure 19: Closed Loop Motor Control Schematic

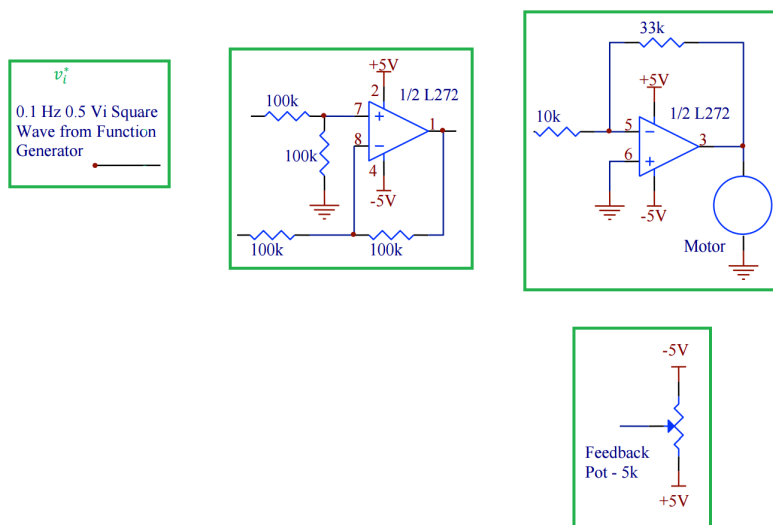
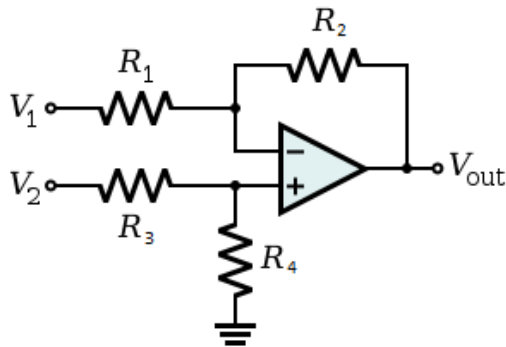


Figure 20: Closed Loop Motor Control System

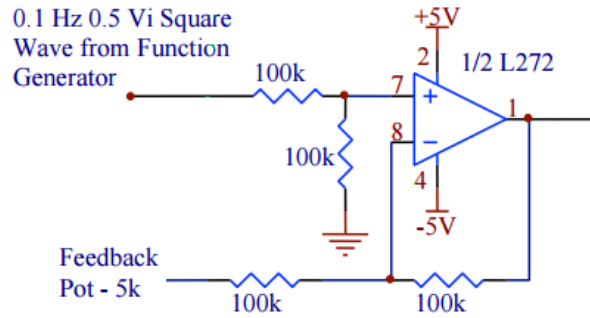


2. Based on the results from Parts A and B, the component values given in figure 19 and your research in parts C1, calculate all of the transfer functions in your functional diagram (figure 20). Update the functional diagram, labeling all components and interfaces.

Difference Op-amp:



(a) Standard Difference Op Amp



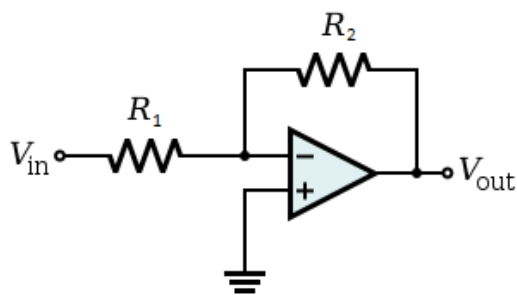
(b) System Difference Op Amp

Figure 21: Difference Op-amp System

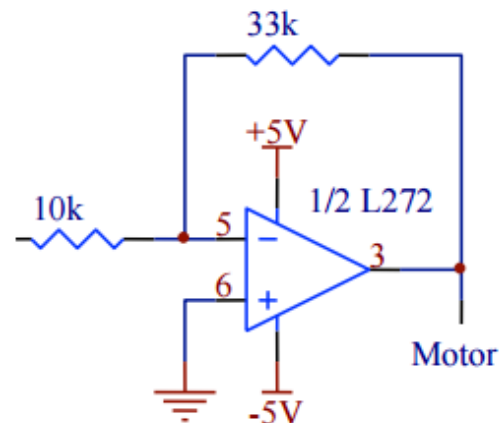
$$\frac{V_o(s)}{V_{in}(s)} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_3}{R_4}} V_2 - \frac{R_2}{R_1} V_1$$

$$\frac{V_o(s)}{V_{in}(s)} = V_o(s) - V_p(s)$$

Inverting Op-amp:



(a) Standard Inverting Op Amp



(b) Inverting Op-amp System

Figure 22: Inverting Op-amp System

$$\frac{V_i(s)}{V_d(s)} = \frac{R_2}{R_1}$$

Note: The polarity on the inverter transfer function has been flipped.

**Motor:**

$$\frac{V_p(s)}{V_i(s)} = \frac{K_m}{s(s + \alpha)}$$

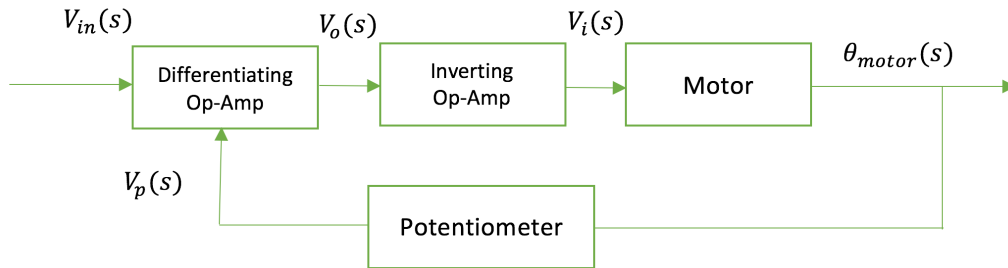


Figure 23: Updated Functional Diagram

**System Transfer Function:**

$$\begin{aligned}
 G_c(s) &= \frac{V_p(s)}{V_{in}(s)} \\
 &= \frac{V_p(s)}{V_i(s)} \times \frac{V_i(s)}{V_d(s)} \times \frac{V_d(s)}{V_{in}(s)} \\
 &= \frac{K_m}{s(s+\alpha)} \times \frac{R_2}{R_1} \times (V_i(s) - V_p(s)) \\
 &= \frac{-K_m R_2}{R_1} \left( \frac{V_i(s) - V_p(s)}{s(s+\alpha)} \right)
 \end{aligned}$$

From Inverting OP amp:  $V_m(s) = \frac{R_2}{R_2} \times V_o(s)$

From Motor:  $V_m(s) = \frac{s(s+\alpha)V_p(s)}{K_m}$

$$\begin{aligned}
 \therefore \frac{s(s+\alpha)V_p(s)}{K_m} &= \frac{R_2}{R_2} \times V_o(s) \\
 V_o(s) &= \frac{R_1 s(s+\alpha)}{K_m R_2} V_p(s)
 \end{aligned}$$

From Difference Op Amp:  $V_o(s) = V_i(s) - V_p(s)$

$$\begin{aligned}
 \therefore \frac{R_1 s(s+\alpha)}{K_m R_2} V_p(s) &= V_i(s) - V_p(s) \\
 V_p(s) \left[ 1 - \frac{R_1 s(s+\alpha)}{K_m R_2} \right] &= V_i(s) \\
 \frac{V_p(s)}{V_i(s)} &= \frac{1}{1 + \frac{R_1 s(s+\alpha)}{K_m R_2}} \\
 &= \frac{1}{1 + \frac{R_1}{K_m R_2} (s^2 + \alpha s)} \\
 &= \frac{1}{\left( \frac{R_1}{K_m R_2} \right) s^2 + \left( \frac{\alpha R_1}{K_m R_2} \right) s + 1} \\
 &= \frac{\frac{K_m R_2}{R_1}}{s^2 + \left( \frac{\alpha R_1 K_m R_2}{K_m R_2 R_1} \right) s + \frac{K_m R_2}{R_1}} \\
 &= \frac{\frac{K_m R_2}{R_1}}{s^2 + \alpha s + \frac{K_m R_2}{R_1}}
 \end{aligned}$$

### Ideal System Transfer Function:

$$G_c(s) = \frac{KG(s)}{1 + KG(s)H(s)}$$

$$G(s) = \frac{K_m}{s(s + \alpha)}$$

$$H(s) = 1$$

$$K = \frac{R_f}{R_1}$$

$$G_c(s) = \frac{\frac{R_f}{R_1}G(s)}{1 + \frac{R_f}{R_1}G(s)}$$

$$G_c(s) = \frac{\frac{R_f}{R_1} \frac{K_m}{s(s+\alpha)}}{1 + \frac{R_f}{R_1} \frac{K_m}{s(s+\alpha)}}$$

$$G_c(s) = \frac{\frac{\frac{R_f}{R_1} K_m}{s(s+\alpha)}}{1 + \frac{\frac{R_f}{R_1} K_m}{s(s+\alpha)}}$$

$$G_c(s) = \frac{\frac{R_f}{R_1} K_m}{s(s + \alpha) + \frac{R_f}{R_1} K_m}$$

$$G_c(s) = \frac{\frac{R_f}{R_1} K_m}{s^2 + s\alpha + \frac{R_f}{R_1} K_m}$$

Where  $K_m = 326$ ,  $\alpha = 38.61$ ,  $R_f = 33k$  and  $R_1 = 10k$ . Thus,

$$G_c(s) = \frac{\frac{33000}{10000} K_m}{s^2 + s\alpha + \frac{33000}{10000} K_m}$$

$$G_c(s) = \frac{3.3 * K_m}{s^2 + s\alpha + 3.3 * K_m}$$

$$G_c(s) = \frac{3.3 * 326}{s^2 + 38.61s + 3.3 * 326}$$

$$G_c(s) = \frac{1075.8}{s^2 + 38.61s + 1075.8}$$

### 3. C4 - Matlab - Declan?

4. Calculate the gain required in the final stage to produce a 5% overshoot. Choose resistor values to match the required gain.

Recall, for 5% overshoot,  $\zeta = \frac{-\ln(5/100)}{\sqrt{\pi^2 + \ln^2(5/100)}} = 0.69$

And, the systems estimated overall transfer function;  $\frac{k_m \frac{R_f}{R_1}}{s^2 + s\alpha + k_m \frac{R_f}{R_1}}$

Whereas, the general second order transfer function;  $\frac{W_n^2}{s^2 + 2\zeta W_n s + W_n^2}$   
Moreover,

$$\alpha = 2\zeta W_n$$

$$W_n = \frac{\alpha}{2\zeta}$$

$$W_n^2 = k_m \frac{R_f}{R_1}$$

$$\frac{R_f}{R_1} = W_n^2 / k_m$$

$$K = \left(\frac{\alpha}{2\zeta}\right)^2 / k_m$$

From section B, we know  $k_m = 326$  and  $\alpha = 38.61$ . We also calculated the required  $\zeta$  previously, as 0.69.

$$K = \left(\frac{38.61}{2 * 0.69}\right)^2 / 326$$

$$K = 2.4$$

Therefore, the gain required to achieve a 5% overshoot is as stated above; Moreover, to calculate the desired resistor values to achieve this game, we must make an initial assumption about either  $R_f$  or  $R_1$ .

Assuming  $R_1 = 10k$  (as to avoid changing both resistors);

$$K = 2.4$$

$$\frac{R_f}{R_1} = 2.4$$

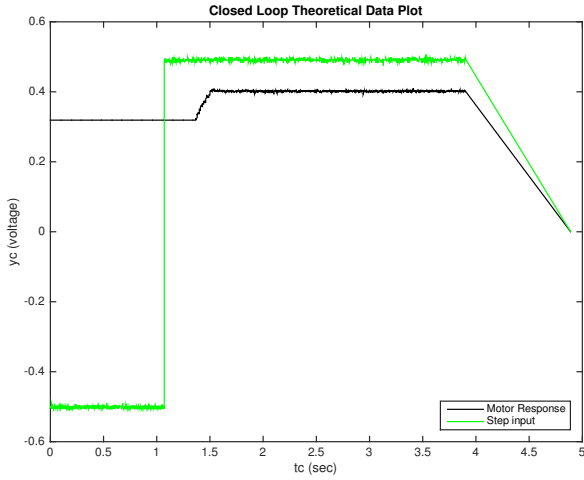
$$R_f = 2.4 * R_1$$

$$R_f = 2.4 * 10000$$

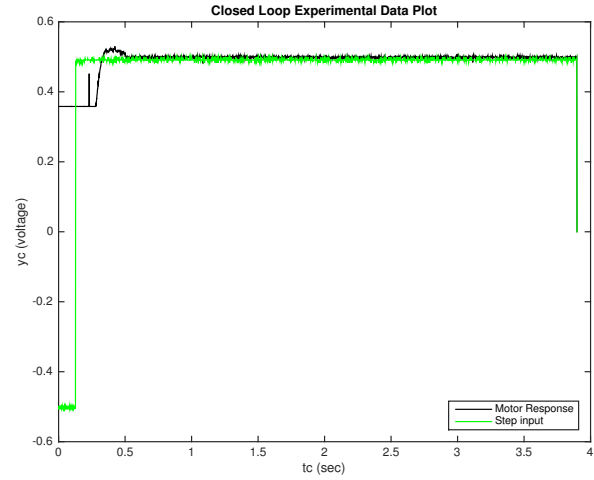
$$R_f = 24000$$

Thus, theoretically, to achieve 5% overshoot a gain of  $K = 2.4$  is required, to achieve this,  $R_f = 24k \approx 22k + 1.8k + 220 = 24.2k$ , and  $R_1 = 10k$ .

5. Import experimental results into MATLAB. Compare your closed loop response data against your predicted model data  $Y_c(t)$ . Note any differences between the experimental result and the predicted result. What does this suggest about the model derived in part A and B?

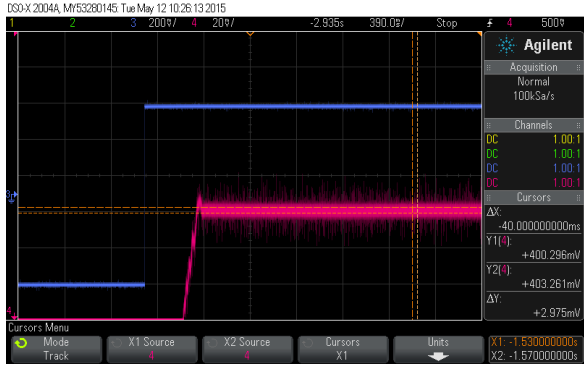


(a) Theoretical Closed Loop Response

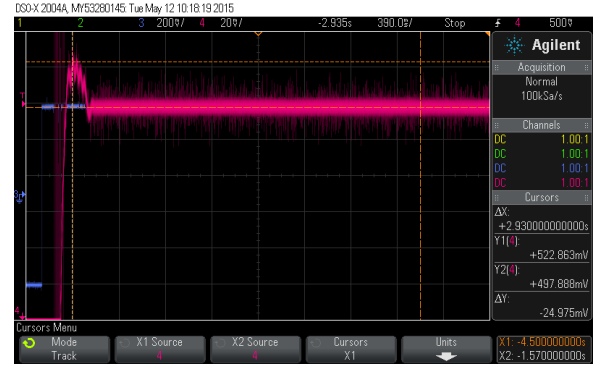


(b) Experimental Closed Loop Response

Figure 24: Servo Motor Closed Response



(a) Theoretical Closed Loop Response



(b) Experimental Closed Loop Response

Figure 25: Servo Motor Closed Response

$$\%OS = \frac{V_{max} - V_{avg}}{V_{avg}} \times 100$$

$$\begin{aligned} \%OS_{theoretical} &= \frac{403.261 - 400.296}{400.296} \times 100 \\ &= 0.7407\% \end{aligned}$$

$$\begin{aligned} \%OS_{experimental} &= \frac{522.863 - 497.888}{497.888} \times 100 \\ &= 5.016\% \end{aligned}$$

The motor response of the theoretical response was derived from  $R_f = 25k$  ohms and  $R_1 = 10k$  ohms with a calculated overshoot of 5%. As shown in the calculations above, the theoretical percentage overshoot is much smaller. To obtain a 5% overshoot,

6. Compare your experimentally derived 5% overshoot gain value against your predicted value. What is the percentage error? If your overshoot was too large for your derived gain value, could you use a controller other than the proportional controller to reduce overshoot?

If your steady state error was large, what other controller type could you use to minimize this error? What are the drawbacks of this type of controller? What control applications can you think of that require very low steady state error?

From the procedure outlined in **experiment C**, an experimental gain of  $K = 6.28$  resulted in an overshoot of 5%, and in **step 5** it was shown that the theoretical gain required to achieve this was  $K = 2.4$ .

The percentage error between the calculated and experimentally found gain values has been calculated below.

$$\begin{aligned}\%_{error} &= \left| \frac{K_{theoretical} - K_{experimental}}{K_{experimental}} \right| \times 100 \\ \%_{error} &= \left| \frac{6.28 - 2.4}{2.4} \right| \times 100 \\ \%_{error} &= 61.8\%\end{aligned}$$

A large % error value, as indicated above; provides strong evidence for model inaccuracies. The difference in gain between the theoretical and the practical values is likely caused by **WHAT**.

The overshoot resulting from the derived gain value was under 5%.

Steady state error was noticeable in the system, likely caused by mechanical losses (gearbox, heat, etc). To alleviate this issue, a PI compensator (integrator) could be used; this is because the PI controller adds up error over time and would remove the steady state error. Moreover, a PI controller retains a maximum overshoot and settling time similar to that of the proportional controller (adjusting the gain alone).

However, the drawbacks for a PI controller include, but are not limited too; **WHAT**.

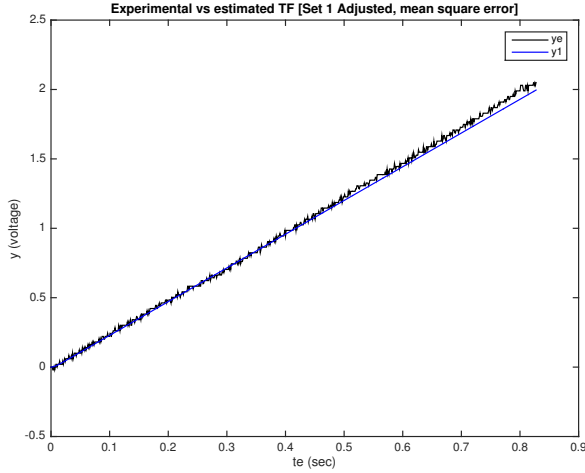
What control applications require very low SSE?

Add the actual OS from prac/theo

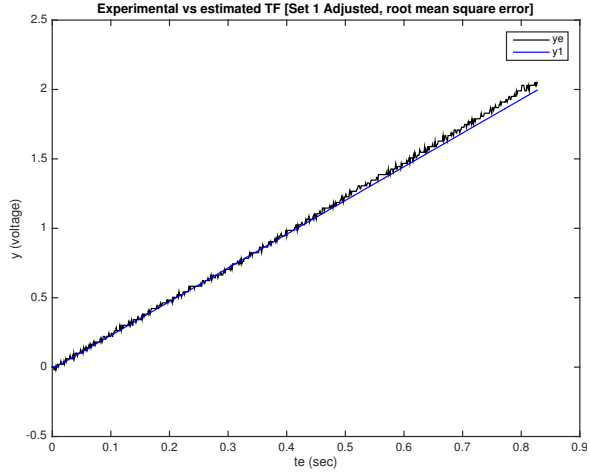
7. Another method of calculating TF? (bode)

### 7.2.3 Part D

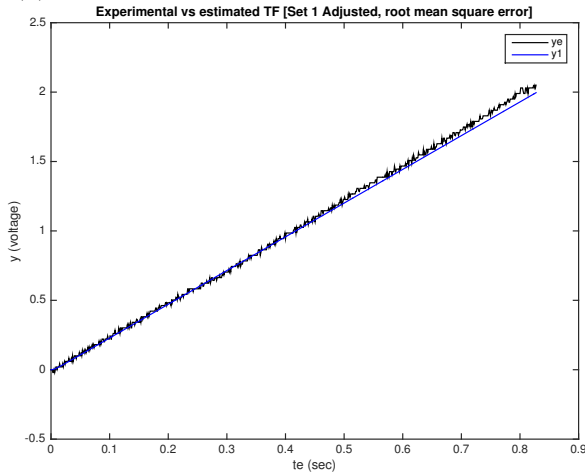
1. stuff
2. The overshoot was measured over five different input frequencies in order to determine the effect over varying the input signals frequency. The systems response to these signals was also recorded, and can be found as a set of graphical time domain plots below.



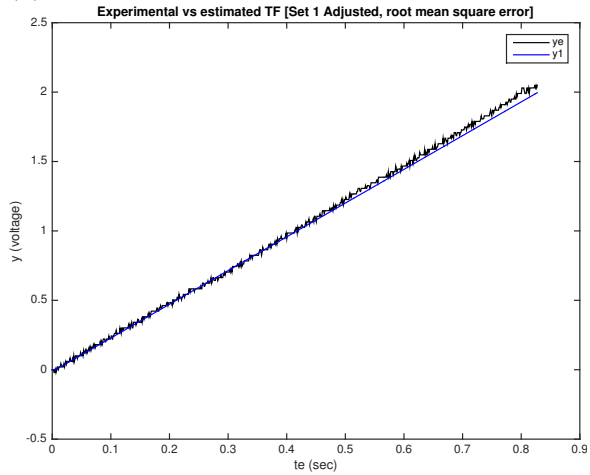
(a) Closed loop time domain response to 0.5Hz input.



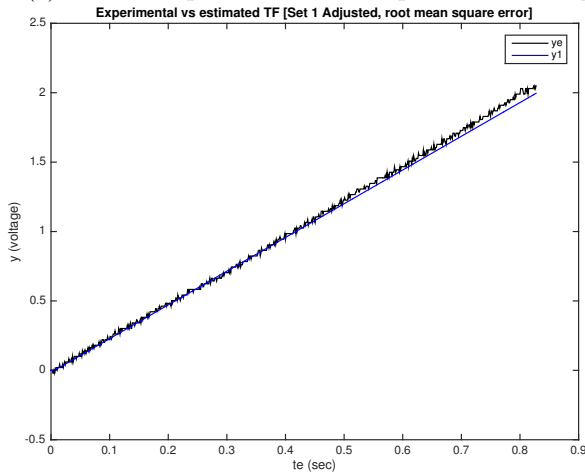
(b) Closed loop time domain response to 0.75Hz input.



(c) Closed loop time domain response to 1Hz input.



(d) Closed loop time domain response to 1.25Hz input.



(e) Closed loop time domain response to 1.5Hz input.

Figure 26: Systems response to various input frequencies.



The percentage overshoot was calculated using the cursors on the digital CRO machine to measure the peak overshoot and the steady state voltage (average).

$$\%OS = \frac{V_{peak} - V_{average}}{V_{average}}$$

$$OS(0.5Hz) = \frac{525 - 495}{495} = 6.1$$

$$OS(0.75Hz) = \frac{523 - 495}{495} = 5.7$$

$$OS(1Hz) = \frac{525 - 495}{495} = 6.1$$

$$OS(1.25Hz) = \frac{525 - 495}{495} = 6.1$$

$$OS(1.5Hz) = \frac{524 - 495}{495} = 5.8$$

The results of this analysis can be found in the following table.

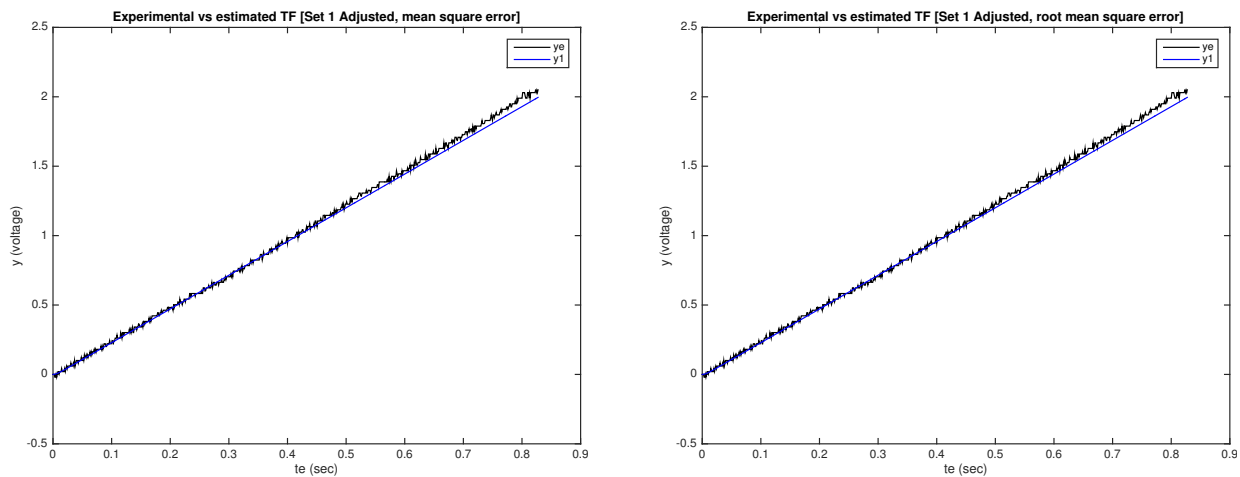
Input Frequency (Hz)	Overshoot (%)
0.5	6.1
0.75	5.7
1	6.1
1.25	6.5
1.5	5.8

As can be seen almost immediately in the previous plots, as the frequency of the input signal is increased, the output has less time to reach a steady state value. Eventually, the increasing frequency limits the systems ability to reach a steady state value.

It is also evident from the previous figures and tables, that neither the overshoot, settling time or the steady state error are effected; until eventually the system does not have enough time to reach a steady state value. In addition to this, were the frequency to keep increasing, eventually the op-amps physical components would not be able to switch fast enough, and the output would be attenuated.

The frequency does not effect any of the aforementioned properties, because quite simply; the transfer function to which these properties can be derived, is independent of frequency. Which is to be expected, as there are no energy storing components in the system (capacitors, inductors).

3. To examine the impact of changing the gain value, the systems response data has been captured, recorded, and displayed below.



- (a) Closed loop time domain response to 0.5Hz input. (b) Closed loop time domain response to 0.75Hz input.

Figure 27: Systems response to various gain values.

As you would expect, changing the gain value **increases OS?** and **decreases Ts?**. The above images show large evidence to support this comment; as the correlation between these values can be seen clearly. **WHY**

This is useful because **WHY**

4. **C4 - Matlab - Declan?** simulink
5. **C4 - Matlab - Declan?** PD/PI/PID controller

## 8 CHECKLIST

1. Executive Summary
2. Introduction
3. Procedure Intro
4. Procedure (D) - add new method
5. Results (B)
  - (a) Is the transfer function as we'd expect?
  - (b) Closed loop response figures (theoretical gain or given gain?)
  - (c) What can be seen from the figures
  - (d) Experimental gain figures
  - (e) What can be seen from this
  - (f) Compare models
  - (g) Compare gains
  - (h) **NEW METHOD** for finding TF
7. Results (D)
  - (a) **DO NEW METHOD**
  - (b) Check tables peak overshoot
  - (c) Why is the effect of gain useful?
  - (d) **SIMULINK MODEL**
  - (e) **PI/PD controller**
8. **DISCUSSION and RECOMMENDATIONS**
9. Answers (B) - add more words?
10. Answers (C)
  - (a) Fix figures
  - (b) Add non-ideal method
  - (c) C(4)
  - (d) Finish C(7)
  - (e) **NEW METHOD** for finding TF
11. Answers (D)
  - (a) **DO NEW METHOD**
  - (b) Does frequency affect anything?
  - (c) Prove how gain affects shit
  - (d) **SIMULINK MODEL**
  - (e) **PI/PD controller**

NOTES: on first page, acknowledge assistance from students list group members / lab members