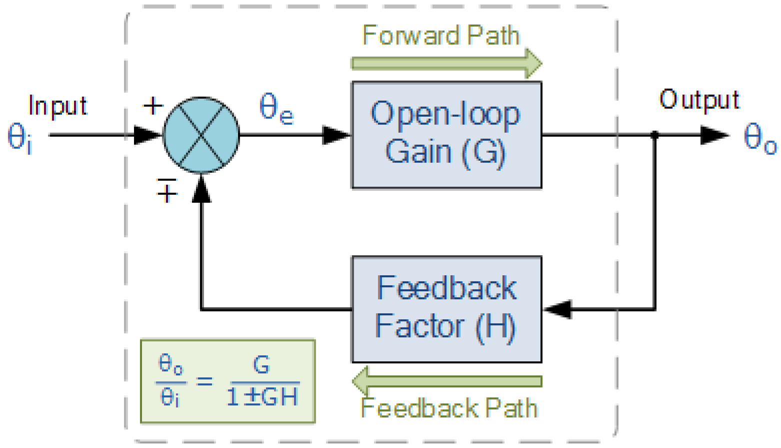
LABORATORY MANUAL

EXPERIMENTS IN

LINEAR CONTROL SYSTEMS



FACULTY OF ENGINEERING

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1	Dr. Muhammad Majid Gulzar	1st Aug 2012	Updated experiments
2	Dr. Ali Nasir	15th Aug 2016	Updated experiment list
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4	Ali Ahmad	22nd Feb 2018	Formatting & Updating
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PREFACE

Dr. Muhammad Majid Gulzar is currently an assistant professor in Faculty of Engineering, University of Central Punjab, Pakistan. He received his Ph.D. degree with specialization in Control Science and Engineering from Department of Automation, University of Science and Technology of China (USTC) in 2016. He received his M.S and B.S degrees in Electrical Engineering from University of Engineering and Technology (UET), Pakistan in 2012 and University of Central Punjab (UCP), Pakistan in 2008 respectively. He is a member of Pakistan Engineering Council and IEEEP (P). His areas of interest are Control Systems, Automation, Multi-agent Networks, Analysis and Design of Linear Systems etc. He has advised number of projects in these areas and has number of publications in international journals and conferences.

INTRODUCTION

Linear Control System lab manual presents a series of experiments dealing with all topics covered in theory course Linear Control Systems and provides an introduction to control system starting with open loop control to feedback control system.

Each experiment is accompanied by a set of objectives, a list of equipment required followed by a discussion of theoretical concepts that are investigated or analyzed. After each experiment, students are required to comment on the results of the experiment and the lab exercise.

The sequence and scope of the experiments in this manual are related to the theoretical material covered in the text book and analysis based on control system application. All the experiments have been tested and revised where necessary to improve clarity. Any comments or suggestions to improve the style, scope or clarity of any experiment are welcome.

I wish to thank **Engr. Muhammad Amer Saeed**, who made constructive suggestions and changes while teaching in this laboratory course. I also thank **Engr. Ali Ahmad** and **Engr. Awais Arshad** who helped me with the formatting, error omissions and editing to finalize the manuscript.

LINEAR CONTROL SYSTEMS LABORATORY

TABLE OF CONTENTS

EXPERIMENT #1

Study and Analysis of DC Motor, Potentiometer and Interface Modules

Objectives

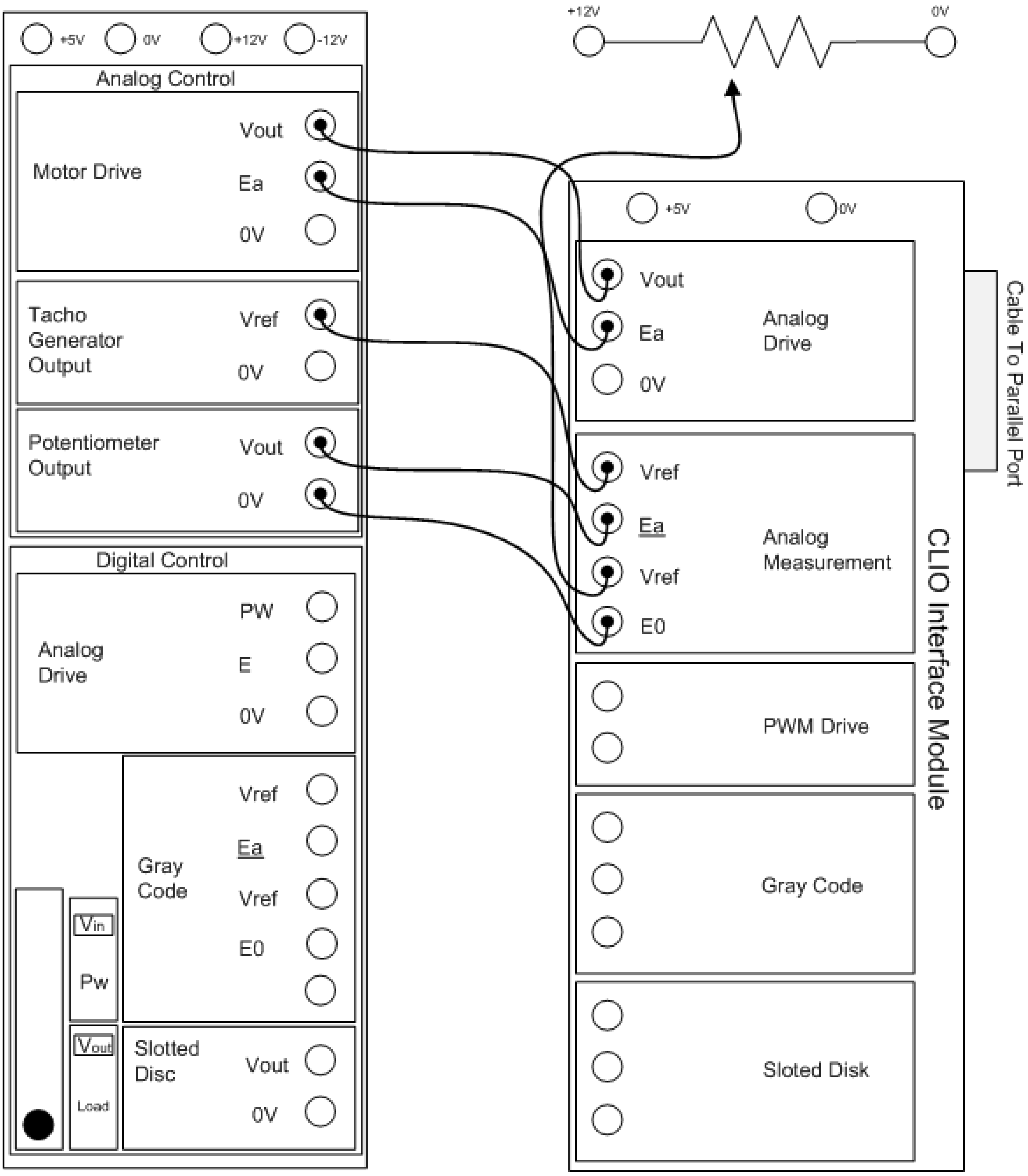
1. To understand the analog features of DC motor, Input Potentiometer and Interface Modules.
2. Connect the modules for analog control study.
3. Analyze the software control to drive DC motor and observe the output.

Lab Equipment

- MS15 Module
- AS3 Command Potentiometer
- Control Laboratory Input/output Interface (CLIO)
- Power Supply
- Connecting leads
- Virtual Control Laboratory (VCL) Software

Theory

To study the behavior of DC Motor, potentiometer and different interface modules, it is essential to perform the practical exercises on hardware and to analyze different waveforms displayed on the PC. A PC with the Virtual Control Laboratory software and CLIO Control Laboratory Input/output interface is used to replace a number of different traditional instruments, eliminating the need for separate signal generator oscilloscope, multi meter or controller. In this first experiment, you will refresh your knowledge of the DC Motor which is used as the PLANT and familiarize yourself with the interface board and the operation of the software. A trainer or collection of components are used (analog and digital) in this experiment are MSI5 module, DC motor, tachogenerator, plant input, velocity output, position output, motor controller, amplifier, potentiometer, tachometer, signal conditioning block and Virtual software. Wiring diagram of MS15 module is shown in Fig. 1.



* All Power supplies ground and Trainer ground should be common

Figure 1: Wiring Diagram of MS15 Module.

Procedure

In this experiment fundamental principles of analog and digital motor control will be studied. This includes a DC motor control module, command potentiometer, windows based control software, input/output interface module, power supply unit and connection leads.
This curriculum makes use of Real-time Windows^{TM} based Virtual Control Laboratory software and a Control Laboratory Input/output (CLIO) interface module which enables the student PC workstation to:

1. Perform as a function generator to supply (if required) the command (reference) input signal in various forms, for example, step or sine wave inputs.

2. Supply a wide range of different adjustable controller configurations, for example, open-loop or PID.

3. Perform as an eight-channel oscilloscope or voltmeter to display various control signals, for example, command input, position output.

4. Make circuit connections using the 4 mm Patching Cords according to the diagram. Whenever you make (or change) circuit connections, it is good practice to always do so with the Power Supplies switch in the OFF position.

5. Switch the Power Supplies ON only after you have made, and checked, your connections. Remember that the Power Supplies switch must be ON in order for you to be able to make the observations and measurements required in the Exercise.

6. At the end of each Exercise, you should return the Power Supply switch to the ’OFF’ position *before* you dismantle your circuit connections.

7. In order to control with computer managed workstation you will require a personal computer (PC) that has been installed with computer managed student workstation software. If you are working in a computer managed environment for the first time, you should first read the operating information that has been provided with your computer managed workstation. This tells you how to:

    a) Log onto the management system and request work.

    b) Make responses to questions in a computer managed environment.

    c) Hand in your work when completed.

    d) Log off at the end of your work session.

VLC Software Window

Table 1 shows the VLC Software window which includes the settings of controller, Plant (MS15), display meter, signal generator and DC Motor Braking.

Table 1: VLC Software Window

File CA06PE01	Controller Open-loop	Plant MS 15 Analog	Display Meter
Signal Generator		**Graph**	
Signal	DC-Level	1 Input	ON
Level	50%	2 Position	ON
Offset	0%		
Rate	10msec	4 Velocity	ON
Reference	External		
DC Motor Brake	0	Output potentiometer Command Potentiometer	Engage 180^{o}

Results

Input Command Potentiometer

Table 2 shows the relationship between Offset-degrees at 0V, degrees at 1V and finally the difference of both of the values. The input command potentiometer sets at 180^0 which is equivalent to 0V. Adjust the command potentiometer so it gives 0 volt output. When it gives 1 V output, then input command potentiometer is at 1 value. At the end, take the difference of both of the values to get the Gain (k_d) degree/volt.

Table 2: Relationship between Offset-degrees at 0V

Offset-Degrees at 0V	**Degrees at 1V**	**Gain (K_d) degree / volt**

Degrees = K_d * V_{out} + Degree Offset

Conclusion

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TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

EXPERIMENT #2

Evaluation and Study of Control Input and Output Relation.

Objectives

1. To learn the basics of control engineering and to find out how it is used in everyday life.
2. To learn the control objectives that how the system will react when it is subjected to different load changes.
3. To study what is meant by Control Model.

Lab equipment

- MS15 Module
- AS3 Command Potentiometer
- Control Laboratory Input/output Interface (CLIO)
- Power Supply
- Connecting leads
- Virtual Control Laboratory (VCL) Software

Theory

Control system engineering is the engineering discipline which uses the control theory to design systems having desired characteristics. It is the part of our daily life although sometimes it is not obvious. A system that is designed, should work appropriately when the load of the system is changed, and also it must respond well to the input applied to it by minimizing the transient response of the system. The purposes of any plant observing system application are as follows:

1. To control the output so that it should reach to the desired value.
2. Its desired output should be maintained irrespective of the load changes.
3. The transient time should be minimized.
4. The Linear Small Signal Model is the behavioral description of the system when small changes are made which do not take the system into nonlinear operating areas.

5. A Plant Model is a description of how a system behaves. It is stated in terms which allow the determination of the steady state and transient performances of the plant. This allows a control engineer to formulate a control scheme which will result in the satisfactory performance of the overall system.

Procedure

Following are the steps to perform that experiment

1) File CA06PE02 is uploaded from the folder
2) Controller should be in open loop
3) DC level should be used 50%
4) Offset should be zero percent
5) Reference should be internal
6) DC motor brake zero position
7) On graph Input and Velocity is on and Position should be off
8) Output potentiometer should be disengaged
9) Command potentiometer is at 180^{o}

Table 2.1: VLC Software Window

File CA06PE02	Controller Open-loop	Plant MS 15 Analog	Display Graph
Signal Generator Signal Level Offset Rate	 DC-Level 50% 0% 10msec	**Graph** 1 Input 2 Position 4 Velocity	 ON OFF ON
Reference	Internal		
DC Motor **Brake**	 0	Output potentiometer Command Potentiometer	Disengage 180^{o}

The above table 2.1 shows the VLC Software window which includes the settings of controller, Plant (MS15), display meter, signal generator and DC Motor Braking.

Measurements and Calculation

Table 2.2: Command Potentiometer Settings

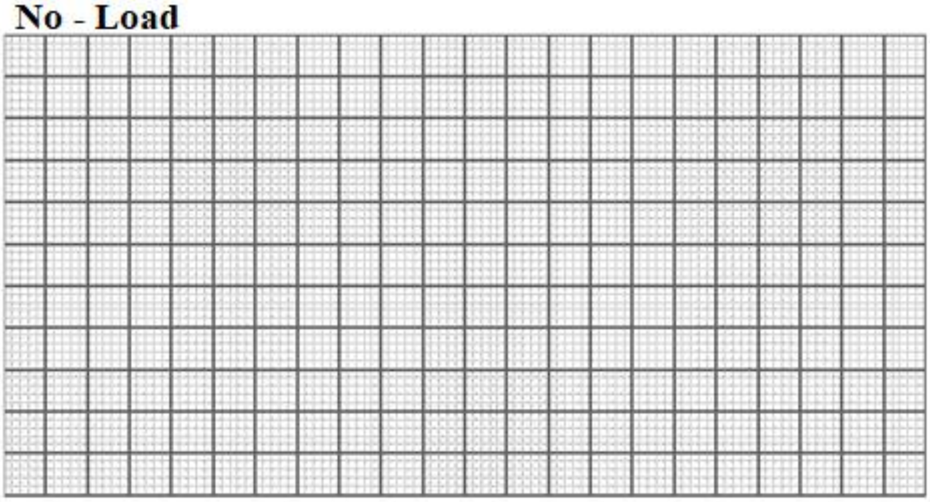
Offset	Input Voltage	Output Voltage No-Load	Output Voltage Half-Load	Output Voltage Full-Load
0				
10				
20				
30				
40				
50				
60				
70				
80				
90				
100				

The above Table 2.2 shows the relationship between offset, input voltage, output voltage at no-load, half load and full-load. When offset is changed, the relationship between input voltage and output voltage at no load, half load and full load can be seen. As offset is increased, other quantities mentioned above also increased in a similar manner. After that, different graphs are made which are of no load, half load and full load, in the graphs given below.

At 50% offset

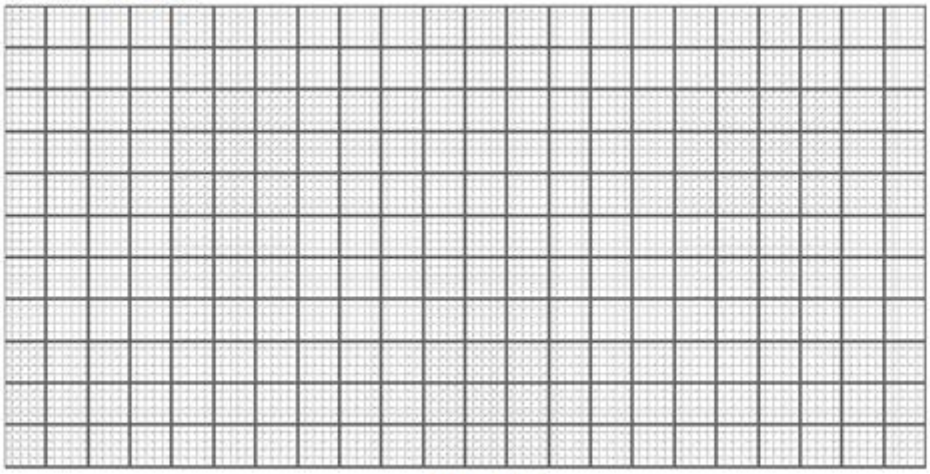
Loading	Tacho voltage
No load	
Half Load	
Full Load	

No - Load



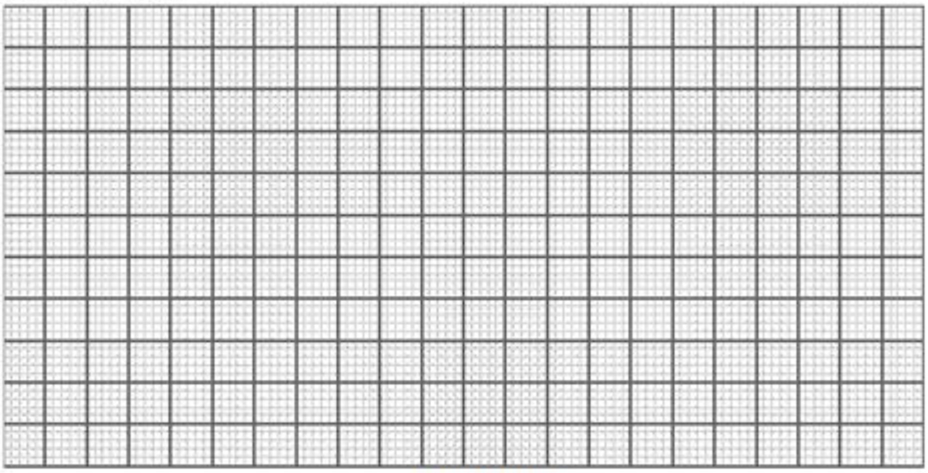
Graph 1

Half - Load



Graph 2

Full - Load



Graph 3

Conclusion

While we design the control system we should know the desired output of that system and the reaction of the system on loaded conditions. Also we should know how to minimize the transient time. In this experiment we observe when we increase the offset the input voltages increases and also the output voltages increases gradually. In the start the input voltage increases but the output corresponding to that voltage is increasing slowly but after a while the input and output voltages increase is approximately same.

TASK: Submit a separate report according to the format given in appendix C.

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Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

EXPERIMENT #3

Mathematical Modelling and Block Diagram Reduction of Systems using MATLAB

Objectives

1. To learn how to define a polynomial, to find roots of a polynomial, to multiply two polynomials and to evaluate a polynomial at a value of the independent variable.
2. To learn how to find the transfer function of a system and to compute the step response and impulse response of a system.
3. To learn how to compute the transfer function from the block diagram of a system.

Lab Equipment

- PC workstation
- Tool MATLAB

Theory

Dynamic Systems

These are the systems that change or evolve in time according to a fixed rule. For many physical systems, this rule can be stated as a set of first-order differential equations:

$$\boldsymbol{x}' = \frac{\boldsymbol{dx}}{\boldsymbol{dt}} = \boldsymbol{f}(\boldsymbol{x}(\boldsymbol{t}), \boldsymbol{t})$$

In the above equation, x(t) is the state vector, a set of variables representing the configuration of the system at time t. For instance in a simple mechanical mass-spring-damper system, the two state variables could be the position and velocity of the mass. U(t) is the vector of control inputs at time t, representing the externally applied "forces" on the system, and f is a possibly nonlinear function giving the time derivative (rate of change) of the state vector, dx/dt for a particular state, input, and time.

Mechanical Systems

Newton's laws of motion form the basis for analyzing mechanical systems. Newton’s second law, the below equation states that the sum of the forces acting on a body equals its mass times acceleration. Newton's third law, for our purposes, states that if two bodies are connected, then they experience the same magnitude force acting in opposite directions

$$\sum F = ma = md^2x/dt^2$$

Transfer Function Representation

LTI systems have the extremely important property that if the input to the system is sinusoidal, then the output will also be sinusoidal at the same frequency but in general with different magnitude and phase. These magnitude and phase differences as a function of frequency are known as the frequency response of the system.

The transfer function from input U(s) to output Y(s) is therefore:

$$G(s) = Y(s)/U(s) = b_m s^m + b_{m-1} s^{m-1} + \ldots\ldots + b_1 s + b_0 / a_n s^n + a_{n-1} s^{n-1} + \ldots\ldots + a_1 s + a_0$$

It is useful to factorize the numerator and denominator of the transfer function into the so called **zero-pole-gain** form.

$$G(s) = N(s)/U(s) = K\,(s-z_1)\,(s-z_2)\ldots\ldots(s-z_{m-1})\,(s-z_m)\;/\;(s-p_1)(s-p_2)\ldots\ldots(s-p_{n-1})(s-p_n)$$

The zeros of the transfer function, $z_{1\ldots\ldots}z_m$ are the roots of the numerator polynomial, i.e. the values of s such that N(s) = 0. The poles of the transfer function, $p_{1\ldots}p_2$ are the roots of the denominator polynomial, i.e. the values of s such that D(s) = 0. Poles may be complex valued (have both real and imaginary parts). The system Gain is $K = b_m/a_n$

Procedure

1. Figure 3.1 is a **MASS-SPRING-DAMPER SYSTEM**, having body of mass ‘M’. With the provided data, we have to create a mathematical model of the given system. Whereas Figure 3.2 shows the net forces acting on a body of mass ‘M’ in different directions.

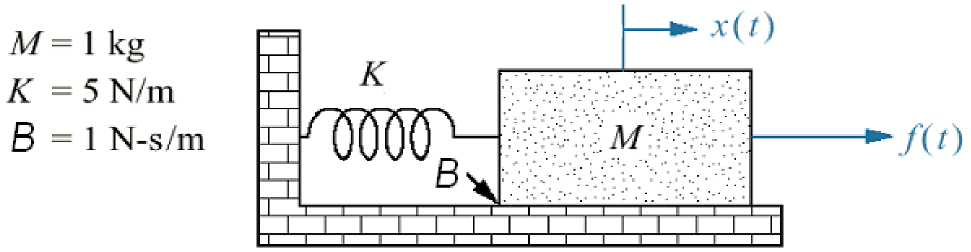

Figure 3.1: A Mass-Spring-Damper System.

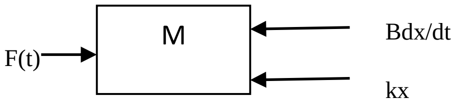

Figure 3.2: Net Forces Acting on ‘M’

$$\sum F = ma = mdx^2/dt^2$$

$$F-ma-bv-kx=0$$

$$ma+bv+kx=F$$

$$md^2x^/dt^2+bdx/dt+kx=F$$

$$mdx^2/dt^2+bdx/dt+kx=F$$

2. Verify that the transfer function of the system shown above is

   $G(s) = X(s)/F(s) = 1 / (Ms^2 + Bs + K) = 1 / (s^2 + s + 5)$

To perform the above step, we use MATLAB tool installed in the PC workstation of the lab. Initialize the variables used in the above equation in the command window of MATLAB and get the result of G(s).

3. The above mentioned transfer function can be defined using MATLAB as:

   (i) m = 1; k = 5; b = 1;

   (ii) num = [1]; den = [m b k];

   (iii) sys = tf (num, den);

   num and den must be defined before using the transfer function tf.

   This step involves evaluation of the transfer function of the given system. For this, we use MATLAB command ‘tf’ and then put the values of numerator ‘num’ and denominator ‘den’. Remember, that the values of ‘m’, ‘k’ and ‘b’ has to be initialized first as we did in step 1.

   What is the characteristic equation of the system?

4. Calculate the frequency of oscillations $\omega_d = \omega_n \sqrt{(1-\varsigma^2)}$ from the characteristic equation. Use hand calculator or calculate using MATLAB in the calculator mode.

   Hint: General form of equation is $s^2+2\ \omega_n \varsigma\ s +\omega_n{}^2= 0$

   In this step, simply initialize the variables used in this equation and put them back in the formula used.

ω_d = rad/sec. and f = Hz.

Step response:

1. Step response is the output of a system when step input is applied. In MATLAB, the step response can be plotted using step function as shown below.
   Step (sys);

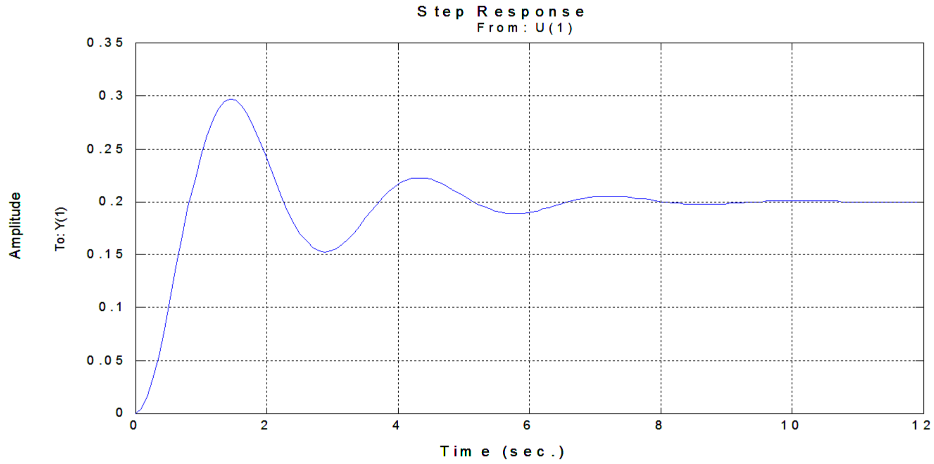

Figure 3.3 Step response of the system shown in Figure 3.1.

Step response is shown in Figure 3.3. Calculate the frequency of oscillations ω from the step response. It should be $\omega_n \sqrt{(1-\varsigma^2)}$ you calculated earlier.

The step response shown above terminates at 12s is generated as the MATLAB detects that the response is settled in a steady-state. The final time can be defined by the user as shown below where the step response is calculated for 20s.

2. Sketch the step response for the following three cases.

Case-1: Eliminate spring (k=0) while m=1 and b=1.

Case-2: Eliminate damping (b=0) while m=1 and k=5.

Case-3: Eliminate mass (m=0) while b=1 and k=5.

Label the step response in each case properly. You may use different line colors.

3. Calculate the natural *undamped* frequency ω_n, *damping ratio* ς, and the *frequency of oscillation* ω for each case as shown in the following Table 3.1.
   Table 3.1: Comparison Table.

	Eliminating Spring m=1; **k=0**; b=1;	Eliminating Damping m=1; k=5; **b=0**;	Eliminating Mass **m=0**; k=5; b=1;
ω_n			
ς			
ω_d			

Write your comments on the step response of each case.

Impulse response:

4. Sketch the impulse response for the following three cases.

Case-1: Eliminate spring (k=0) while m=1 and b=1.
Case-2: Eliminate damping (b=0) while m=1 and k=5.
Case-3: Eliminate mass (m=0) while b=1 and k=5

Label the impulse response in each case properly. You may use different line colors

Write your comments on the impulse response in each case.

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Block Diagram Reduction

1. Series Block Reduction:

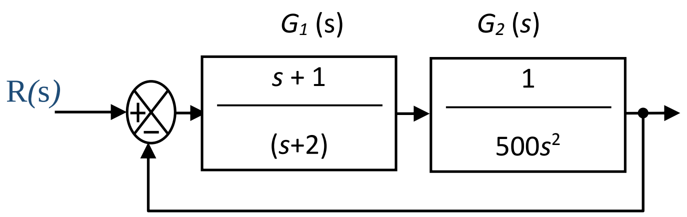

Figure 3.4: Series Blocks in Forward Path

The above (Figure 3.4) system have two transfer function G_1 (s) & G_2 (s) and they are connected in series with each other as shown in Figure 3.4 which has two blocks in series in the forward path. The feedback path has unity gain. Transfer function of such a system can be computed as:

(a) numc = [1 1] ; denc = [1 2] ; // initialzing denominator and nominator of block G_1 (s)

(b) numg = [1] ; deng = [500 0 0] ; // initializing denominator and nominator of block G_2 (s)

(c) [num1, den1] = series(numg, deng, numc, denc); // Multiplied G_1 (s) and G_2 (s)

(d) [num, den] = cloop(num1, den1) ; // cloop is closed loop

(e) sys = tf(num, den) ;// This command results a series-multiplied transfer function.

Derive the transfer function of the above system manually to verify the MATLAB generated transfer function.

2. Parallel Block Reduction

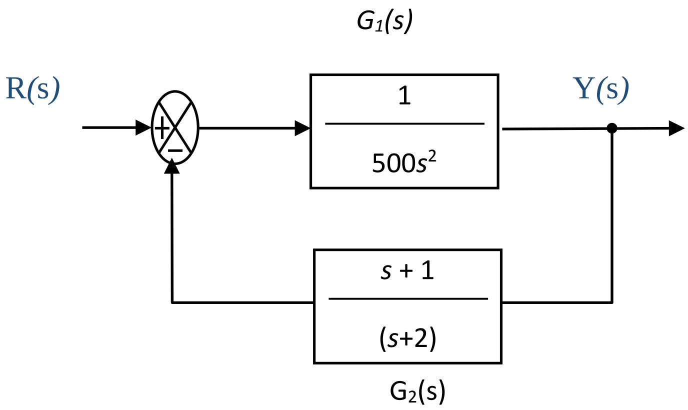

Figure 3.5: A non-unity Feedback System

The system shown in Figure 3.5 have two transfer function G_1 (s) & G_2 (s) and they are connected in parallel with each other as shown in Figure 3.5 which has two blocks in parallel. The feedback path doesn't have unity gain. Transfer function of such a system (Figure 3.5) can be computed as:

(a) numg = [1] ; deng = [500 0 0] ; // initializing block G1 variables

(b) numh = [1 1] ; denh = [1 2] ; // initializing block G2 variables

(c) [num, den] = feedback(numg, deng, numh, denh, -1) ; //feedback

(d) sys = tf(num, den) ; //This command results a parallel transfer function.

Derive the transfer function of the above system manually to verify the MATLAB generated transfer function.

Exercise

For the mechanical system shown in Fig 3.6,

(a) Write differential equation of the system.

(b) Write the transfer function. $G(s) =$

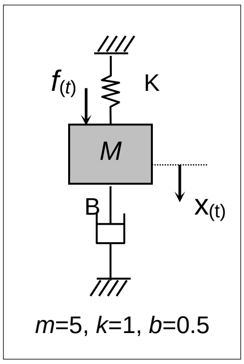

Fig 3.6

(c) Write MATLAB commands to determine the transfer function of the system and to sketch the impulse and step response.

Sketch the unit step response.

Answer the following questions.

(a) What is the settling time of the system?

(b) What are the roots of the characteristics equation?

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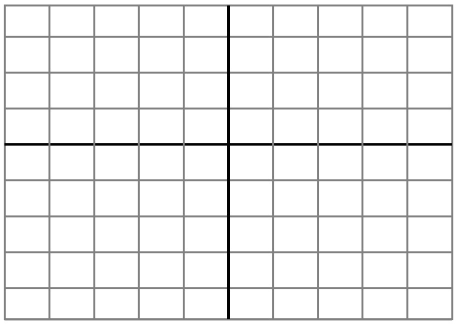
(c) Show the position of poles in *s*-plane.



s-plane

(d) What is relationship between the real part of the roots, time constant and settling time?

(e) What is relationship between the imaginary part of the roots and the frequency of oscillations of the step response?

Conclusion

TASK: Submit a separate report according to the format given in appendix C.

Registration Number------------------------------

Student Name------------------------------

Teacher Signature ------------------------------

EXPERIMENT #4

Design and Analysis of State Variable Models using MATLAB

Objectives

1. To learn how to covert the transfer function of a system into state variable representation and vice versa.
2. To learn how to simulate a system expressed in state variable form.

Theory

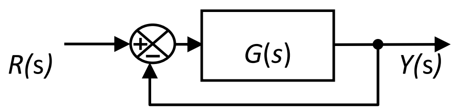
Lab equipment PC master Table Matlab
New MATLAB commands to learn in this experiment

MATLAB Command	Description
tf2ss	TF2SS Transfer function to state-space conversion. [A,B,C,D] = TF2SS(NUM,DEN) calculates the state-space representation:
ss2tf	SS2TF State-space to transfer function conversion. [NUM,DEN] = SS2TF(A,B,C,D,iu) calculates the transfer function:
Lsim	LSIM(SYS,U,T) plots the time response of the LTI model SYS to the input signal described by U and T. The time vector T consists of regularly spaced time samples and U is a matrix with as many columns as inputs and whose i-th row specifies the input value at time T(i).

Procedure

Section-1

- A feedback control system is shown Fig. 4.1.



$$Where\ \ G(s) = \frac{2(s+1)(s+3)}{s(s+2)(s+4)}$$

Figure 4.1: A unity feedback system

Determine the closed-loop transfer function $Y(s)/R(s) = G(s) / [1+G(s)]$.

$Y(s)/R(s) =$

Write Matlab commands to determine the closed-loop transfer using the numerator and denominator polynomials.

```
>>

>>

>>
```

- Transfer function to state-space conversion can be accomplished as

  [A, B, C, D] = tf2ss(num, den);

  where, num and den are the numerator and denominator of the closed-loop transfer function.

  The following command will print the state-space model.

  printsys(A, B, C, D);

  Matrices A, B, C and D can be printed by entering the matrix name.

  Write matrices of the state-space model returned by the Matlab.

  A = B =

  C = D =

- A system expressed in state-space can be converted to transfer function. Following statement is used to convert the state-space representation of a system discussed before into transfer function.

[num1, den1] = ss2tf(A, B, C, D);

Write the Verify that the num1 and den1 are the same as num and den used in the first step of this section.

num1 = den1 =

Section-2

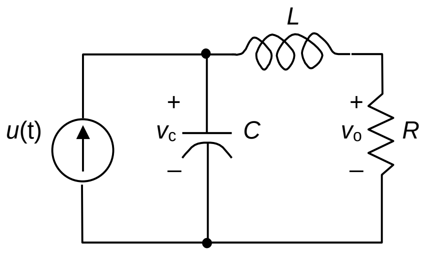
- ☐ Time response of a system represented in state-space can be computed by using function lsim. For this purpose, all four matrices (A, B, C, D) of a state-space model along with initial conditions, a time vector (range of time) and an input vector are required. RLC circuit shown Fig. 4.2. In this model, state variables x1 and x2 are the capacitor voltage and inductor current respectively and the output y is the resistor voltage.
  R = 3; L = 1; C = 0.5;

A = [0 –1/C; 1/L –R/L];

B = [1/C; 0];

C = [0 R];

D = [0];



An RLC circuit.

Fig. 4.2

x0 = [1 1]; % initial conditions.

t = [0:0.01:5]; % time range is 0 to 5 sec with an increment of 0.01 sec.

u = 0*t ; % zero input.

[y, x] = lsim(A, B, C, D, u, t, x0);

lsim function returns two parameters, output matrix y having one column and state variable matrix x having two columns. Use size(y) and size(x) to see the number of rows and columns in y and x.

Note: Number of rows in x and a y matrix is equal to the number of data points in time vector t.

- ☐ Use following commands to observe the time response of the system defined in previous step.

subplot(3, 1, 1); % divide the figure window into 3 rows and 1 column.

plot(t, x(:,1)); % plot the 1st state variable, column 1 of matrix x.

```
xlabel('time'); ylabel('x1');

subplot(3, 1, 2);

plot(t, x(:,2));                   % plot the 2nd state variable, column 1 of matrix x.

xlabel('time'); ylabel('x2');

subplot(3, 1, 3);

plot(t, y);             % plot the output state variable.

xlabel('time'); ylabel('output (y)');
```

Sketch the state variables x_1, x_2 and the output y. Label all the curves appropriately.

State variable x_1 vs time.

State variable x_2 vs time.

Output variable y vs time.

- Change the system parameters R, L and C in the circuit shown above to generate four types of time responses as shown in the following table. Also, show the values of R, L and C and position of poles for each type of response.

Case	Type of Response	System Parameters	Position of Poles
1	Overdamped	R = L = C =	
2	Critically Damped	R = L = C =	
3	Underdamped	R = L = C =	
4	Oscillatory	R = L = C =	

Sketch the output y (resistor voltage) for all four cases.

Case-1: Overdamped.

Case-2: Critically damped.

Case-3: Underdamped.

Case-4: Oscillatory.

Write your comments on this experiment.

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TASK: Submit a separate report according to the format given in appendix C.

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EXPERIMENT #5

Part (a): Time Response of the DC Motor---1st Order Model

Objectives:

1. In this experiment we are going to determine a model, which describes the change in output speed when the input voltage is changed.
2. The step response of the motor has to be measured.

Lab Equipment:

- MS15 Module
- AS3 Command Potentiometer
- Control Laboratory Input/output Interface (CLIO)
- Power Supply
- Connecting leads
- Virtual Control Laboratory (VCL) Software

Theory

There are two parts to any output time response when there is a change in input:

- **Transient period:**
  Transient response is important because it affects the speed of the system.
- **Steady state condition:**
  A steady state condition which is reached after the transient has died out. The system seems to have settled down to the influence of the input.

The elements within the plant which cannot respond instantly produce transient situation. Mass in a mechanical system and capacitance in an electrical system both store energy so it takes time to change the velocity of a mass or to change the voltage across the capacitor. The parts of the DC motor, like motor armature, disks, dials etc have mass and they need energy to move and stop. Actually, the energy needed is not due to the mass of these elements but due to inertia of the elements since these are all rotating bodies. In order to better the response of the system, terms like rise time, settling time, overshoot must be understood.

The First Order Lag:

The step response obtained is characteristic of a First Order Time lag. A first order lag produces an exponential rise to a step input. The two parameters that define the model are Gain and Time constant. Gain (k) is the Steady State relationship between input and output. Time Constant defines the Transient Time.

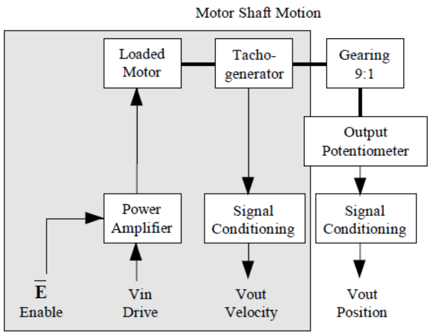

Figure 5.1: Block diagram of DC Motor

Figure 5.1 is the block diagram of DC motor. It consists of loaded motor, tachogenerator, gearing, power amplifier, signal conditioning, and potentiometer.

Table 5.1: VLC Software window

File	**Controller**	**Plant**		**Display**
CA06PE03	Open-loop	MS15 Analog		Graph
Signal Generator		**Graph**		
Signal	Step	1 Input	ON	
Level	60 %	2 Position	OFF	
Offset	0 %			
Rate	20 m sec	4 Velocity	ON	
Reference	Internal			
DC Motor Output Potentiometer			Disengage	
Brake	0		**Command Potentiometer**	
180^{o}				

Table 5.1 is the VLC software window which shows settings of different parameters like signal level, offset, rate and braking.

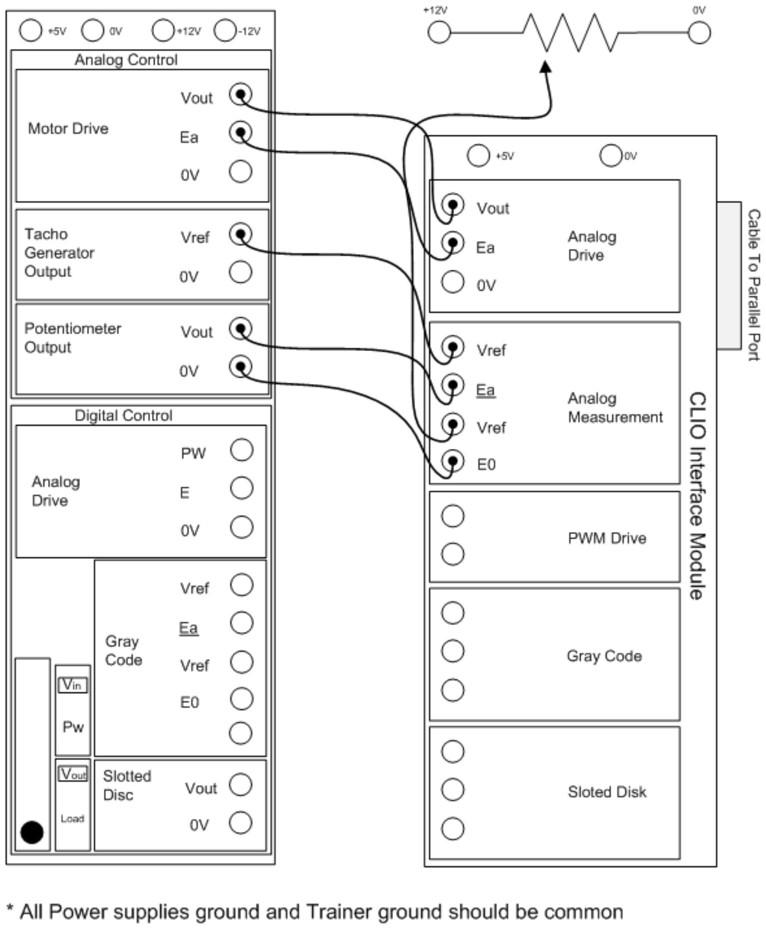

Figure 5.2: Wiring Diagram

Procedure:

1. The system should be wired with the standard analog system connections.
2. Start the VCL software and load setup CA06PE03.
3. According to the wiring diagram shown in Figure 5.2, make connections.
4. Do the VCL Software settings as shown in Table 5.1.
5. On MS15 trainer, disengage the output potentiometer then switch power ON and Enable the motor.
6. The output velocity trace (purple) on the PC shows what is called the Step Response.

Input Span:

Input span is the amount by which the input changes.

7. Select channel 1/Input/Dark Blue. The scale will show the input channel scale.

8. Select line A by clicking within the A box. The box and the line will change colour.
9. Click in the B box and, in the same way, position line B over the lower part of the dark blue trace.
10. The difference between A and B is the Input Span.
11. Input span = A1 – B1= ________

Output Span:

Output span is the amount by which the output changes in response to the input changes.

12. Change to channel 4/Velocity/purple and repeat the measurements on the purple trace.
13. Output span= A4 – B4 = +2.75 – (- 2.75) = ________

Gain:

Gain or magnitude ratio or Amplitude ratio, is the ratio between input and output when they have reached a steady state.

14. The spans have been measured when the output has reached a steady state.

15. Gain = output span/input span = (A4 – B4)/(A1 – B1) = ___________

Transient Response (Initial Slope Method)

16. Make sure that the lines A and B are the final and initial values of trace 4 respectively.
17. Click on the slope box. The line from the beginning of the transient sloping up to the right has changed to blue. This allows you to measure the initial slope of the velocity trace. The slope of the line can be changed by clicking in the graph area. The top of the line will move to the time at which you clicked.
18. Move the slope line until its slope is the same as that of the initial part of the transient such that the blue line covers the initial part of the purple velocity trace line.
19. Click on the Time box. The vertical time line is high lightened.
20. Click where the slope line crosses line A. The time shown is the Time Constant measured by the initial slope method.

Time constant = t_1 = ______

Settling Time Method:

The time constant can also be calculated from the time it takes the transient to reach the final value.

21. Move the Time Line to the time at which the velocity trace first reaches its final value. The time shown is 5 time constants from the start of the transient.

Time Constant = t_2 = __________

63 % Method:

Another time measurement is the time it takes for the transient to change by 63%.

22. From above, the output span = A4 – B4. The 63 % level is then,

B4 + 0.63(A4 – B4) = _________

23. Now click the Time Box and move the time line to the time at which the velocity trace reaches its 63% level. The time shown is the Time Constant measured by the 63% method.

Time Constant= t_3 = _________

24. Experience has shown that the 63% method is more accurate than the other two techniques so use t_3 as the time constant in your model.

Result:

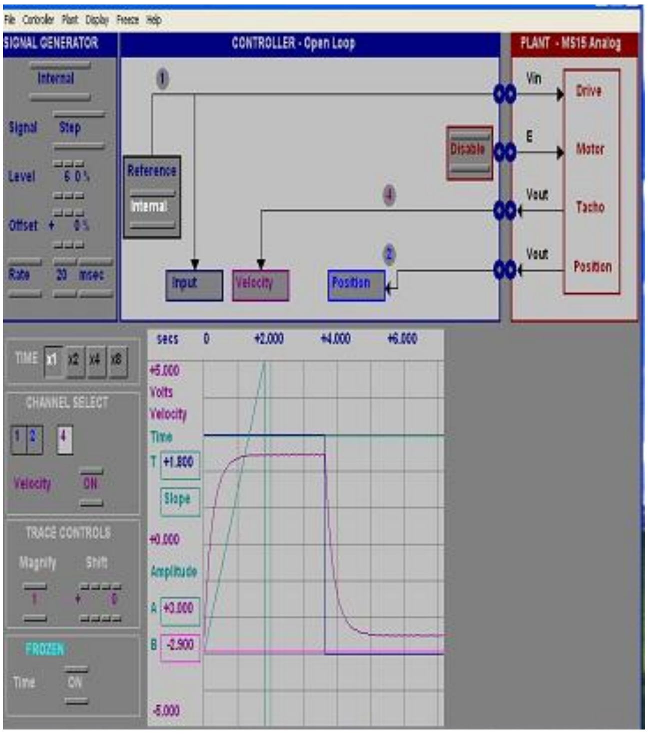

Figure 5.3: Step response

Step Response:

Input Span = A1 - B1 = =

Output Span = A4 - B4 = =

Gain= Output Span /Input Span = A4-B4/A1-B1 =

Time Constant t1 = seconds

Time Constant t2 = seconds

63% Method

From above, the output span = A4 - B4. The 63% level is then:

B4 + 0.63 (A4 - B4) = volts

Time Constant t3 = seconds

Table 5.2:

Plant gain kp	unit less
Time contant t	msec

Table: 5.3:

T1	T2	T3	Input span	Output span	Gain

From steps 20, 21and 23 put the values of t1, t2 and t3 in the Table 5.3.

Conclusion:

It is concluded that the open loop takes more time to settle but the closed loop takes less time to settle down. A device who have more time to settle down have more stability and have also more steady state error.

TASK: Submit a separate report according to the format given in appendix C.

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Part (b): Time Response of the DC Motor---2nd order Model

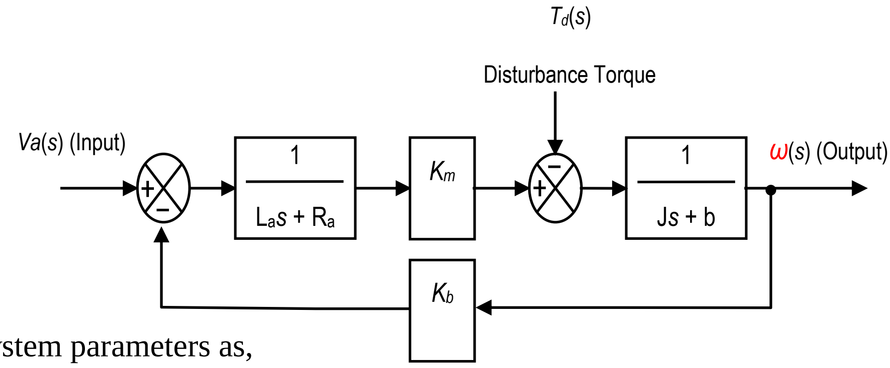
Objectives

1. To explore the steady-state error of a control system.
2. To explore the sensitivity of a control system.

Theory

Section-1

- An open-loop speed control of a separately excited DC motor is shown below,



with the system parameters as,

R_a	L_a	K_m	J	b	K_b
1	0.005	10	2	0.5	0.1

- For the open-loop speed control system of a dc motor (shown above), the transfer function $\omega(s)/T_d(s)$ with $T_d(s)=0$ using the given system parameters can be determined by using the following commands.

```
Ra = 1;  La = 0.005; Km = 10;  J = 2;  b = 0.5;  Kb = 0.1;

num1= [1];  den1=[La Ra] ; num2 = [Km]; den2 = [1] ; num3 = [1]; den3 = [J b] ;

sys1 = tf(num1, den1) ;

sys2 = tf(num2, den2) ;

sys3 = tf(num3, den3) ;

sys4 = series(sys1, sys2) ;

sys5 = series(sys4, sys3) ;

sys = feedback(sys5, Kb) ;
```

- ☐ Write sys1, sys2, sys3, sys4, sys5 and sys returned by the MATLAB and verify all these transfer functions manually.

sys1 = sys2 = sys3 =

sys4 = sys5 =

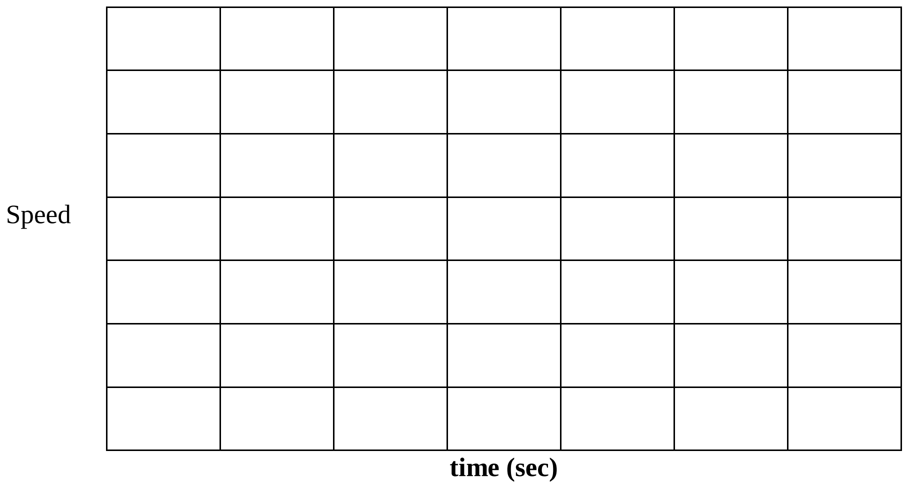
sys =

what is the following transfer function

$$G(s)\big|_{T_d=0} = \omega(s)/V_a(s) =$$

- ☐ Sketch the open-loop step Response. Label the speed and time axes properly.

Open-loop Step Response



- Determine the transfer $G(s)|_{Va=0} = \omega(s)/T_d(s)$ manually.

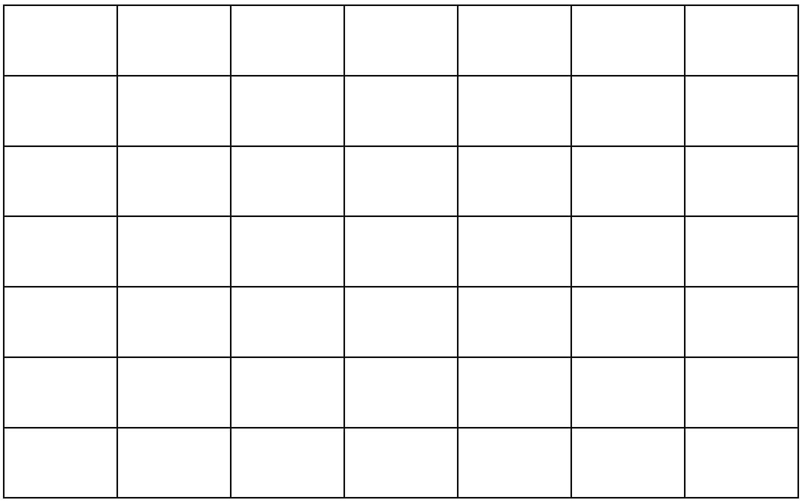
$G(s)|_{Va=0} = \omega(s)/T_d(s) =$

- Now write MATLAB commands to determine the above mentioned transfer function.

- ☐ Sketch the open-loop step Response. Label the speed and time axes properly.

Open-loop Disturbance Step Response

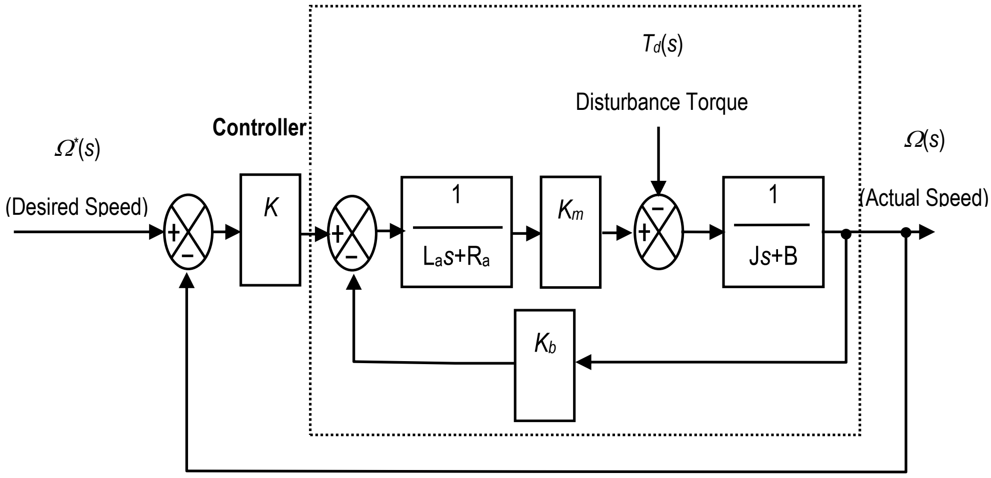
Speed



time (sec)

- ☐ Write your comments on the step response due to Va (Td=0) and due to Td (Va=0).

- A block diagram model of a closed-loop speed control of a DC motor with unity-feedback is shown below. A proportional controller with gain K is used in this system.



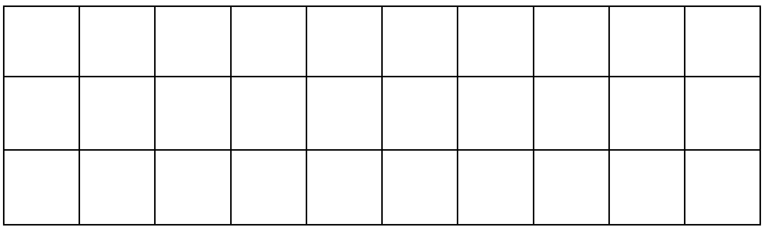
- Write the transfer function manually with $T_d(s)$=0.

$$T(s)\big|_{Td(s)=0} = \Omega^*(s)/\Omega(s) =$$

- Determine the step response for K=1 and K=20 and K=50 and sketch the step response in each case.

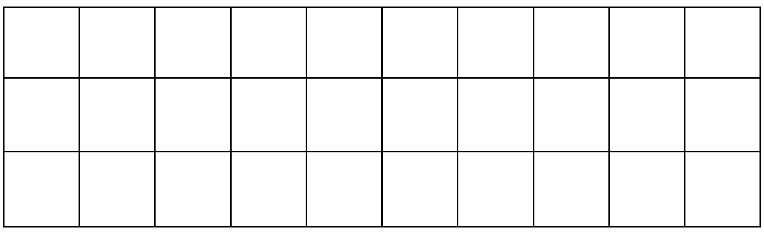
Step Response

$y(t)$ for K=1 when D(s)=0



time (sec)

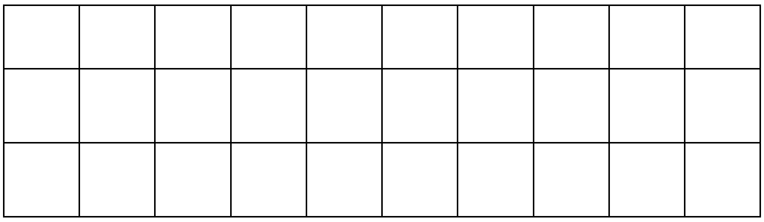
$y(t)$ for K=20 when D(s)=0



time (sec)

$y(t)$ for K=50

when D(s)=0



time (sec)

- ☐ Comment on the effect of *K* on the settling time and overshoots.

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Comment on the selection criterion of *K*.

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TASK: Submit a separate report according to the format given in appendix C.

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EXPERIMENT #6

Study the Behavior of 2^{nd} Order System using MS15 Module

Objectives:

1. To understand the behavior of 2^{nd} order system.
2. Damped and natural frequencies.
3. PID controllers.

Lab Equipment:

- MS15 Module
- AS3 Command Potentiometer
- Control Laboratory Input/output Interface (CLIO)
- Power Supply
- Connecting leads
- Virtual Control Laboratory (VCL) Software

Theory:

Second order system:

A second order system exhibits a wide range of responses that must be equally analyzed and described. Changes in the parameter of a second order system can change the form of the response.

PID Controller:

- A PID stands for Proportional Differentiator and Integrator.
- Differentiator is a sensitive controller. We use it to measure transients as it for sharp changes.
- Integrator is used for the elimination of the steady-state error.

Setting time T_S

The amount of time it takes for the system's oscillatory response to be damped to within a certain band of the steady-state value. That band is typically 2%.

Peak time T_P

The amount of time it takes for a system to reach its first peak.

Rise time T_R

The amount of time it takes for the step response of the system to reach within a certain range of the reference value. Typically, this range is 10%-90%.

Decay time

The amount of time it takes for the oscillations to die away.

Steady state error

At steady state, the amount by which the system output differs from the reference value.

Percent overshoot

The amount by which the step response overshoots the steady-state value, in percentage of the steady-state value.

Dead time

Time shift between the output change and the related effect. One sees "Lag" used for this action sometimes.

Damped and Natural Frequencies of Oscillation:

- The damped or damping frequency (ω_d) of oscillation is the frequency at which the system gives damped oscillations.
- Natural frequency (ω_n) of a second order system is the frequency of oscillation of the system without damping.

OVERSHOOT

Overshoot is when a signal or function exceeds its target or the amount by which a response goes beyond the steady state value before settling down.

Overshoot can be measured from the step response. It is the ratio:

$$\frac{peak\ output\ change - steady\ state\ output\ change}{steady\ state\ output\ change}$$

Damping factor

The term damping factor can also refer to the damping ratio in any damped oscillatory system. This factor indicates the amount of overshoot in a system. Damping Factor has the symbol ζ.

$0< \zeta <1$ Under damped – Decaying Oscillations

$\zeta=1$ Critically Damped – Just No Overshoot

$\zeta>1$ Over damped – System Sluggish

The objective of a control system design is often to achieve a fast response without any overshoot or with just a little overshoot. Systems are usually designed for ζ in the range 0.7 to 1.

Damping factor is measured by:

$$\zeta = \sqrt{\frac{1}{1+(\frac{\pi}{\ln(\text{overshoot ratio})})2}}$$

$$\textbf{Overshoot ratio} = e^{-\zeta\pi/\sqrt{1-\zeta^2}}$$

$$\textbf{\% overshoot} = 100 \times e^{-\zeta\pi/\sqrt{1-\zeta^2}}$$

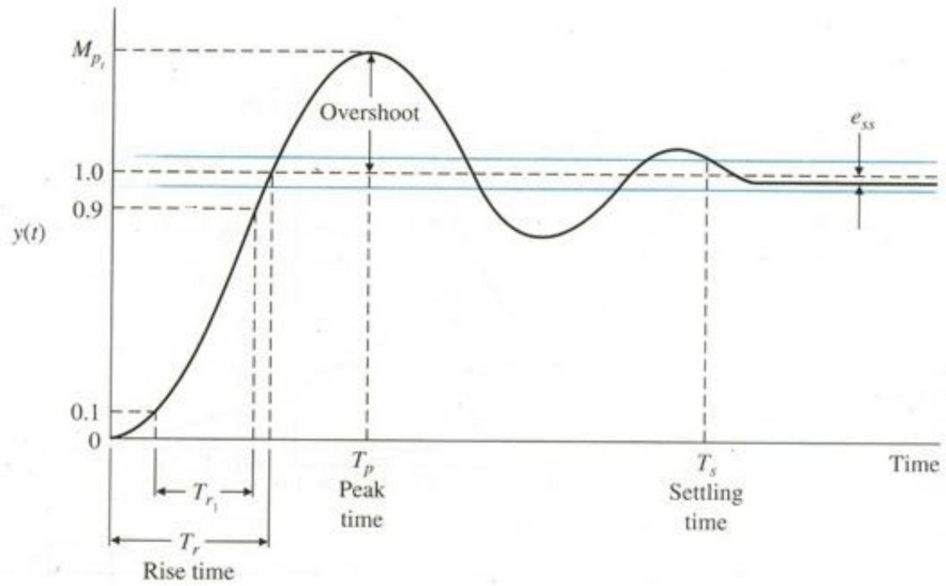

Figure 6.1:

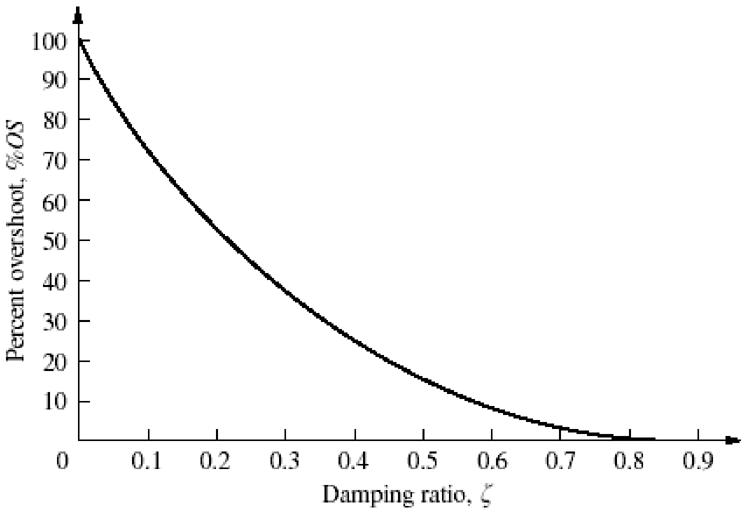

Figure 6.2:

Damping frequency oscillation

The frequency at which an under damped system oscillates is called the Damped Frequency ω_d. this can be measuring the time between successive positive peaks.

The inverse of the period of cycle is its frequency in Hertz:

$f_d = 1/T_d = 2\pi f_d = 2\pi/T_d$ where T_d is the period of the oscillation.

The time to the first peak, T_d is half the period. The damped frequency is measured by:

$\omega_d = \pi/T_d$

Natural frequency oscillation

If there is no damping then the system would continuously oscillate at a frequency which is called natural frequency of the system. The relationship between natural and damped frequencies is:

$$\omega_n = \frac{\omega d}{\sqrt{1-\zeta^2}}$$

$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

As gain is increases ω_d is increases, which means that increasing the gain makes the system work faster but at the expense is increasing the overshoot.

Relating ζ and ω_N to open loop parameters

Second order systems are characterized by their damping factor and natural frequency from which the overshoot and damped frequency can be obtained.

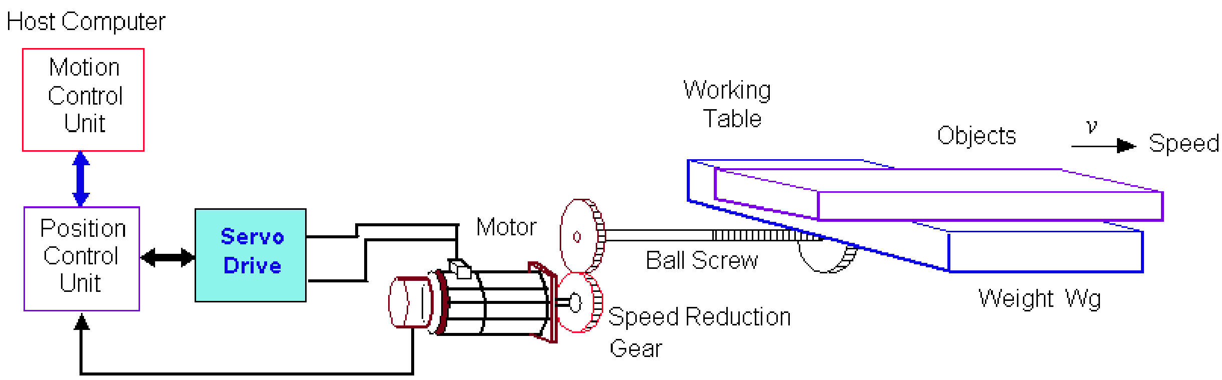

Figure 6.3:

To design a system we must know how ζ and ω_N are related to the plant parameters K_p, K_i and τ.

Two parameters describe the system is gain ($K_p \times K_i$) and time constant τ.

The time constant is inverse of cutoff frequency ω_c. The forward loop gain in servo motor is $K = K_p \times K_i \times K_c$

Damping factor

Analysis of system:

Damping factor $\zeta = \sqrt{\frac{\omega_c}{4K}}$

Critical damping is when ζ=1, this occur when K = $\frac{\omega c}{4}$

When K >$\frac{\omega c}{4}$, $\zeta < 1$ and the system is underdamped.

With K<$\frac{\omega c}{4}$, $\zeta > 1$ and the system is overdamped.

Natural frequency

Natural frequency is equal to $\omega_n = \sqrt{K\omega c}$

From above equation the natural frequency will be:

$$\omega_c = \sqrt{K\omega c(1-\zeta^2)}$$

Substituting equation

$$\omega_d = \sqrt{K\omega c - \frac{\omega_c^2}{4}}$$

Experimental check of these relationships

As we seen that increasing gain should increase the damped frequency and reduce the damping factor. But natural frequency and damping factor are not directly measureable so we measure overshoot and time to first peak.

Table 6.1: VLC Window Settings

File	**Controller**	**Plant**	**Display**
CA06PE07	Open-loop	MS15 Analog	Graph
Signal Generator		**Graph**	
Signal	Step	1 Input	ON
Level	30 %	2 Position	ON
Offset	0 %	3 Error	OFF
Rate	10 m sec	4 Velocity	OFF
Reference	Internal	5 Drive	ON
DC Motor Output Potentiometer		Engage	
Brake	0	**Command Potentiometer**	180°

Table 6.1 shows the VLC window settings which include signal, level, offset, rate and potentiometer settings.

Procedure Steps:

1. Connect the trainer in the desired form as shown in Figure 6.2.
2. Set the settings according to Fig 6.1.
3. Set the gain Kc to 1.5 and Kv to 0.
4. Switch on and when you see a complete graph has drawn on the screen, freeze the traces and enable the time markers.
5. Using the markers, measure the steady-state output change and the peak output change. This allows the overshoot to be calculated.
6. Obtain the damping factor.
7. Calculate the damping frequency and then the natural frequency.
8. Fill the table 6.2.
9. Using the model obtained in the previous experiments, calculate the expected values for damping factor and natural frequency with Kc=1.5, and enter the values into table 6.3 given below:

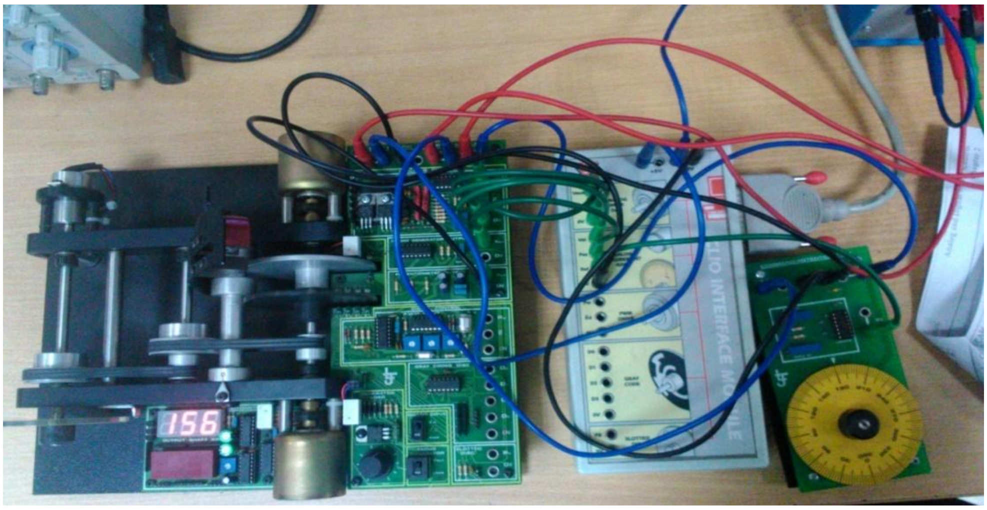

Figure 6.4: Experimental Setup

Results:

Table 6.2: Measurement of damping factor and natural frequency without controller

Gain K_c	overshoot	ζ	T_p seconds	ω_d rad/sec	ω_n rad/sec

Table 6.3: Calculated values for damping factor and natural frequency with controller

K_c	K_p	K_i	ω_c rad/sec	ζ	ω_n rad/sec

Conclusion:

We observed the waveform of a second order differential equation and observed its response. From the steady-state response we found the time response. Poles and zeros of a transfer function can be used to determine the time response of a control system. We also observed the natural and damping frequencies of the system.

TASK: Submit a separate report according to the format given in appendix C.

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EXPERIMENT #7

Part (a): Proportional Speed Control of DC Motor by Using AS4 PID Controller

Objectives:

- Introduction to AS4 PID Controller.
- Speed Control of DC Motor by using AS4 PID Controller.

Equipment:

- MS15 DC Motor Module
- AS3 Command Potentiometer
- AS4 PID controller
- Power Supply unit
- Signal Generator
- Digital Storage Oscilloscope
- CLIO Interference Module with PC Connection Lead
- System Power 90 Power Supply (or equivalent) 4mm Connection Leads

Theory:

A feedback loop is a common and powerful tool when designing a control system. Feedback loops take the system output into consideration, which enables the system to adjust its performance to meet a desired output response.

When talking about control systems it is important to keep in mind that engineers typically are given existing systems such as actuators, sensors, motors, and other devices with set parameters, and are asked to adjust the performance of those systems. In many cases, it may not be possible to open the system (the "plant") and adjust it from the inside: modifications need to be made external to the system to force the system response to act as desired. This is performed by adding controllers, compensators, and feedback structures to the system.

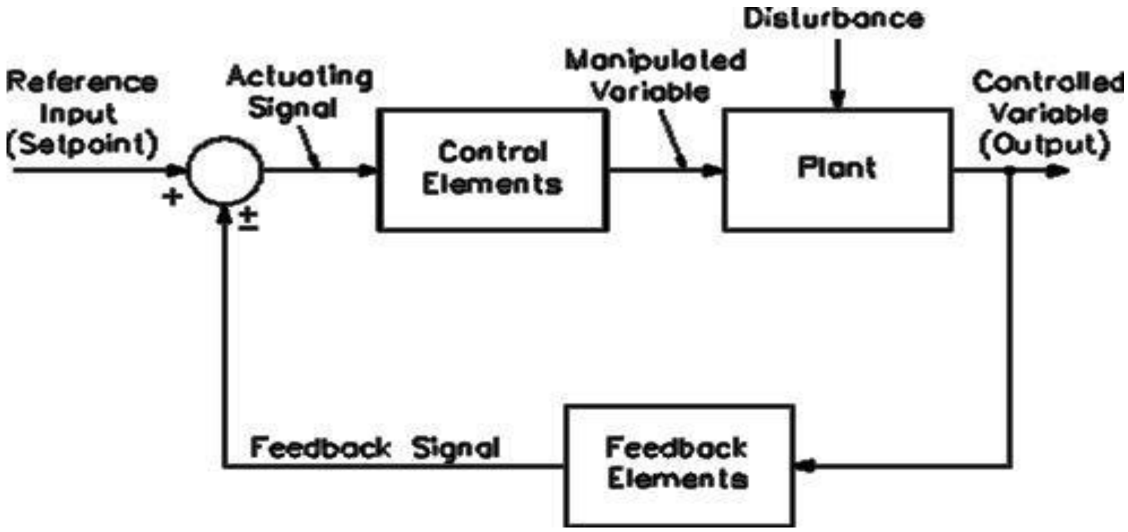


Figure 7.1: Feedback Control System Block Diagram

There is a variable whose value is to be controlled and a variable which represents the value of the output required. This output is passed back via a feedback block to be subtracted from the output to form error. The error is manipulated by the controller to provide the drive which is the signal which tells the plant what to do.

By measuring what the output is doing and feeding this back to be compared with the input, a closed loop feedback control system has been created.

Transfer function

To analyze a closed loop feedback system, we should have the knowledge about each element of the system.The term transfer function is used to describe the relationship between the input and the output of a block and usually represented by G.

$$\textbf{Transfer Function (G)} = \frac{\boldsymbol{Output}}{\boldsymbol{Input}}$$

$$\boldsymbol{Output = G \times Input}$$

Transfer function can be the equations in time or frequency. With the help of the transfer function we can find the output if input is known.

Transfer function in series

If the blocks described by the transfer function are connected in series then they will be multiplied to each other.as shown in figure:

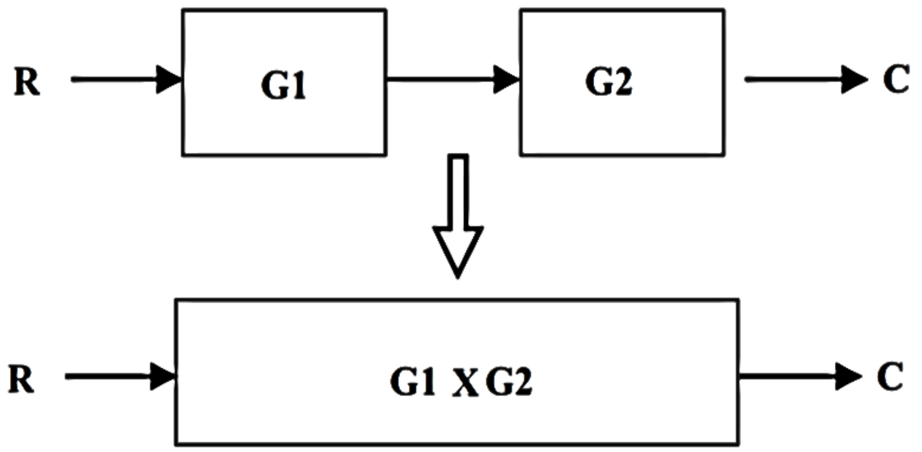


Figure 7.2: Transfer function block in series

Transfer function in parallel

If the blocks described by the transfer function are connected in parallel then they will be add up to each other.as shown in figure:

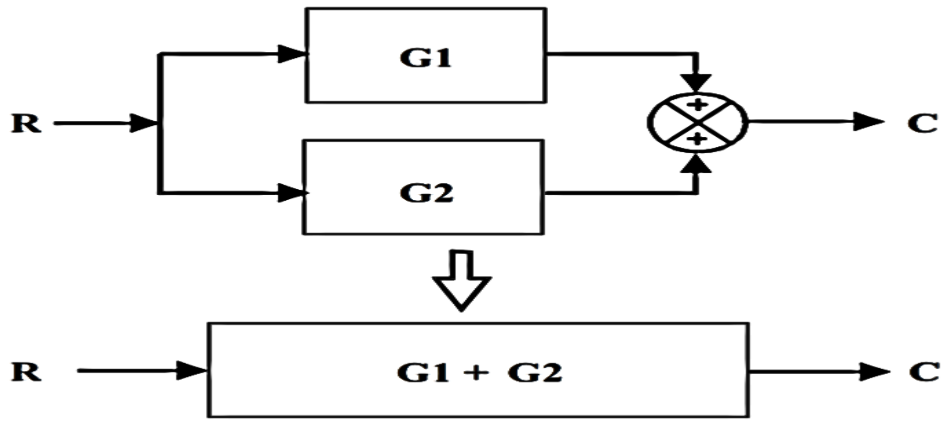


Figure 7.3: Transfer function blocks in parallel

Gain

A special term is used when the output is directly proportional to the input, such that there are no time constants involved.

Attenuation

The gain can be less than 1 it is called attenuation.

Closed loop transfer function

As shown in figure. Each block has a transfer function symbol. K is the transfer function of controller. G is the symbol of the plant. H is the symbol for the transfer function of feedback.

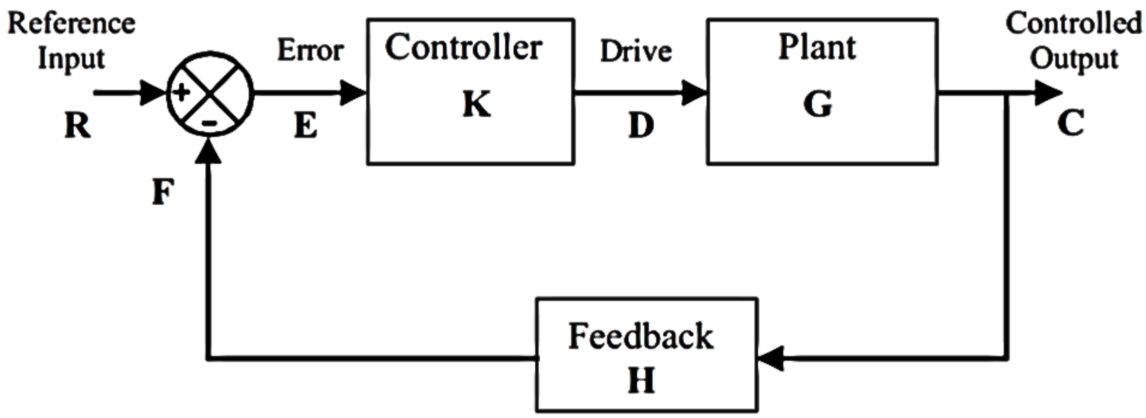


Figure 7.4:Block diagram of a General Control System

$$\text{Output(C)} = \text{K} * \text{G} * \text{Error (E)}$$

$$\text{C} = \text{K} * \text{G} * \text{E}$$

$$\text{Error (E)} = \text{Input(R)} - \text{H} * \text{Output(C)}$$

$$\text{E} = \text{R} - (\text{H} * \text{C})$$

$$\text{C} = \text{K} * \text{G} * \text{E} = \text{K} * \text{G} * [\text{R} - (\text{H} * \text{C})] = \text{K.G.R} - \text{K.G.H.C}$$

$$\text{Output(C)} = \frac{\text{K.G}}{1 + \text{K.G.H}} * \text{R}$$

$$\text{Transfer function} = \frac{\text{C}}{\text{R}} = \frac{\text{K.G}}{1 + \text{K.G.H}}$$

K.G is called the forward loop transfer function and K.G.H is called the open loop transfer function

$$\text{Closed Loop Transfer Function} = \frac{\text{Forward Loop Transfer Function}}{1 + \text{Open Loop Transfer Function}}$$

Error transfer function

The difference between the input and the output is called error.it is very important factor.

$$\frac{\text{E}}{\text{R}} = \frac{1}{1 + \text{K.G.H}}$$

Closed loop performance-steady state

The closed loop performance is described by the closed loop transfer function.

For steady state performance we do not need to consider the dynamic effects so each of the transfer function can be represented by its gain.

$$\frac{C}{R} = \frac{1}{\left(\frac{1}{K.G}\right) + H}$$

In most cases feedback is equal to 1, known as unity feedback

K is under our control so we could make K.G large.1/K.G will be less than 1 and this term can be ignored and output equal to input.

$$C = R$$

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

Part (b): Study and Analysis of Controllers (P, PD, PI, PID) using MATLAB/SIMULINK

Objective:

Study of Controllers.

Lab equipment

PC Matlab

Minimum required software packages: MATLAB, Simulink and the Control System Toolbox.

Theory

Points to remember:

Controller	Tr	%OS	Ts	SS Error
Kp	Decrease	Increase	Small change	Decrease
Kd	Small change	Decrease	Decrease	Small change
Ki	Decrease	Increase	Increase	Eliminate

Proportional Controller = Tr decreases, %OS increases

Derivative Controller = %OS decreases, Ts decreases but increase stability.

Integral Conroller = S.S Error eliminate but make transient response worse.

Goal for ideal response:

1. Tr decreases

2. %OS decreases

3. Steady state error (S.S error)=0

Step1: Without any controller.

Step2: With proportional controller.

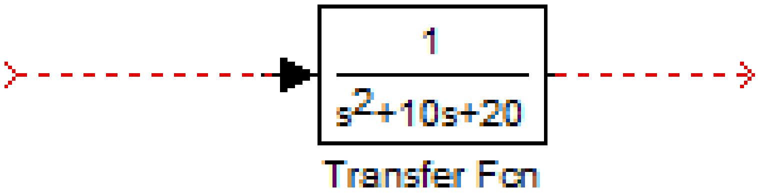
Step3: With proportional derivative controller.

Step4: With proportional Integral controller.

Step5: With proportional integral derivative controller.

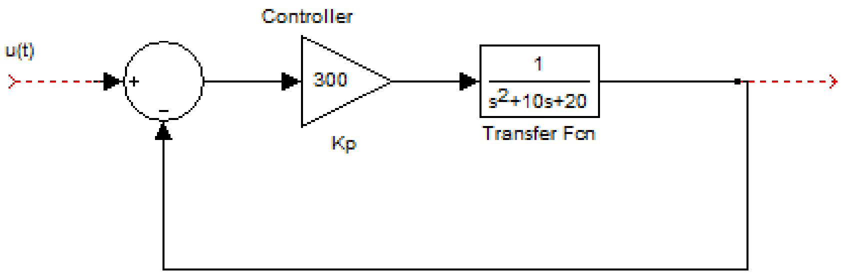
1. Given the transfer function implement it in matlab command window and note down the Tr, Ts and Steady state values in LTI view.

Tr	Ts	Steady state value



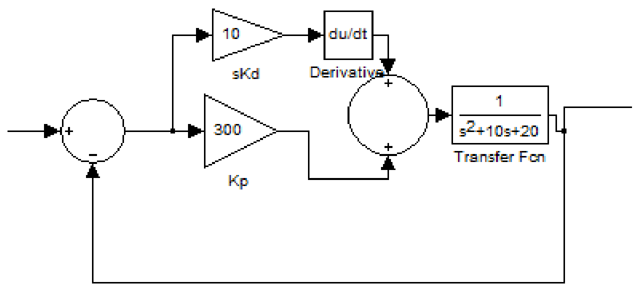
2. Given the transfer function by adding proportional controller in it, implement it in matlab command window and note down the Tr, Ts and Steady state values in LTI view.

Tr	Ts	Steady state value



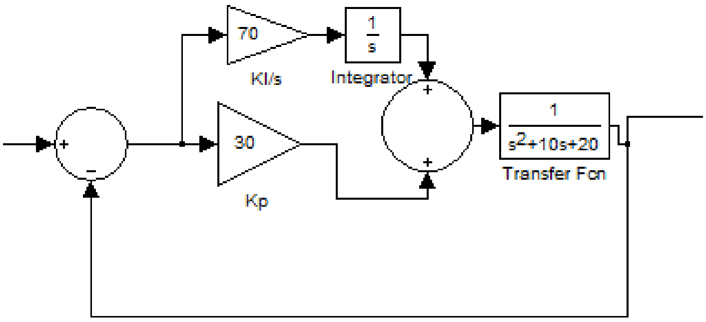
3. Given the transfer function by adding proportional derivative controller in it, implement it in matlab command window and note down the Tr, Ts and Steady state values in LTI view.

Tr	Ts	Steady state value



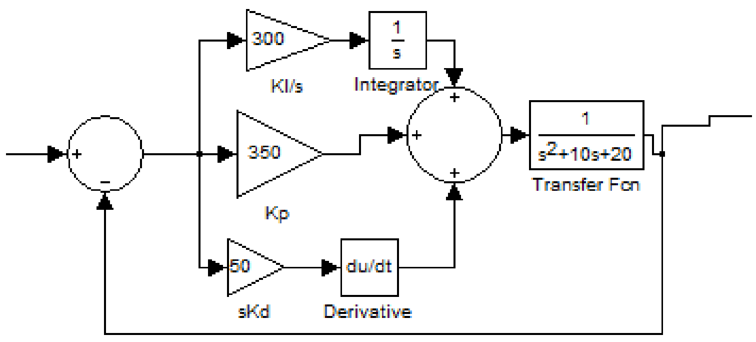
4. Given the transfer function by adding proportional integral controller in it, implement it in matlab command window and note down the Tr, Ts and Steady state values in LTI view.

Tr	Ts	Steady state value



5. Given the transfer function by adding proportional integral derivative controller in it,implement it in matlab command window and note down the Tr, Ts and Steady state values in LTIview.

Tr	Ts	Steady state value



Now compare your results with and without adding controllers in your system and compare the values to achieve the ideal goal.

Controllers	Tr	%OS	Ts	SS Error
Ideal				
Kp				
Kd				
Ki				
Kpid				

What kind of controller you add in your system to achieve best possible ideal goal?

_ _

_ _

Assignment: Consider a block diagram model of a closed-loop speed control of a DC motor with unity-feedback in experiment no.2,Check the response without any controller with disturbance=0. Design the controller for the system to achieve the Overshoot minimum, rise time minimum and zero steady state error by considering the output response achieving without controller.

TASK: Submit a separate report according to the format given in appendix C.

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EXPERIMENT #8

Principles of Feedback

(Proportional Speed Control of DC Motor)

Objectives:

1. To understand the feedback and concepts of different transfer functions.
2. To understand concepts of gain and attenuation.
3. Closed loop response and frequency response.

Lab Equipment:

- MS15 Module
- AS3 Command Potentiometer
- Control Laboratory Input/output Interface (CLIO)
- Power Supply
- Connecting leads
- Virtual Control Laboratory (VCL) Software

Theory

Introduction to Feedback

A feedback loop is a common and powerful tool when designing a control system. Feedback loops take the system output into consideration, which enables the system to adjust its performance to meet a desired output response.

Closed loop transfer function

As shown in Figure 8.1, each block has a transfer function symbol. K is the transfer function of controller. G is the symbol of the plant. H is the symbol for the transfer function of feedback.

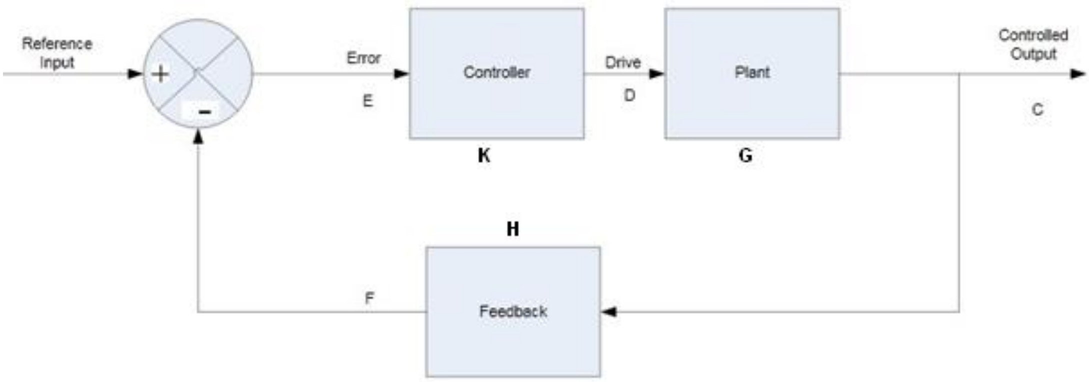


Figure 8.1: Closed loop Transfer Fuction

$$\text{Output}(C) = K * G * \text{Error (E)}$$

$$C = K * G * E$$

$$\text{Error (E)} = \text{Input}(R) - H * \text{Output}(C)$$

$$E = R - (H * C)$$

$$C = K * G * E = K * G * [R - (H * C)] = K.G.R - K.G.H.C$$

$$\text{Output}(C) = \frac{K.G}{1 + K.G.H} * R$$

$$\text{Transfer function} = \frac{C}{R} = \frac{K.G}{1 + K.G.H}$$

K.G is called the forward loop transfer function and K.G.H is called the open loop transfer function

$$\text{Closed Loop Transfer Function} = \frac{\text{Forward Loop Transfer Function}}{1 + \text{Open Loop Transfer Function}}$$

Gain

A special term is used when the output is directly proportional to the input, such that there are no time constants involved.

Error transfer function

The difference between the input and the output is called error.it is very important factor.

$$\frac{E}{R} = \frac{1}{1 + K.G.H}$$

Closed loop performance-steady state

The closed loop performance is described by the closed loop transfer function.

For steady state performance we do not need to consider the dynamic effects so each of the transfer function can be represented by its gain.

$$\frac{\mathrm{C}}{\mathrm{R}} = \frac{1}{\left(\frac{1}{\mathrm{K.G}}\right) + \mathrm{H}}$$

In most cases feedback is equal to 1, known as unity feedback

K is under our control so we could make K.G large.1/K.G will be less than 1 and this term can be ignored and output equal to input.

$$C = R$$

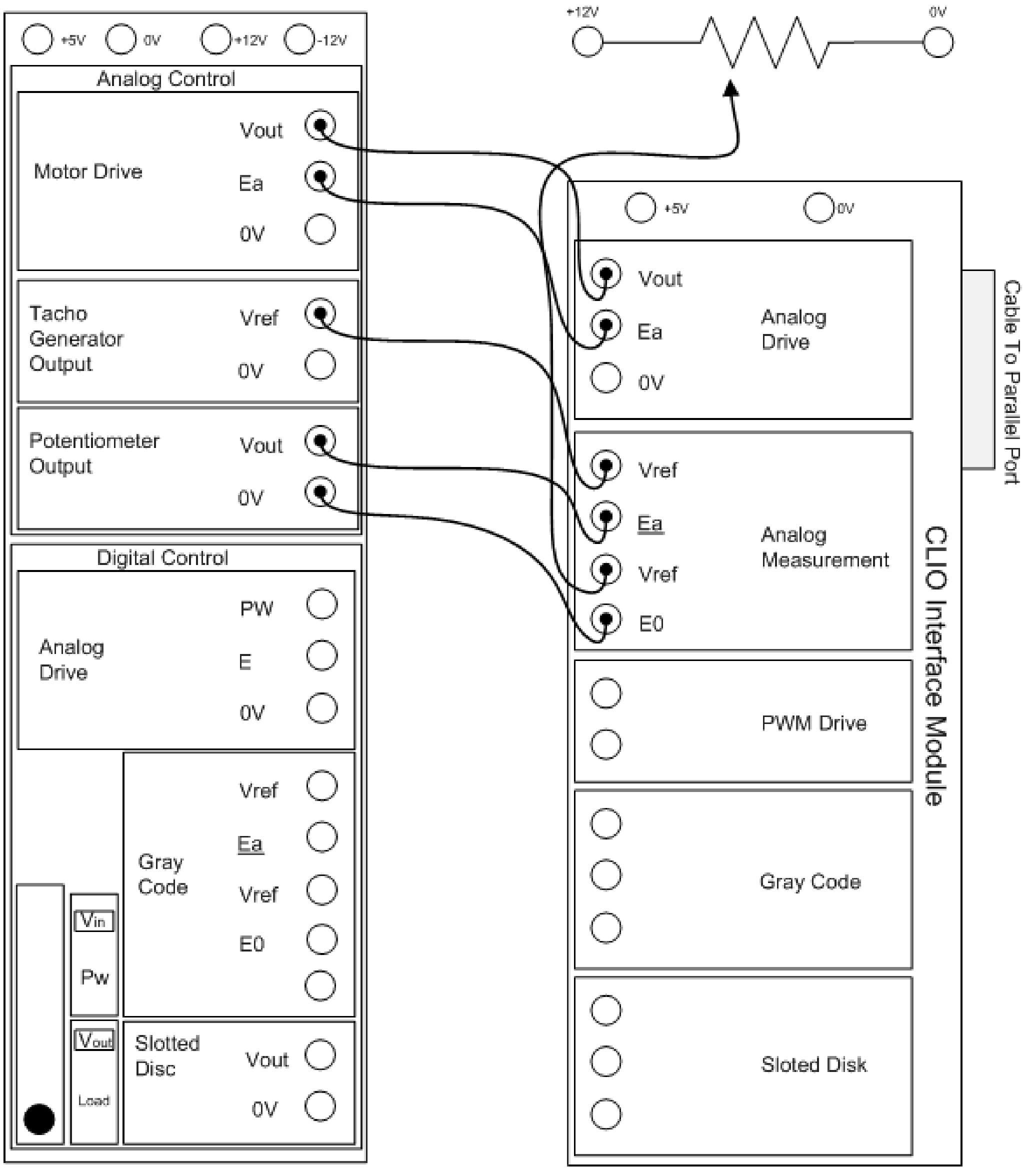
Difficulties of increased gain

- Transient response will be effected
- Noise will be added

Procedure Steps:

Following are the steps to perform this experiment with offset 50 %.

1) File CA06PE05 is uploaded from the folder
2) Controller should be PROPORTIONAL.
3) Make the connections as shown in wiring diagram.
4) DC input is applied 0% level
5) Offset should be 50percent
6) Rate 10 msec.
7) Reference should be internal
8) DC motor brake zero position
9) On graph Input, Velocity, Position and Drive should be on Output potentiometer should be disengaged.
10) Command potentiometer is at 180^{o}.
11) Increase the value of K from 1 to onwards and check the velocity in table 8.2.



* All Power supplies ground and Trainer ground should be common

Figure 8.2: Wiring Diagram

13) Draw the measurements graphically in graph 8.1.

Table 8.1: VLC Software Window

File **CA06PE05**	**Controller** **Proportional**	**Plant** **MS 15 Analog**	**Display** **Graph**
Signal **Generator** **Signal** **Level** **Offset** **Rate**	 DC-Level 0% 50% 10 msecs	**Graph** 1 Input 2 Position 4 Velocity 5 Drive	 ON ON ON ON
Reference	Internal		
DC Motor **Brake**	 0	Output potentiometer Command Potentiometer	Disengage 180^{o}

The table 8.1 is the VLC software window which shows settings of different parameters like signal level, offset, rate and braking.

Now closed loop transfer function becomes

$$\text{Closed loop TF} = \frac{\text{C}}{\text{R}} = \frac{\text{K. Kp}}{1} = \text{K. Kp}$$

And the error response is $\frac{\text{E}}{\text{R}} = \frac{1}{1+\text{K.Kp}}$

Measurements and Calculations:

Table 8.2:

Gain K	Velocity Volts	C/R	C/R Theory	Error Volts	E/R	E/R Theory
1						
2						
5						
10						
20						
50						
100						

- Disable the motor.
- Steady state error decreases as loop gain increases.
- Noise increases as gain increases.

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

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EXPERIMENT #9

Part (a): Control of DC Motor Module by using Proportional Position Controller

Objectives:

1. Account for the excellent steady-state performance of a proportional servo position system.
2. Account for the poor transient performance of a proportional servo position system.

Equipment:

- MS15 DC motor module.
- AS3 command potentiometer.
- CLIO Interface module with PC connection lead.
- System power 90 power supply.
- 4mm connection leads.
- PC running VLC virtual control laboratory software

Theory

Position control using DC motor is one of the major applications of control. Many of the control solutions were developed for this type of problem mainly to do with the aiming of artillery weapons by the military.

There are many more peaceful applications for this type of control. The DC motor is also called a servo motor and this branch of control is called servomechanisms.

In its simplest type of application, the artillery operator turns one dial to rotate the weapon barrel to point at the required horizontal direction and another dial to elevate the barrel to point at the required vertical angle to the horizon. When the weapon on target as quickly as possible. The Sketch of Simple Servo Motor is given in Figure 9.1 and Figure 9.2 gives an idea about respective feedback controller for complete understanding of whole closed loop system.

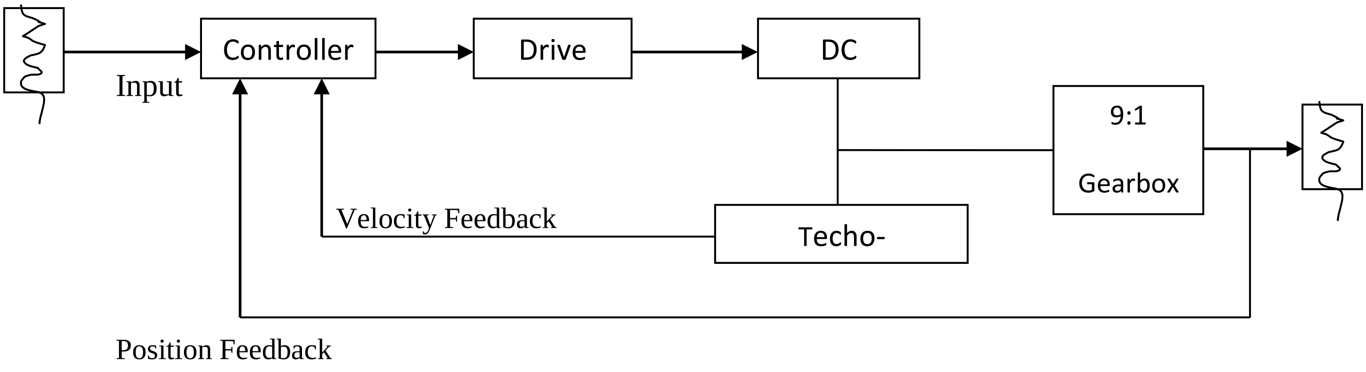


Figure 9.1: Sketch of Simple Servo Motor

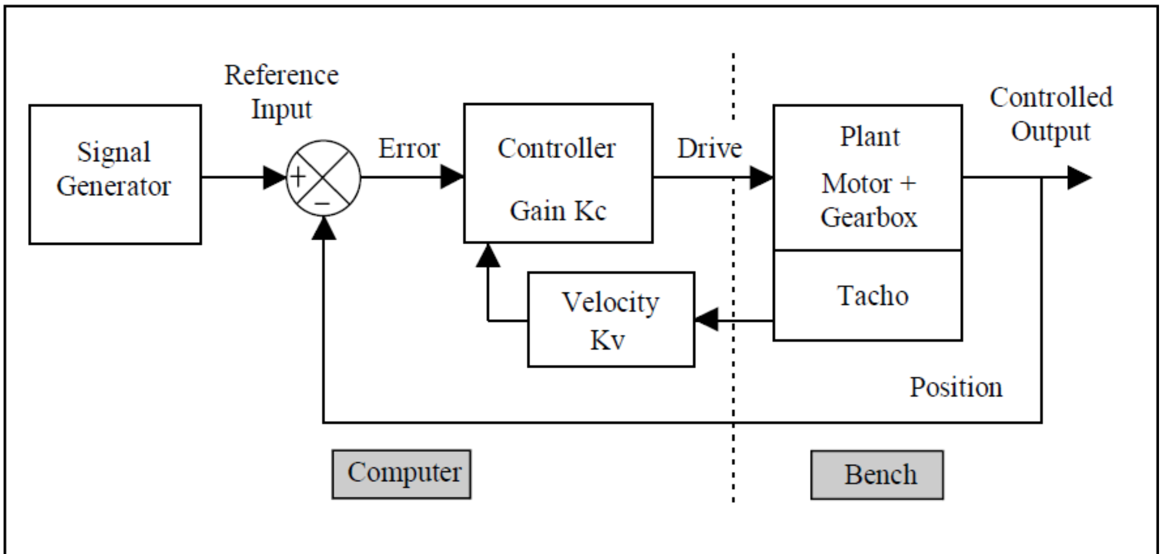


Fig 6.2 Block Diagram of a Servo System

Figure 9.2: Block Diagram of Servo Mechanism

Procedure Steps:

We will investigate the behavior of a position control system with proportional control.

1. Start VCL software and Load setup CA06PE07.

2. Check that controller gain Kc is set to 0.8 and VFB is OFF.

3. The additional feedback control box labeled VFB is not acting during this investigation. Make sure that the output potentiometer is engaged then switch power ON.

4. Rotate the command potentiometer between 30 degree and 300 degree and watch the output dial follow, albeit rather sluggishly.

5. Increases Kc to 5 and turn the input dial again.

6. This time the output dial moves much faster but wobbles (oscillate) around before it settles to a steady value. Somewhere between these two gains there may be an optimum setting.

7. You can see the behavior of system on the screen. Trace1 (dark blue) is the input position and trace 2 (blue) is the output position. The other three traces Error, Velocity, Driver are available for other parts of the exercise but are currently OFF.

8. Set Kc = 2.5 and compare the input and output traces once the transient has died away. You will see that are indistinguishable. Even with this low gain, the steady-state conditions have been met.

Table 9.1: VCL Software Settings

FILE (CA06PE07)	**Controller SERVO**	**Plant (MS15) analog**	**Display graph**
Signal generator Signal Level Offset Rate Reference	 STEP 20% 0% 10 msec External	Graph 1 input ON 2 position ON 4 velocity OFF 3 Error OFF	 5 Drive ON
DC MotorOutput potentiometer **Brake**	Engage 0	 command potentiometer	 180 degree

Steady-state Behavior:

The steady-state transfer function for a unity feedback system would be:

$$(C/R) = (K.G)/(1+ (K.G)) = 1/ ((1/K.G) +1)$$

A high gain is required to give a closed loop transfer function of 1. But, from the observation just made, it would appear that (C/R) = 1 with a low value of gain Kc. Why is this so???

The answer lies in the integration effect between velocity and position. At any steady velocity, after an infinite time you will have travelled an infinite distance so we can say that the steady state gain of an integrator is infinite.

The effect of the integral can be looked at another way. Any position error will drive the motor. The feedback ensures that the motor will be driven to reduce that error. The motor will stop turning when there is no error.

This can be explained diagrammatically. Examine Fig 9.3. When the error, and hence velocity is a steady value the position will be a ramp ignoring the transient lag effects of the motor. Position is the integral of velocity, or in other words the sum of all the velocities over a time.

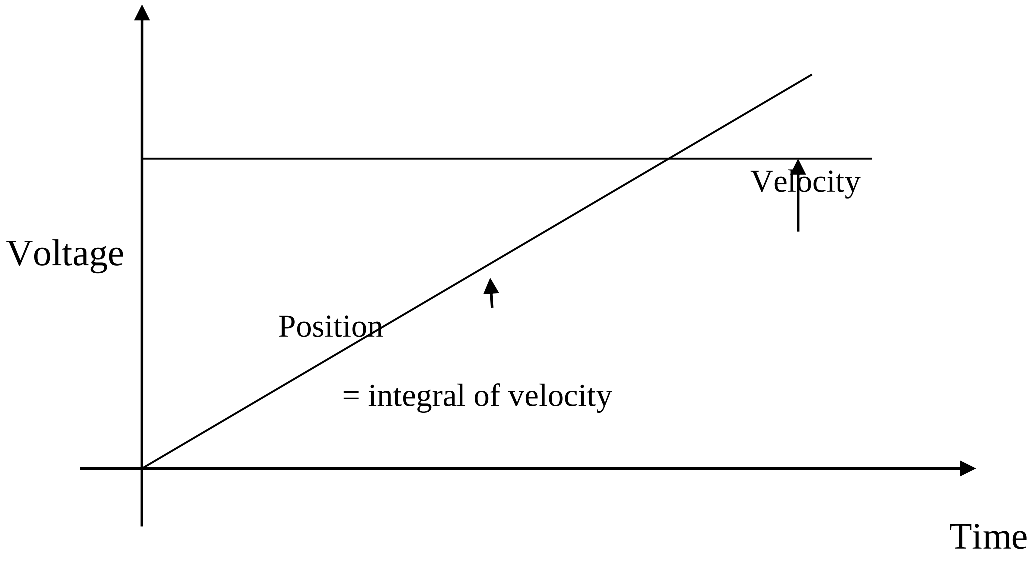


Figure 9.3: Signals within the System

You can see what happens to the motor if you look at little time slices of the signal. This is shown in Fig 9.4 When the step is applied, there is large error so the motor runs at high speed and the position ramps up quickly. At the end of the 1st period, the output has moved towards the input, so the error is reduced and the motor now runs slowly. The position also changes more slowly. At the end of each period the motor is running more slowly. At the end of each period, the motor is running more slowly and the position is changing more slowly but it will eventually get to where we cannot distinguish the output position from the input position.

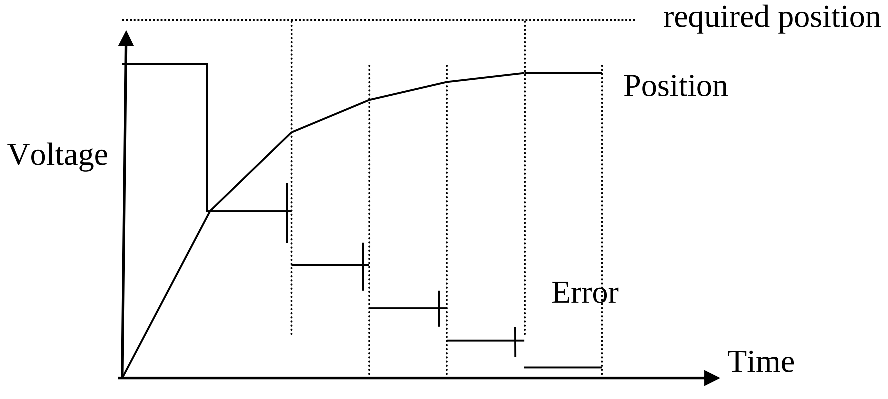


Figure 9.4: position response to a Step

Transient Behavior:

Compared with the speed control system, having the additional integration effect between velocity and position eliminates the steady-state error. However, the integration does create problems with the transient behavior.

Increase Kc to 3 and you will see the problem. Although the steady-state value is reached, eventually there is a lot of trouble getting there. If you were on the lift and it oscillated like this, you would not be very pleased.

We could just leave the gain at 0.8 but this would not give the speediest response.

In Fig 9.4, the effects of the motor lag were ignored. This is adequate at low gain but not when the gain is increased. Including the lag effect gives signals as in Fig 9.5.

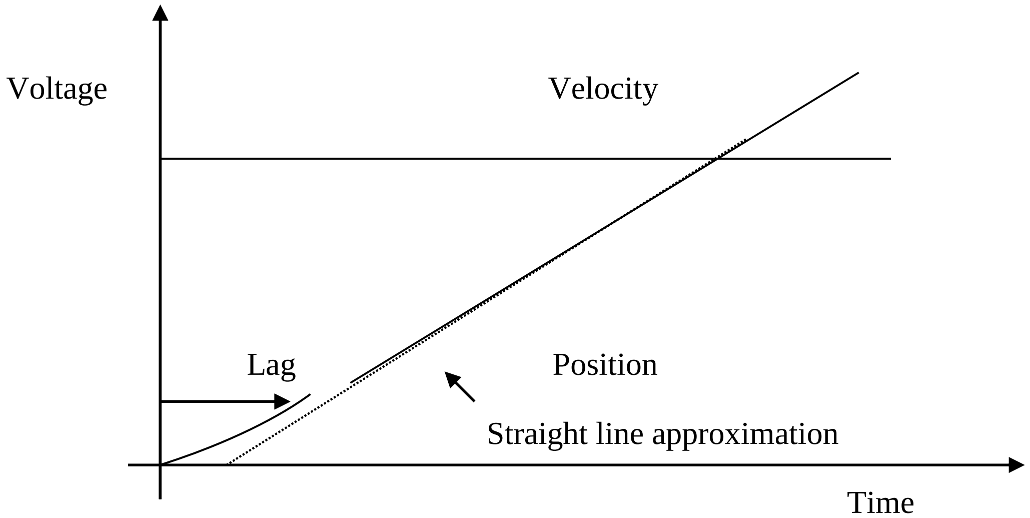


Figure 9.5: Signals within the system including the effect of motor lag

When the step is applied, there is a delay before the motor reaches the speed demanded. This causes the position to lag behind the ideal signal. If this lag is added to the linear approximation, the response shown in Fig 9.6.

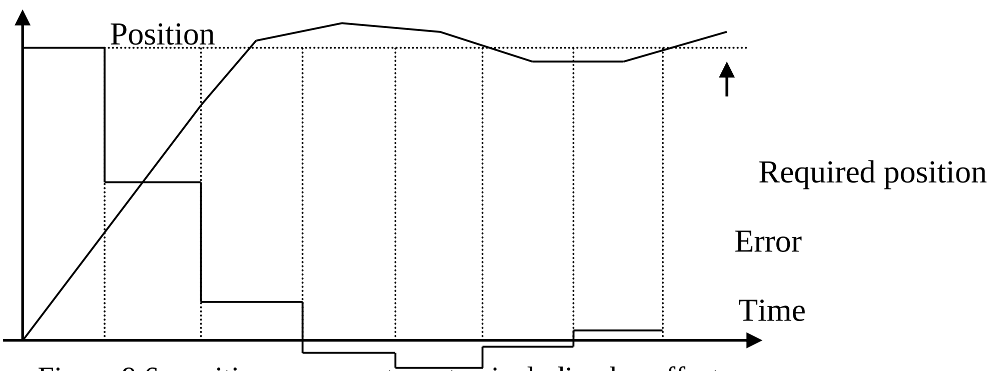


Figure 9.6: position response to a step including lag effect

Within the time slice, the change in position is lagging behind the signal driving the velocity. When the error signal reaches zero telling the motor to stop, the motor runs on beyond the required position owing to its inertial lag.

The motor than has to be reversed to allow the position potentiometer to reach the required position. The lag tends to make the system less stable.

The servo system with only proportional control can give an adequate response but with only one control, a system can be designed for a particular speed of response or for a particular degree of oscillation.

Conclusion:

Position control adds an integration effect into the system. This give excellent steady-state performance but the gain setting can give a variety of transient responses ranging from the sluggish to the oscillatory depending on the load. An understanding of the oscillatory performance is required before ways of increasing the speed of response without causing oscillations can be introduced.

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

Part (b): Position Control of DC Motor Module with Velocity Feedback

Objectives:

- The concept of velocity feedback by using AS4 module.
- Transient velocity feedback of DC motor by using AS4 PID controller.

Equipment:

- MS15 DC Motor control module
- AS3 Command Potentiometer
- AS4 PID Controller
- CS1 Set of $36 \times 4mm$ leads
- Power supply unit
- Digital Storage Oscilloscope
- Function Generator

Theory:

Velocity feedback is to be introduced as a potential solution to the unresolvable situation but the proportional gain affects both the damping ratio and natural frequency. Natural frequency is not a function of damping but by increasing ω_n, damping ratio falls and the system cannot stop instantly.

This shows that zeta will rise first order time lag is reduced. Thus, a velocity signal is used to form a closed loop speed control mechanism inside the position loop with a view to reducing the time lag occurring in the forward path.

If there is insufficient feedback in the inner loop the oscillation associated with the given proportional gain will persist. Excessive feedback will reduce the steady state gain of inner loop and increase in Kp to overcome it.

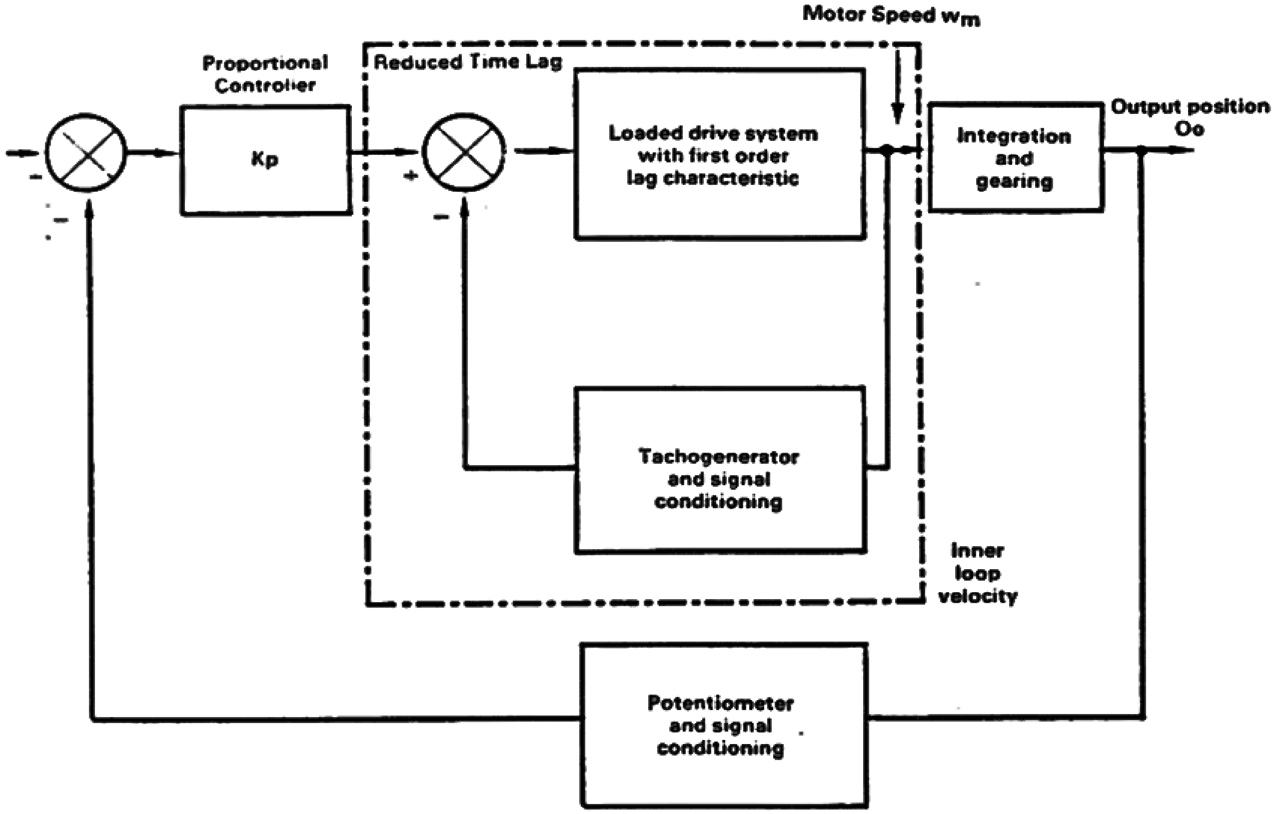


Figure 9.7: Position control with velocity feedback

To achieve the system shown in figure 9.7 the tachogenerator output is amplified using the auxiliary amplifier then fed into the inner loop error detector.

The system in figure 9.8 removes the steady state component of velocity feedback. To do this high pass filter is inserted in the velocity loop. High pass filter shown in figure 9.9. As the frequency in transient oscillations is very low the RC values will have to be very high. The output voltage is dependent on current through the the resister and the same current depends on rate of change of voltage thus, the filter generates a derivative. For this reason the system is known as *acceleration feedback*.

On AS4 PID Controller a capacitor is provided that should be connected to the input of auxiliary amplifier.

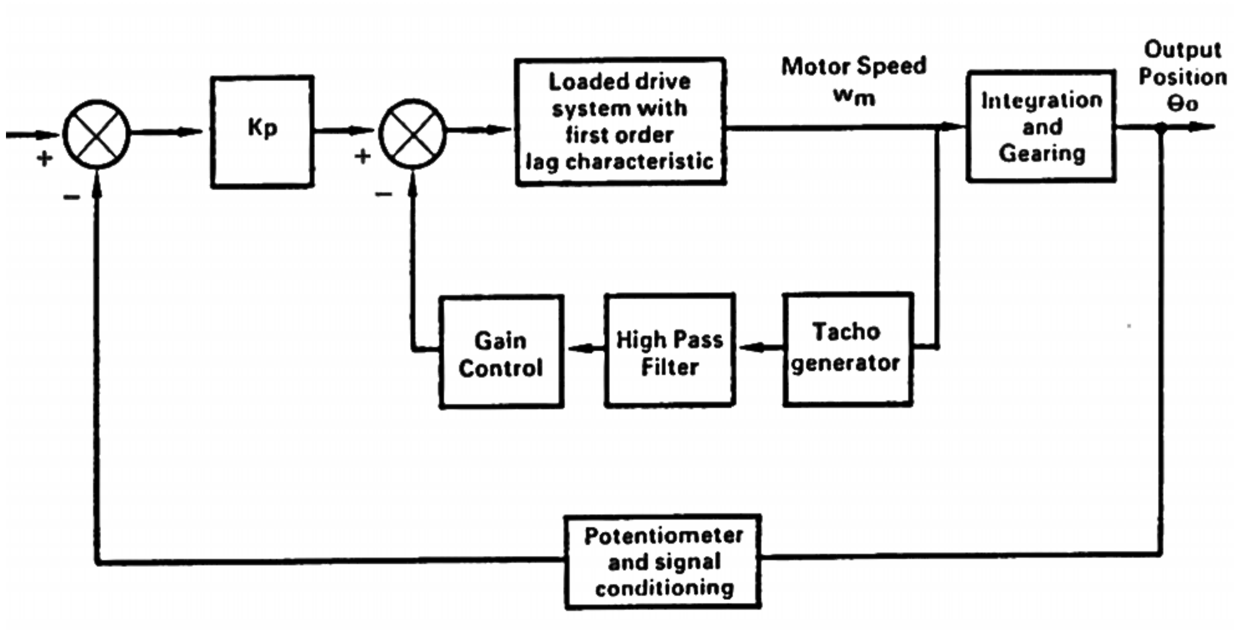


Figure 9.8: Position control with transient velocity feedback

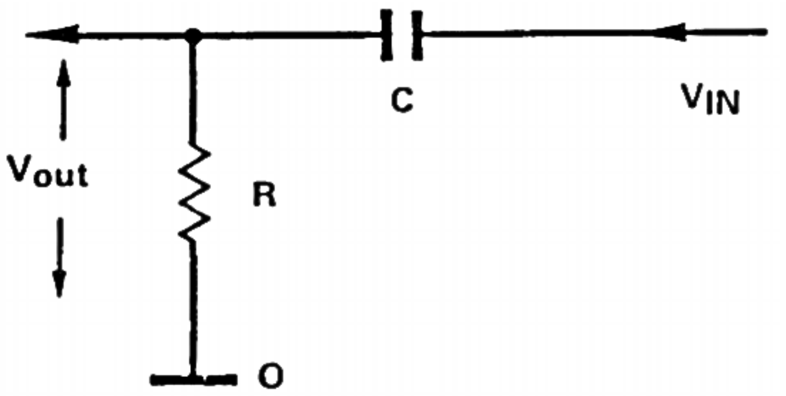


Figure 9.9: High Pass Filter

Procedure:

Part 1: Position Control with velocity feed back

1. Construct the system shown in figure 9.10. The amplifier in the inner loop allows the amount of velocity feedback to be adjusted.
2. Set the following:
    - Proportional in, Kp=1.
    - Integral out
    - Derivative out
    - Filter out
    - Auxiliary amplifier gain=0.1

3. Set the signal Generator to supply $\pm 0.5V$ steps. The output response resembles critical damping.

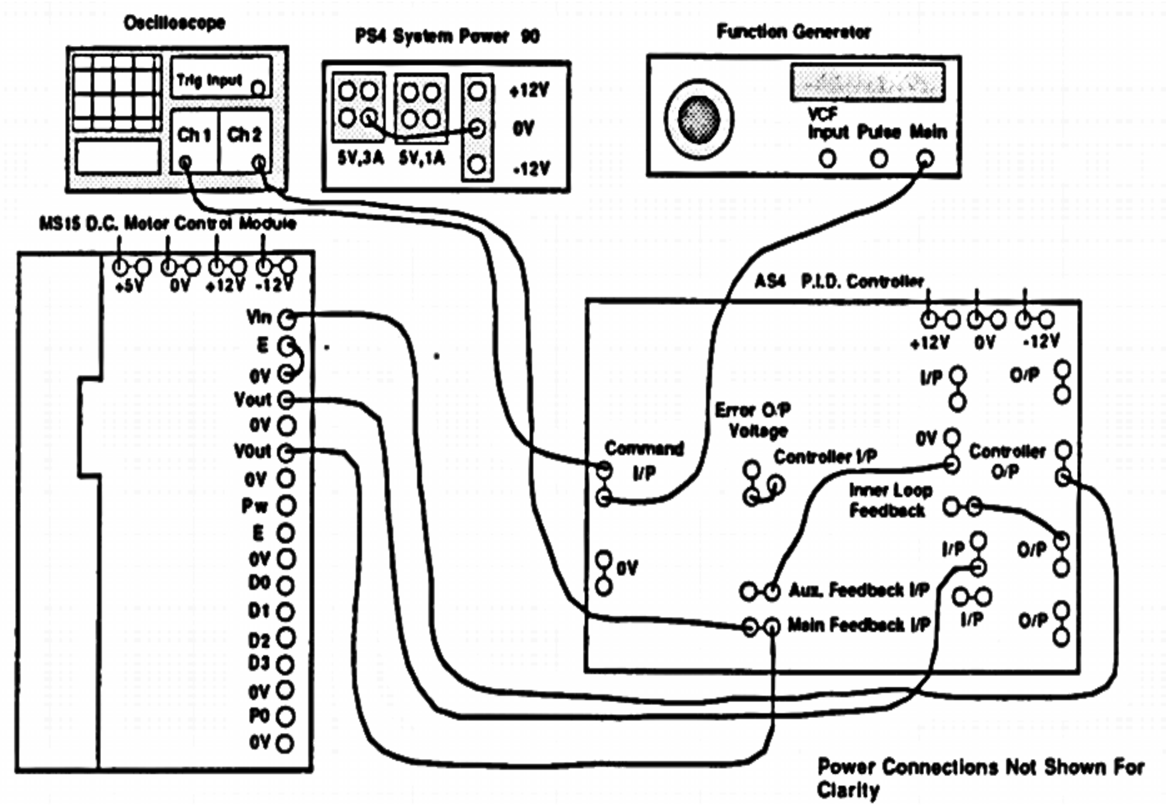
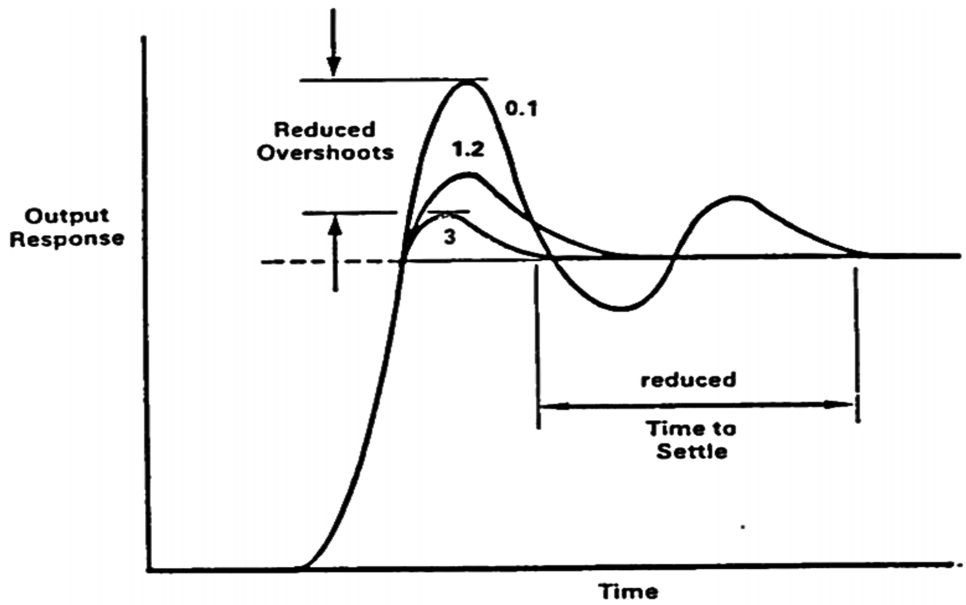


Figure 9.10: Wiring Diagram

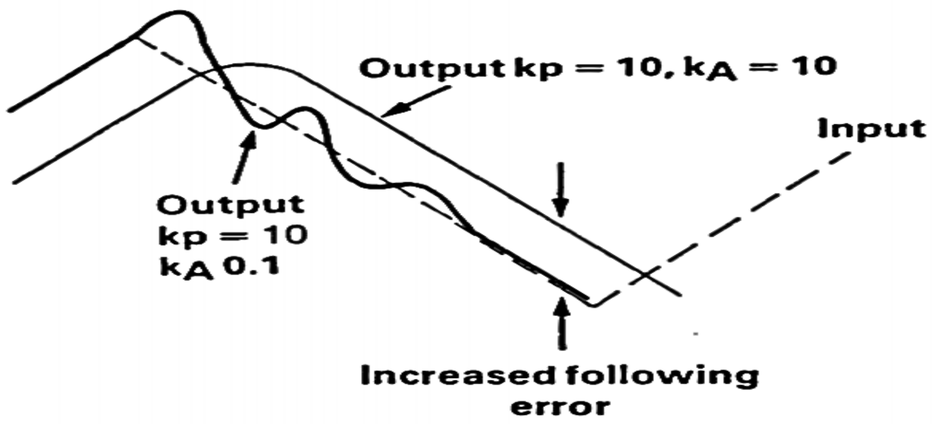
4. Increase the proportional gain Kp to 4.
5. Now gradually increase the auxiliary amplifier gain. The overshoot will reduce and the system will settle in a shorter time.
6. Now, set kp=4 and auxiliary gain=0.1. Apply ramp input of 5V peak to peak at 0.4 Hz. Again observe the results.
7. Set kp=10, the input to 0.4Hz and increase the velocity feedback by increasing the auxiliary amplifier gain from 0.1 up to 8.

Observations and Results:

- From figure 9.10 by applying the gains of 0.1, 1.2 and 3 at auxiliary amplifier gives us following waveform.



- The proportional gain controls and the gain of the velocity loop controls zeta.
- Velocity feedback increases following error.



Part 2: Position Control with Transient Velocity Feedback.

1. Construct the circuit shown in figure 9.11.

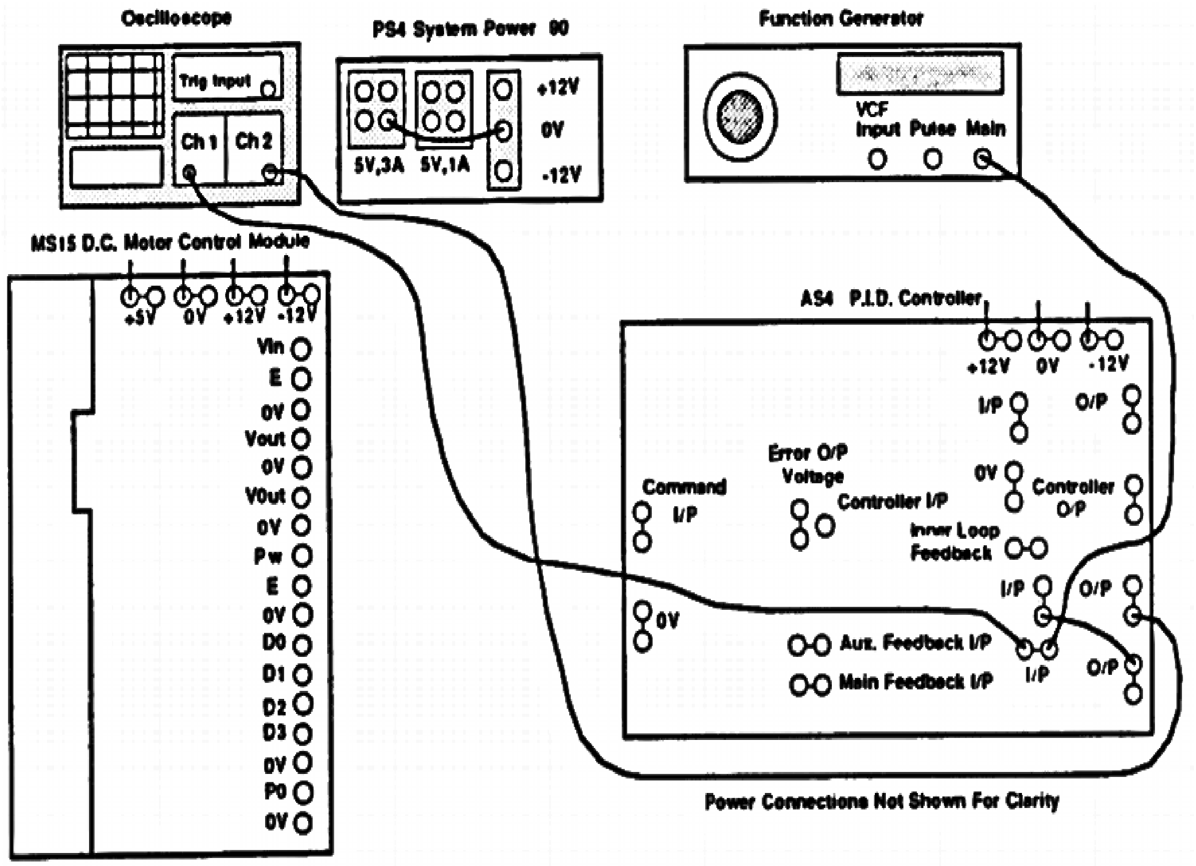


Figure 9.11: Wiring Diagram

2. Set the auxiliary amplifier gain to 1.
3. Apply $\pm$0.5V square wave at 0.2Hz and observe output waveform.
4. Switch to 200Hz and observe the output.
5. Repeat for sinusoid.
6. Construct the circuit shown in figure 9.12 which has transient velocity feedback.
7. Temporarily remove tachogenerator and set the followings:
    - Proportional IN
    - Integral OUT
    - Derivative OUT
    - Filter OUT
8. Use equal gain of 0.2V/divn and apply $\pm$0.5V peak ramp at 0.6Hz.Set proportional gain to 6. Observe the rusting waveforms.

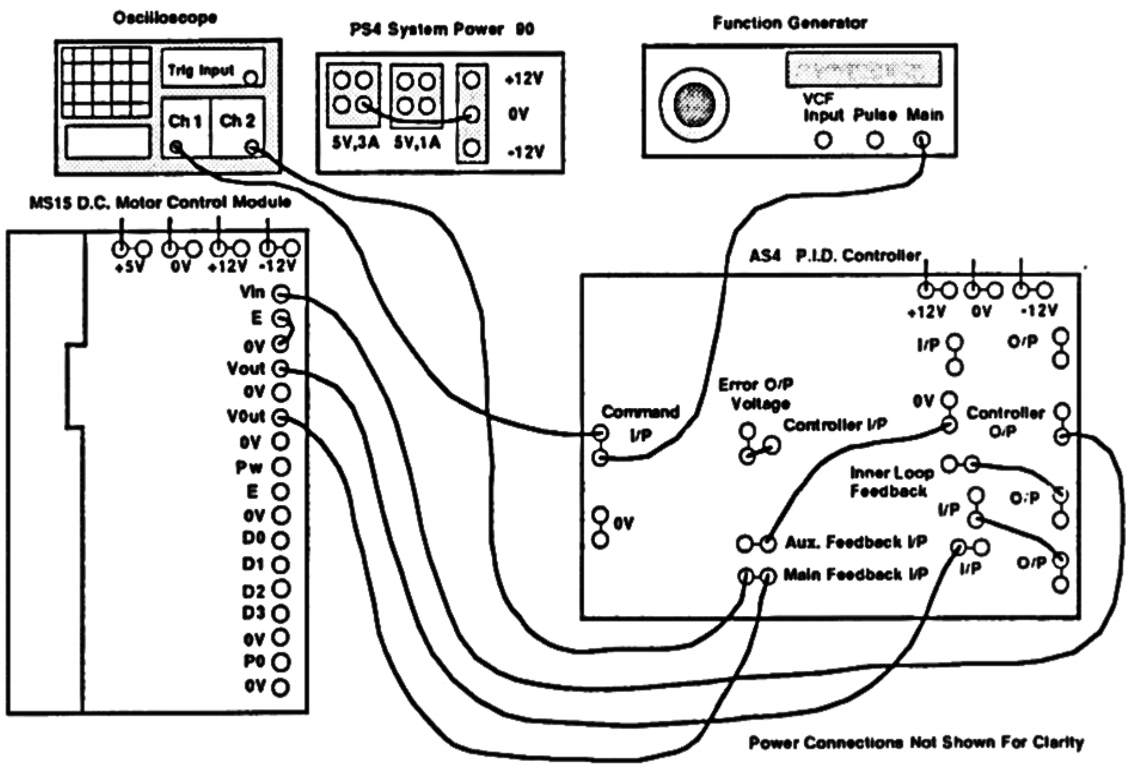
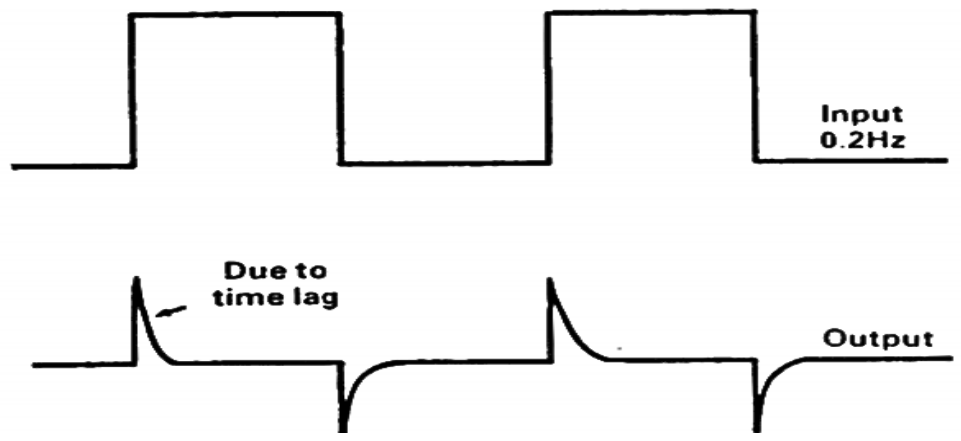


Figure 9.12: Wiring Diagram

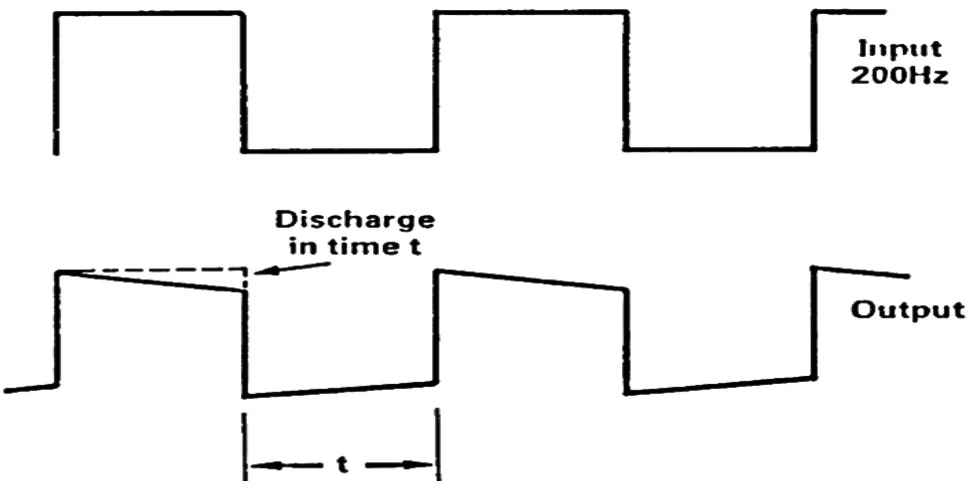
9. Now connect tachogenerator input to the capacitor’s input as in figure 12.6 and observe the results.

Observations and Results:

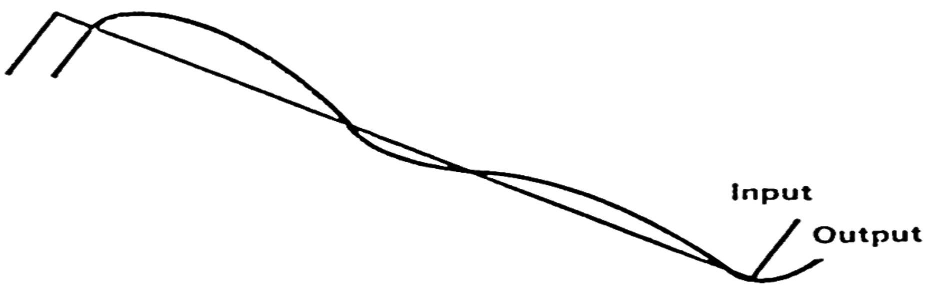
- Output obtained by figure 9.12 approximates a derivative of input. The effect of time lag is shown below:



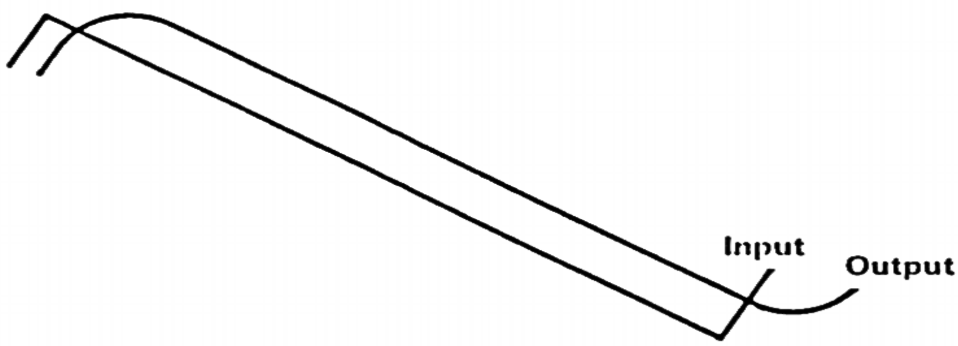
- Switching to 200Hz results in output very similar to input because time lag in the filter prevents the capacitor discharging shown by below waveform.



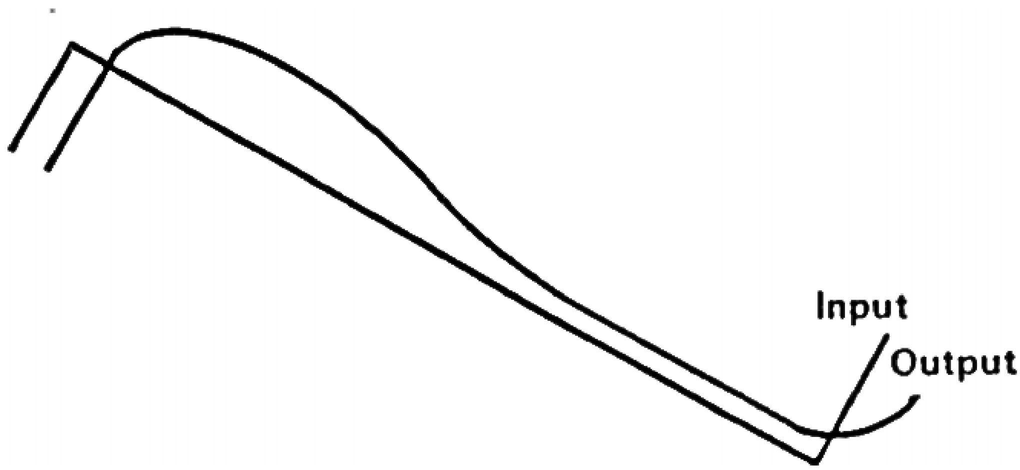
- For sinusoids the output phase lead approaching 90° at low frequency which is actually a sinusoid derivative.
- In figure 9.12, by temporarily tachogenerator signal directly to amplifier input and get a waveform shown below.



- Adjust auxiliary gain of about 3 to remove oscillations as shown in below waveform.



- Output of wiring diagram shown in figure 9.12 reverts the original following error when steady state conditions are reached.



Summary:

The system thus performed its intended functions.

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

EXPERIMENT #10

Perform a DC Motor Static and Dynamic Parameter Estimation, to develop a first order transfer function of a dc motor using Quancer DCMCT Trainer.

Objectives:

1. Determine the maximum velocity
2. Determine the coulomb friction
3. Perform Bump test
4. Develop a first order transfer function
5. Comparison of transfer function obtained

Lab Equipment:

1. Quancer DCMCT Trainer
2. USB QICII Software on PC work station

Theory

Quanser's QET DC Motor Control (Refer APPENDIX for detail) Trainer provides an ideal way to demonstrate the fundamentals of motor control, tuning and haptics using several integrated experiments. The system consists of a motor instrumented with an encoder. The motor is driven using a linear power amplifier. The power to the system is delivered using a wall transformer. Signals to and from the sys-tem are available on a header as well as on standard connectors for control via a data-acquisition (DAQ) board. Thus the system may be controlled using an external PC equipped with a DAQ board.

There is also a socket that accommodates a PIC micro controller. The PIC can measure the encoder, apply voltages to the motor amplifier, and communicate with a laptop or PC using a USB cable. In addition, analog controllers can be implemented on the breadboard. In the context of this workbook, the QET is used as a plant that is interfaced with a DAQ board and controlled using Quanser's own rapid prototyping and real-time control software, QuaRC, to perform various control experiments. QuaRC allows a user to generate real-time code from a Simulink diagram and run the code on the same (or a remote) PC. This allows for parameter tuning on the fly, data collection, and plotting.

Block Diagram

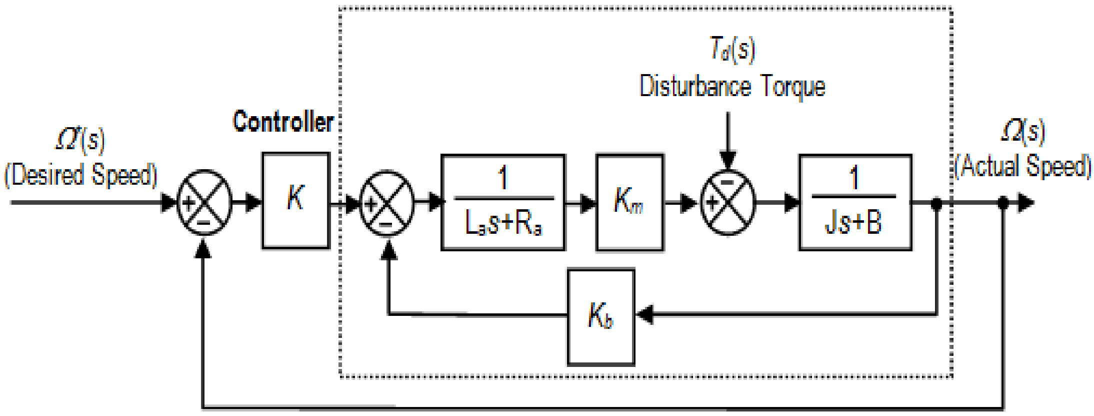


FIGURE: 10.1

Part 1:
INITIAL TEST EXPERIMENTS:

Determining Maximum Velocity and Starting Voltage

PROCEDURE:
A procedure of this type is very useful to make sure that a system functions properly. Please follow the steps described below.

Step1: Run the system open-loop by changing the voltage to the motor. The motor Voltage is set by the signal generator. With zero signal amplitude, change the signal offset to generate a constant voltage. Sweep the voltage gently over the full signal range and observe the steady-state speed, current, and velocity.
What happens to the variables as you change the offset?

OBSERVATION:
As the constant input voltage increases, the motor output velocity also increases, and vice versa. For a given input voltage polarity, the current stays around the same value, mostly indicative of the Coulomb friction in the system.

Step2: Determine the maximum velocity and compare with calculations. Note: Although the motor maximum input voltage is 15 V, the Offset numeric input is limited to 5 V.

OBSERVATION:
Setting the Offset to 5 V results in an output velocity of approximately 100 rad/s. Extrapolating to the end of the motor linear range, an input voltage of 15 V. Result to a maximum velocity of 3 * 100 = 300 rad/s. This is fairly close to the theoretical value.

Step3: Start with zero voltage on the motor and increase the voltage gradually until the Motor starts to move. Determine the voltage when this occurs. Repeat the test with negative voltages.

OBSERVATION:

From the rest position, a positive voltage of 0.75 V or a negative voltage of -0.70 V are required to start the motor. Because of friction in the motor it is necessary to apply a small current to make the rotor move. The friction can be measured by determining the voltage required to start the motor from rest. The voltages obtained are highly varying, they depend on the direction of rotation and how long the motor has been running. Typical values are in the range 0.2 V to 0.8 V. The friction is particularly severe for velocities around zero because friction changes sign with the direction of rotation. This can be avoided in the experimental tests by making sure that the velocity does not change sign.

ESTIMATING THE MOTOR RESISTANCE

Some of the parameters of the mathematical model of the system can be determined by Measuring how the steady-state velocity and current changes with the applied voltage. To experimentally estimate the motor resistance, follow the steps described below:

Step1: Set the generated signal amplitude to zero. If the signal offset is different from zero then the motor will spin in one direction, since a constant voltage is applied. You can change the applied voltage by entering the desired value in the Offset numeric control of the Signal Properties box. You can also read the actual motor current from the digital display. The value is in Amperes.

Step2: For each measurement **hold the motor shaft stationary** by grasping the inertial load to stall the motor. Note that for zero Volts you will measure a current, I_{bias} that is possibly non-zero. This is an offset in the measurement which you need to subtract from subsequent measurements in order to obtain the right current. Note also that the current value shown in the digital display is filtered and you must wait for the value to settle before noting it down.

Now fill the following table keeping in mind the above instructions:

Table 10.1:

SAMPLE: I	**V_M(I) [V]**	**OFFSET CURRENT [A]**		
0				
SAMPLE: I	**V_M(I) [V]**	**OFFSET CURRENT [A]**	**CORRECTED FOR BIAS: I_M(I)[A]**	**RESISTANCE: R_M(I)[Ω]**
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
AVERAGE RESISTANCE: R_{AVG}[Ω]				

Step3: Calculate for each iteration the motor resistance *Rm(i)* and obtain an average value for it, *Ravg*. Explain the procedure you used to estimate the resistance *Rm*.

SOLUTION:

Measure the current at zero Volts. This value is Ibias. Measure the current at each of the specified voltages Vm(i), with i from 1 to 10. The measured current for each of these voltages is Imeas(i). Correct the current measurement for each applied voltage by applying:

$$\boldsymbol{Im}(\boldsymbol{i}) = \boldsymbol{Imeans}(\boldsymbol{i}) - \boldsymbol{Ibias}$$

Then the estimated resistance Rm(i) for each measurement, i, is given by:

$$\mathbf{Rm(i)} \ = \frac{\mathbf{V_m(i)}}{\mathbf{I_m(i)}}$$

Lastly, the average resistance value can be calculated from:

$$\mathbf{R_{avg}} = \frac{\mathbf{1}}{\mathbf{10}}\left(\sum_{\mathbf{i=1}}^{\mathbf{10}} \mathbf{R_m(i)}\right)$$

Step4: The system parameters are given in Table 10.1. Compare the estimated value for Rm (i.e. Ravg) with the specified value and discuss your results.

OBERVATION:

The specified value for *Rm*is 10.6 Ω ±10 %. The estimated value is 13.71 Ω (in this specific case). This variation is likely due to the current sense accuracy which is specified as ±10 % and to other sensor errors.

ESTIMATING THE MOTOR TORQUE

To experimentally estimate the motor back-EMF constant, follow the steps described below:

Step 1: With the motor free to spin, apply the same procedure as above. You can read a value for the motor angular speed from the digital display. Wait a few seconds after you enter a new voltage value as the displayed speed values are low-pass filtered. The angular speed value is in radians per seconds. The current measurement may have an offset which you will need to account for. The speed measurement will have a very small offset which will need to be compensated for.

Calculate the motor back-EMF constant for each measurement iteration and then calculate an average for the 10 measurements. You should use the value of Rm that you estimated in the previous section.

Now fill the following:
Table 10.2:

SAMPLE: I	**V_M(I) [V]**	**I_{bias} [A]**	**R_{avg} [Ω]**	
0				
SAMPLE: I	**V_M(I) [V]**	**Measured Speed $\omega_m(i)$ [rad/s]**	**I_M(I) [A]**	**I_{means}(i) [A]**
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
AVERAGE BACK EMF-CONSTANT: $K_{m\text{-}avg}$ [V.s/rad]				

Step 2: Explain the procedure you used to estimate km.

SOLUTION:

Measure the current at zero Volts. This value is Ibias. Measure the motor current, Imeas(i), and angular speed, ωm(i), at each of the specified voltages Vm(i), with i from 1 to 10. Correct the current measurement for each applied voltage by applying:

$$I_m(i) = I_{means}(i) - I_{bias}$$

Then the estimated back-EMF (or torque) constant k_m(i) for each measurement iteration,I is given by:

$$km(i) = \frac{Vm(i) - RmIm(i)}{\omega(i)}$$

Lastly,the average back-EMF constant value can be calculated from:

$$k = \frac{1}{10}(\sum_{i=1}^{10} km(i))$$

Step 3: The system parameters are given in Table 10.2. Compare the estimated value for km (i.e. km_avg) with the specified value and discuss your results.

SOLUTION:

The specified value for km is 0.0502 V.s/rad. The estimated value is 0.0483 V.s/rad(in this specific case). These are fairly close (less than 4 % difference). Any discrepancies would be due to sensor errors.

OBTAIN THE MOTOR TRANSFER FUNCTION

Calculate the parameters of the transfer function as shown below:

$$\mathbf{G_{\omega,v}(s) = \frac{K}{\tau s + 1}}$$

The above transfer function can also be written as:

$$\mathbf{G_{\omega,v}(s) = \frac{1}{k_m(\frac{J_{eq}R_m s}{k_m^2} + 1)}}$$

The transfer function steady-state gain and time constant can thus be expressed by:

$$\mathbf{K = \frac{1}{k_m}} \quad \text{and} \quad \mathbf{\tau = \frac{J_{eq}R_m}{k_m^2}}$$

Summarizing the other data from the motor specification sheet, we have:

Jeq = 0.0000221 [kg m^2]

Km = 0.0502 [Nm/A]

Rm = 10.6 [ohm]

Substitute the values into the above mentioned equations and find values of the DC gain and time constant. Finally, use these values to simplify an equation of the open loop transfer function Gw,v (s).

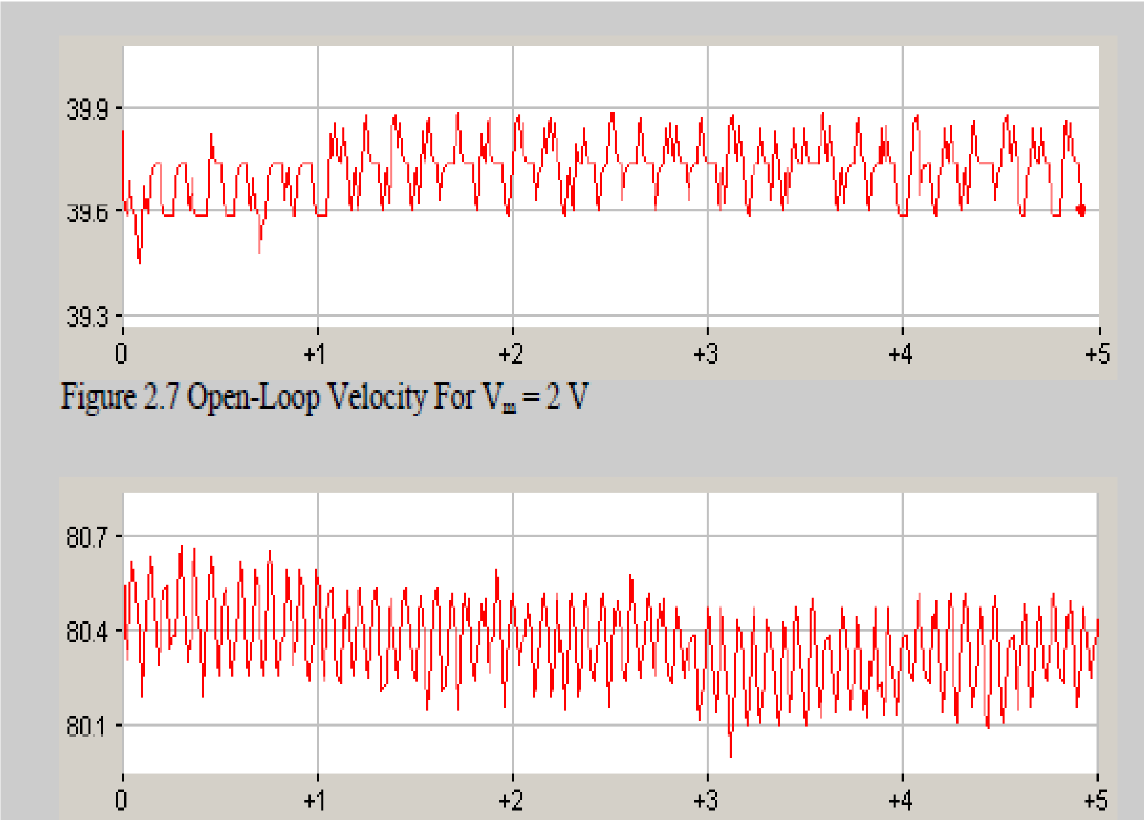
$$\mathbf{G_{\omega,v}(s) = \frac{19.9}{0.0929s + 1}}$$

ESTIMATE THE MEASUREMENT NOISE

Noise is an inherent property of most systems. This plant is no different than others and has noise which can be experimentally viewed or calculated.

1. Apply different voltage levels and observe the output.

Below are graphs for two input voltages, 2V and 4V.



GRAPH: 1

It can be seen from the above graphs that at V=2 volts and V=4 volts, the output speed to velocity ratio almost remains the same but the disturbance frequency increases with increase in voltage. This noise in the output signal is majorly due to the fact that the rotor rotates on ball bearings that support the motor shaft. At higher velocities/voltages, there is lesser friction so the amplitude of this noise decreases.

PART: 2

DYNAMIC MODELS: EXPERIMENTAL DETERMINATION OF SYSTEM DYNAMICS

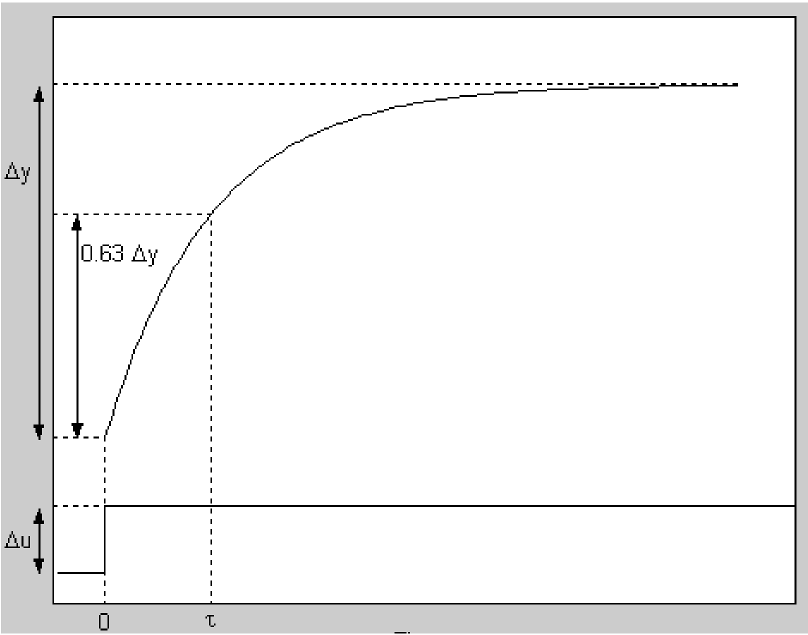
Purely experimental methods can also be used to determine system response. System response is observed for a variety of inputs and systems parameters are changed accordingly until the desired results are obtained. Many different inputs can be chosen.

THE BUMP TEST:

In bump test a constant input is chosen at first and the system is allowed to reach equilibrium. The input is then rapidly changed to a different constant value and the system output is recorded.

$$\mathbf{G_{\omega,v}(s)} = \frac{\boldsymbol{K}}{\boldsymbol{\tau s + 1}}$$

A bump test input and output is illustrated in the following diagram:



GRAPH: 2

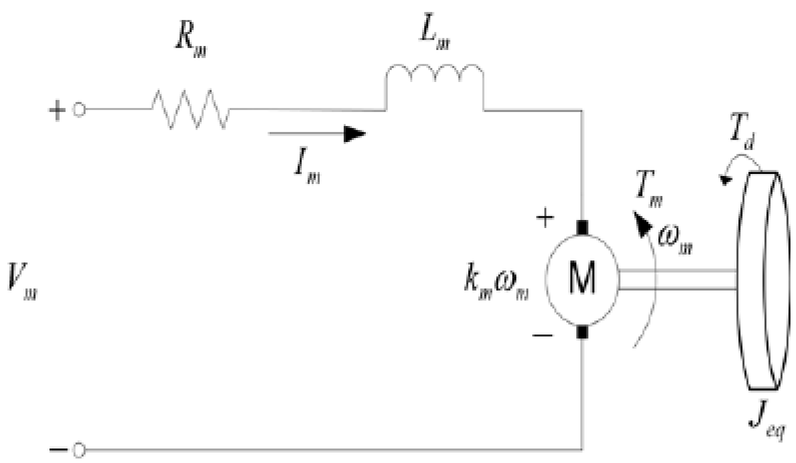
Steady state gain is given by:

K = $\frac{\boldsymbol{\Delta Y}}{\boldsymbol{\Delta U}}$

Where, Δu is changes in input,
Δy is changes is steady state output,
T is given by the time taken by the output to reach 63% of it's final value.

MODELLING:

Figure represents the classic schematic of the armature circuit of a standard DCmotor.



1. Determine the electrical relationship characterizing a standard DC motor.

Solution:
Using Kirchhoff's voltage law, we obtain the following equation:

$$\mathbf{V_m = R_m I_m + L_m \left(\frac{\partial}{\partial t} I_m\right) + k_m \omega_m}$$

This can be expressed in the Laplace domain as follows:

$$\mathbf{R_m I_m + L_m I_m s = V_m - k_m \Omega_m}$$

where the last term represents the back-EMF.

2. Determine and evaluate the motor electrical time constant τe. This is done by assuming that the shaft is stationary.

Solution:
Considering the transient part (i.e. left hand side) of the first-order differential equation [2.s3], the armature time constant results in:

$$\boldsymbol{\tau_e} = \mathbf{\frac{L_m}{R_m}}$$

Considering the values from the specification table:
Lm = 0.82 mH
Rm= 10.6 Ω
we can evaluate that the electrical time constant τe:

$$\boldsymbol{\tau_e} = \mathbf{0.0000774\ [s]}$$

EXPERIMENTAL PROCEDURE:

Different inputs are applied on the QICii module and output is observed.

Step 1: Apply a series of step inputs to the open-loop system by setting the QICii module parameters.

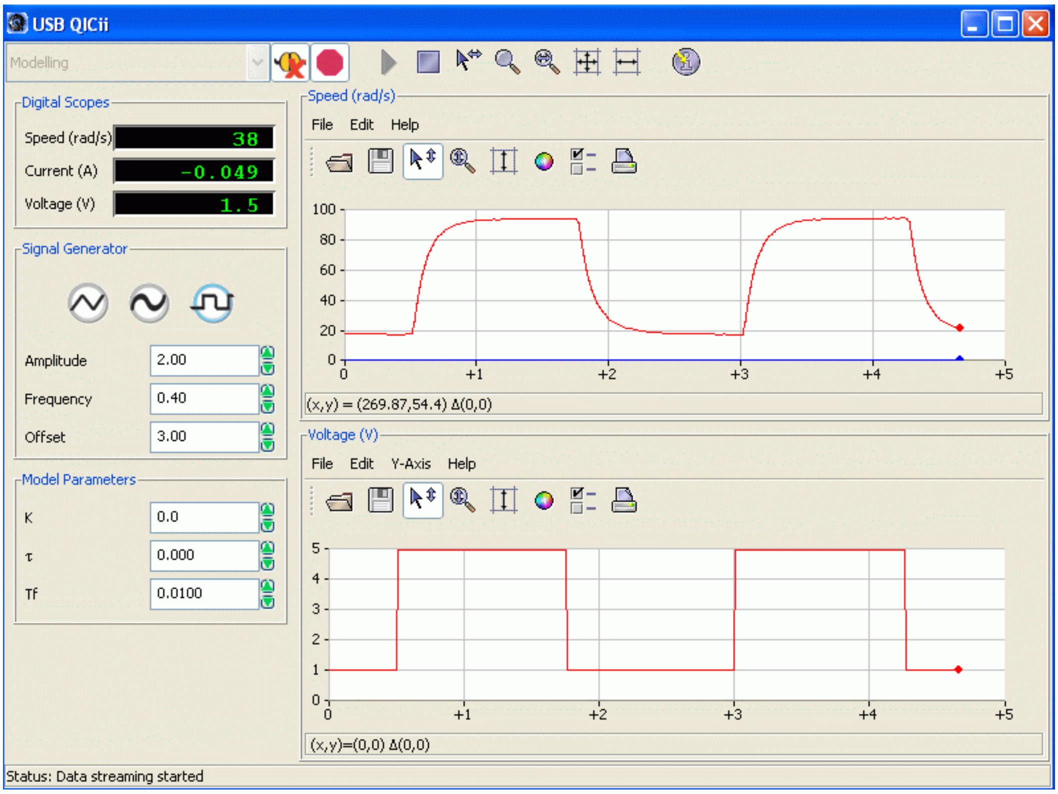
Change the amplitude for different step inputs.

Table 10.3:

Signal Type	**Amplitude (V)**	**Frequency (Hz)**	**Offset (V)**	**K [rad/(V.s)]**	**T(s)**
Square Wave					

Step 2: A constant amplitude square wave is applied to the motor by the controller. The pulse width of the square wave is so long that the system easily reaches steady state at each step. The motor runs at a speed corresponding to the step input. The transfer function can be obtained from voltage Vmto angular velocity ωm using the obtained bump tests.

Typical bump test experiment results are illustrated below:



GRAPH: 3

Step 3: Find the parameters K and τ of the model.
Step 4: Repeat the procedure for a few different signal amplitudes, as well as for rising and falling steps. Average your estimated parameters.

FINDING THE TRANSFER FUNCTION:

Steady state gain is found by:

$$\mathbf{K} = \frac{\Delta Y}{\Delta U}$$

T is found by reading the time taken by the output to reach 63% of it's final value.

Transfer function is given by:

$$\mathbf{G}_{\omega,\mathrm{v}}(\mathbf{s}) = \frac{K}{\tau s + 1}$$

CONCLUSION

We can perform above experiments using this trainer in order to determine the transfer function of the system. We can also detect the damage insulation of motor using this trainer by measuring its resistance.

TASK: Submit a separate report according to the format given in appendix C.

Registration Number------------------------------

Student Name------------------------------

Teacher Signature ------------------------------

EXPERIMENT #11

Study, Analysis and Applications of Root Locus Techniques for Controller Design using MATLAB

Objectives

To explore the root-locus analysis of a control system.

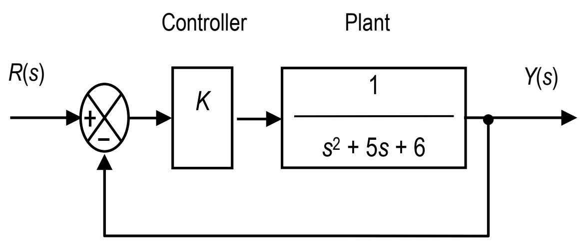
New MATLAB commands to learn in this experiment

Command	Description
rlocus(sys)	Enter **help rlocus**in the Matlab Command Window for a detailed description.

Procedure

Section-1

- A closed-loop control system using a proportional controller and unity-feedback is shown below.



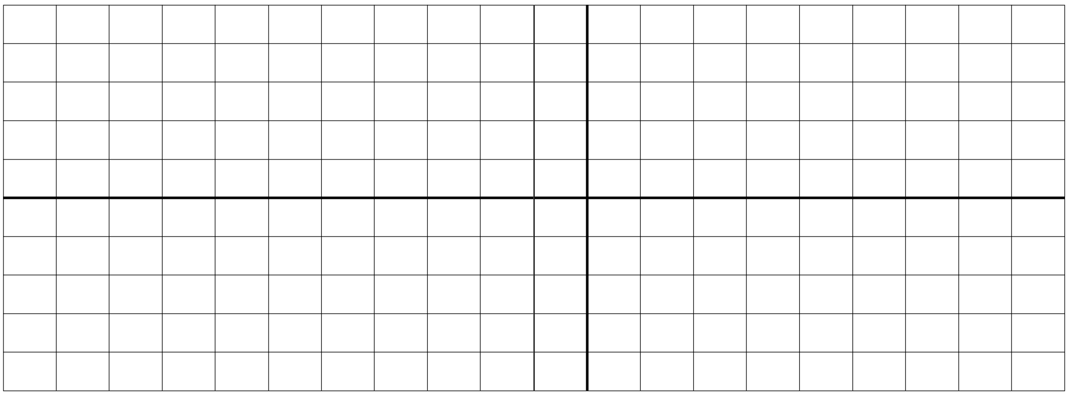
- Determine the open-loop transfer function.

$Y(s)/R(s)$ =

- Determine the closed-loop transfer function.

$Y(s)/R(s) =$

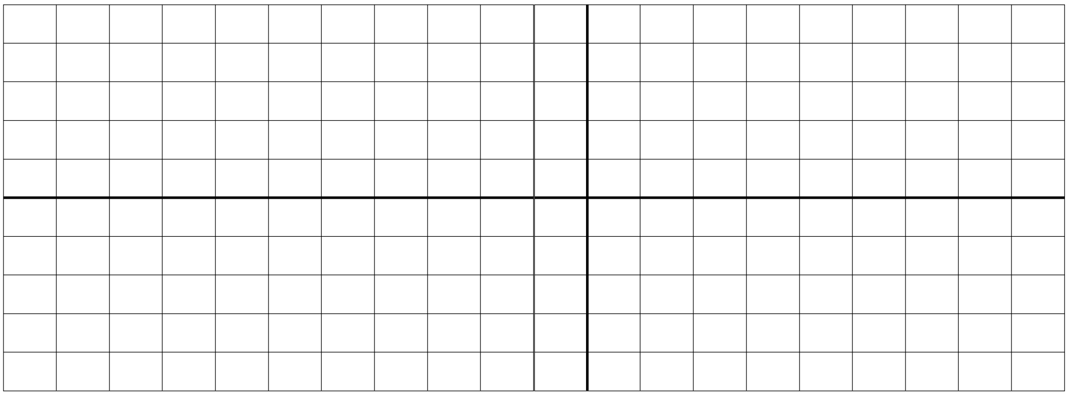
- Show the position of poles and zeros of the open-loop transfer function in the s-plane.



- Write MATLAB commands to determine the open-loop transfer function of the system shown above. Use variable sys for this transfer function.

- Following MATLAB command can be used to plot the root-locus of a system.
  >>rlocus(sys) ;

- Sketch the output of the above command.



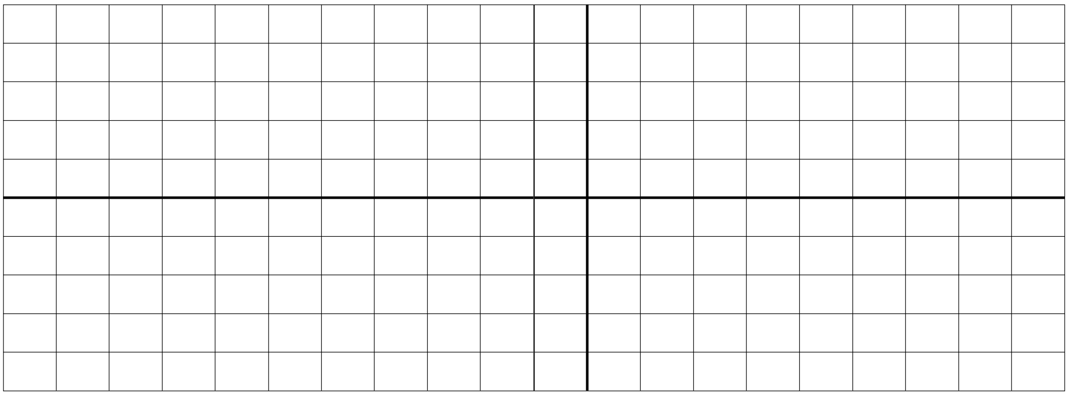
- ☐ What is the range of K for a stable operation?

Section-2

- ☐ In the system shown above, use integral controller K/s and determine the open-loop and closed-loop transfer functions.

Open-loop transfer function with integral controller.   Closed-loop transfer function with integral controller.

- ☐ Plot the root-locus using MATLAB command rlocus and sketch the root-locus.



- ☐ How can you identify an integrator in the *s*-plane?

- ☐ What is the range of *K* for a stable operation?

Section-3

- ☐ In the system shown above, use a proportional integral (PI) controller $K(1+1/s)$ and determine the open-loop and closed-loop transfer functions.

Open-loop transfer function with integral controller.

Closed-loop transfer function with integral controller.

- □ Plot the root-locus using MATLAB command rlocus and sketch the root-locus.

- □ What is the range of *K* for a stable operation?

- □ What is the significant effect of using a PI controller on the system response?

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Write your comments on this experiment.

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TASK: Submit a separate report according to the format given in appendix C.

Registration Number ------------------------------

Student Name ------------------------------

Teacher Signature ------------------------------

EXPERIMENT #12

Part (a): Study, Analysis and Applications of Frequency Response Techniques for Controller Design using MATLAB

Objectives

To explore the Frequency Response of a Control System.

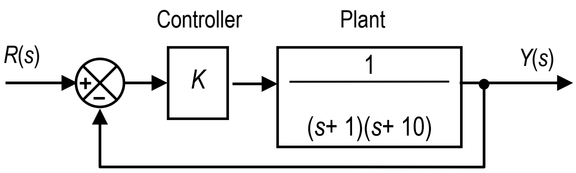
New MATLAB commands to learn in this experiment

Command	Description
bode(n, d)	Enter **help bode** in the Matlab Command Window for a detailed description.

Procedure

Section-1

- A closed-loop system with a proportional controller *K* is shown below.



- Determine the loop-transfer function of the above system for *K*=1 manually and verify the transfer function using MATLAB. Use variable sys for the transfer function.

$G(s) =$

- Following is the MATLAB command used for the Bode magnitude and phase plots.

```
>>bode(sys) ;
```

- Sketch the Bode plot in the following space.

Magnitude

Phase

- Sketch the Bode magnitude and phase plots with controller gain K=20.

Magnitude

Phase

- ◻ Sketch the Bode magnitude and phase plots with controller gain *K*=50.

Magnitude

Phase

Write your comments on the effect of increasing the gain of proportional controller on the Bode plots.

- ☐ Calculate the gain and phase margins in the Bode plots for *K*=1, 20 and 50.

	K=1	K=20	K=50
Gain Margin			
Phase Margin			

- ☐ Use the MATLAB command nyquist(sys) for the Nyquist plot of the above system for controller gains *K*=1, 20 and 50. Sketch all three polar plots in the following space.

How the increasing gain affects the Nyquist plot?

- ☐ For a unity feedback system with forward transfer function $G(s) = K / s(s+2)(s+10)$, sketch the Bode and Nyquist plots.

Magnitude

Phase

Nyquist Plot

- ☐ Determine gain and phase margin from the Bode plot.

- ☐ Determine the range of *K* for a stable operation from the Nyquist plot.

Give your comments on this experiment.

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TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

Part (b): Frequency Response of the DC Motor (1st Order Model)

Objectives:

1. To understand the frequency response of DC motor.
2. To understand the amplitude ratio and how and why it is calculated.
3. To understand the concepts of Bode Plots.

Lab Equipment:

- MS15 Module
- AS3 Command Potentiometer
- Control Laboratory Input/output Interface (CLIO)
- Power Supply
- Connecting leads
- Virtual Control Laboratory (VCL) Software

Theory

For understanding the frequency analysis in control engineering, there are three different strands of development:

1. Process Engineering

The process with running plant at steady condition so it concerned with maintain an output against load fluctuation.

2. Mechanical Engineering

The dynamics of vehicles and their suspension system.

3. Electrical Engineering

This engineering developed a strong frequency bias and a branch of control engineering called servomechanisms.

Frequency Response

As signal is made up from a series of sinusoids of different frequencies and amplitude so there is a definite mathematical relationship between the frequency composition of a signal and its shape.

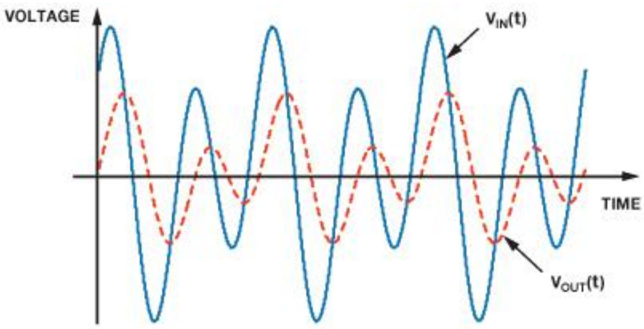


Figure 12.1: Frequency Response

As shown in the figure 12.1, the output can have different amplitude from input and the ratio can be described as:

$\frac{\textbf{output amplitude}}{\textbf{input amplitude}}$ Is called **Amplitude Ratio**.

1. Output sinusoid lags in time behind the input; this lag is measured in Degrees and is called **Phase Lag ϕ**.
2. Phase Lag can be calculated from the time difference the peak of the two sinusoids.
3. The frequency of a signal (in hertz Hz) is number of cycle in one second.
4. The period is the time to complete 1 cycle that is the inverse of frequency:

$$\textbf{Period (seconds)} = \frac{\mathbf{1}}{\textbf{frequency(Hz)}}$$

Since there is 360° in one cycle period.

$$\textbf{Phase Lag } \boldsymbol{\phi} = \frac{\textbf{360}*\textbf{time lag}}{\textbf{period}} = \textbf{360 * time lag * frequency}$$

Frequency response of the DC motor

We are going to measure the frequency response of the motor and from this determine the frequency model of the plant.

Table 12.1: VLC Software window

File CA06PE04	**Controller** Open-loop	**Plant** MS15 Analog	**Display** Graph
Signal Generator		**Graph**	
Signal	Sine	1 Input ON	
Level	60%	2 Position OFF	
Offset	0%		
Freq	100 mHz	4 Velocity ON	
Reference	Internal		
DC Motor		**Output Potentiometer**	Disengage
Brake	0	**Command Potentiometer**	180°

Disengage the output potentiometer, switch ON and Enable the plant.

The above table 12.1 shows the VLC Software window which includes the settings of controller, Plant (MS15), display meter, signal generator and DC Motor Braking.

Procedure Steps:

Starts at 100 MHz then go down the table then come back to 50 MHz and complete the low frequency tests.

At each frequency:

1. Freeze the delay using Freeze option. At low frequency do not initiate the freeze until the trace has begun a cycle at the left of graph.
2. When the frozen message appears, click Frequency ON
3. Measure the peak-peak voltage by placing lines A and B on the maximum and minimum velocity values
4. Select D phase by clicking in the D box. Move the vertical line until it will interest the peak value.
5. The reading in the box is the phase shift relative to 0° of the input trace. As you are measuring the phase shift at the peak the phase lag will be measure value -90°.
   Input amplitude = 6 volts peak-to-peak

Table 12.2: VCL output

Frequency	Output (Volts p-p)	Phase Lag (degrees)	Amplitude Ratio (A)	Amplitude Ratio (dB)
10mHz				
20mHz				
50mHz				
100mHz				
200mHz				
500mHz				
1Hz				
2Hz				
5Hz				
10Hz				

The results in Table 12.2 can be plotted in a number of different ways but the most useful is **Bode Plot**, where amplitude and phase is are plotted separately against log frequency.

The amplitude ratio is converted into decibels by the formulae:

$$\textbf{Amplitude Ratio (dB)} = \mathbf{20\log_{10}\frac{Vout}{Vin}}$$

This amplitude ratio is used to draw Bode Plot.

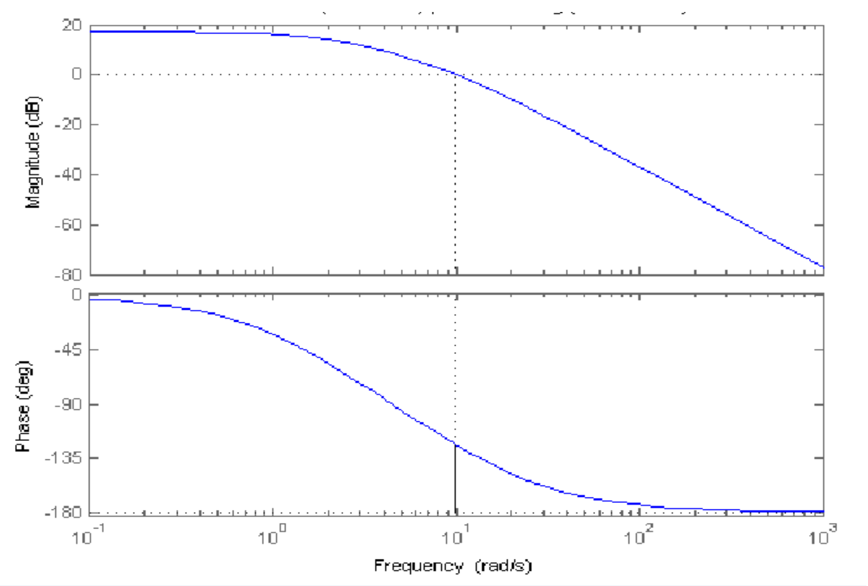


Figure 12.2: Bode Plots of the readings

Bode plots shown in figure 12.2 are the graphical representation of the readings measured in Table 12.2.

Steps to find out the break frequency:

1. Draw a horizontal lone through the low frequency amplitude points.
2. Draw a line at slope -20dB/decade through the high frequency points.
3. The frequency at which these two lines meet is the break frequency.
4. Adjust the lines if necessary to ensure that the actual amplitude curve is at -3dB and the phase shift is -45° at the break frequency.

Table 12.3:

From slope	From -3dB point	From -45°	Average

Relationship between Break Frequency and Time Constant

The break frequency ω_c, in radians/seconds, is inverse of the time constant, τ in seconds for example:

Break Frequency $\omega_c = 2\pi f = \frac{1}{\tau}$ or Time Constant $\tau = \frac{1}{\omega} = \frac{1}{2\pi f}$

τ = 1/(4.49) = 0.22 seconds

Gain K_p = Amplitude Ratio at low frequency = 0.92

Table 12.4:

Test	Gain K_p	Time Constant τ
Time		
Frequency		

Put the values of K_p and time constant τ.

Conclusion

From this we conclude that with the increases in frequency, phase lag between the input voltage and output voltage also increases while the output voltage decreases.

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

EXPERIMENT #13

System Modeling and Stability Analysis

Experiment Purpose

1. Understand basic procedures for mechanism modeling.

2. Know the method to build the mathematical model of linear 1-stage inverted pendulum with mechanism method.

3. Master the basic means to control system stability.

Experiment Requirements

1. Establish the mathematic model of linear 1-stage inverted pendulum with mechanism method.

2. Analyze the stability of linear 1-stage inverted pendulum, and conduct simulation verification in the MATLAB.

Experiment Equipment

1. Linear 1-stage inverted Pendulum.

2. Computer MATLAB platform.

Experiment Principle

System modeling can be divided into two categories: mechanism modeling and experiment modeling. The mechanism modeling establishes the input-output relations within the system through physics, chemistry and mathematics means on the basis of good knowledge of the object's moving rules, while the experiment modeling refers to the systematic input-output relations established via mathematics means on the basis of a series of preset input signals imposed on the object, which is used to stimulate the object so as to detect the observable output through the sensor. This process includes the design and selection of input signal, the precise detection of output signal, and the research of mathematic algorithm etc.
The inverted pendulum system, if some secondary factors are ignored under certain hypothesis, is a classic moving rigid system, which is applicable to the systematic dynamic equation built in inertia coordinate system using the classic mechanics theory. The text below lists the mathematic model of the linear 1-stage inverted pendulum system built under Newton-Euler method.
1. Force Analysis

The linear 1-stage inverted pendulum system may be abstracted into a system composed of cart and uniform bar after the ignorance of air resistance and various friction forces, and it is shown as Fig. 13.1.

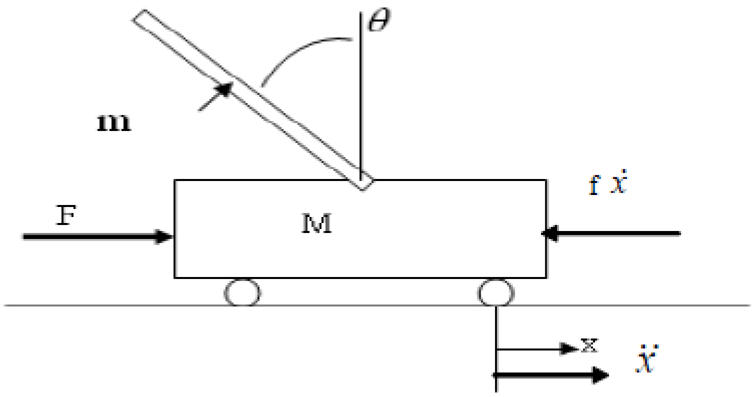


Fig. 13.1Linear 1-Stage Inverted Pendulum System

The symbols, their references and relevant values involved in the inverted system are shown in Table 13.1.

Table 13.1 Parameters Linear 1-Stage Inverted Pendulum System

Symbol	Reference	Value
M	Cart mass	1.096kg
m	Pendulum bar mass	0.109kg
f	Cart friction force	0.1 N/m/sec
l	The length from the rotation axis to the centroid of the pendulum bar	0.25m
I	Inertia of the pendulum bar	0.00223kg*m*m
F	Force on the cart	
x	Cart position	
θ	Included angle between the pendulum bar and the upward vertical direction (as the initial position of the pendulum bar is downward vertical direction)	
F_s	Horizontal disturbing force imposed on the pendulum bar	
F_h	Vertical disturbing force imposed on the pendulum bar	
F_g	Resultant force of F_s and F_h	
g	Acceleration of gravity	$9.8\,m/s^2$

Fig. 13.2 presents the force analysis for the cart in the system. Whereas, N and P are components of the interaction force of the cart and the pendulum bar in horizontal and vertical direction separately.

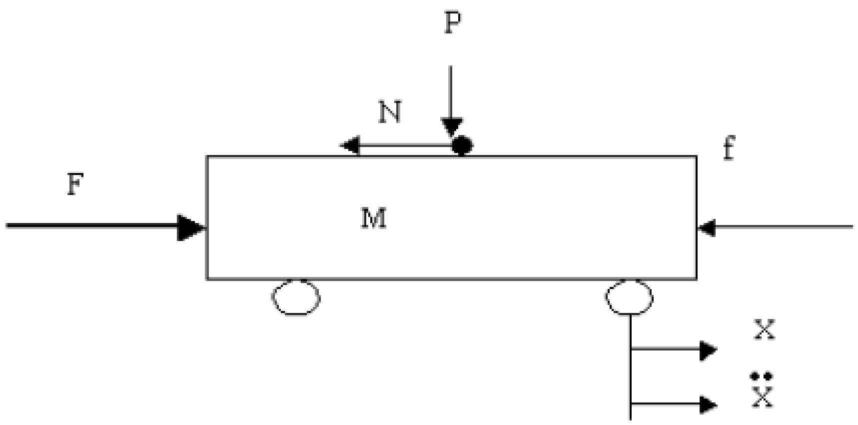


Fig. 13.2: Force Analysis Chart for Cart in the System

Fig. 13.3 shows the force analysis for the pendulum bar in the system. F_s refers to the disturbing force imposed on the pendulum bar in horizontal direction, F_h refers to the disturbing force imposed on the pendulum bar in vertical direction, and the resultant force means the disturbing force F_g forming a included angle of α with the vertical direction.

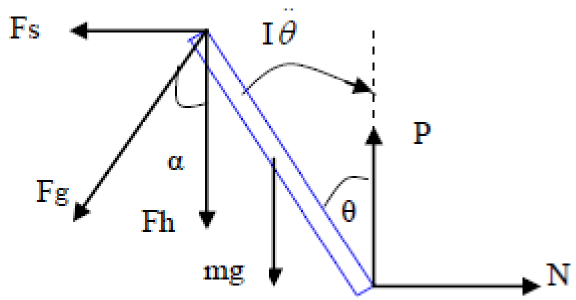


Fig. 13.3: Force Analysis of the

Note: The positive and negative directions of the inspection and implementation devices are determined in actual inverted pendulum system; therefore, the vector direction is defined as shown in the figure, which is the positive direction.

2. Mathematical Model

The analysis of the horizontal resultant force of the cart may lead to the equation below:

$$M\ddot{x} = F - f\dot{x} - N$$

Assume that the disturbing force F_g in the angle of □□to the vertical direction is imposed on the pendulum bar, which can be decomposed into disturbing force in horizontal and vertical force, and the torque generated is equivalent to the torque generated by the horizontal disturbing force F_s and vertical disturbing force F_h on the top of the pendulum bar.

$$F_S = F_g\sin\alpha \qquad F_h = F_g\cos\alpha$$

The force analysis of the pendulum bar in the horizontal direction may lead to the equation below:

$$N - F_S = m\frac{d^2}{dt^2}(x + l\sin\theta)$$

That is

$$N = m\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta + F_f\sin\alpha$$

The analysis of the resultant force in the vertical direction of the pendulum bar as shown in Fig. 1.3 may lead to the equation below:

$$-P + mg + F_h = m\frac{d^2}{dt^2}(l - l\cos\theta)$$

That is

$$-P + mg + F_g\cos\alpha = ml\ddot{\theta}\sin\theta + ml\dot{\theta}^2\cos\theta$$

The torque equilibrium equation is:

$$F_g l\sin\alpha\cos\theta + F_g l\cos\alpha\sin\theta + Pl\sin\theta + Nl\cos\theta + I\ddot{\theta} = 0$$

Substitute with and, then the equation below is obtained N

$$2F_g l\sin\alpha\cos\theta + 2F_g l\cos\alpha\sin\theta + (I + ml^2\cos 2\theta)\ddot{\theta} + mgl\sin\theta - ml^2\dot{\theta}^2\sin 2\theta + ml\ddot{x}\cos\theta = 0$$

If θ = Φ + π (Φ means the included angle between the pendulum bar and the vertical direction, it is in the unit of radian), and apply it into the formula above. Assume that Φ<<1, then proximity processing is possible:

$$\cos\phi = 1, \sin\phi = \phi, (\frac{d\phi}{dt})^2 = 0, \cos 2\phi = 1, \sin 2\phi = \phi$$

$$I = \frac{1}{3}ml^2$$

Because, the equation may be converted into:

$$2F_g(-\sin\alpha - \phi\cos\alpha) + \frac{4}{3}ml\ddot{\phi} - mg\phi = m\ddot{x}$$

Assume that $F_f = F_g(-\sin\alpha - \phi\cos\alpha)$, then formula (2.9) may be transformed into

$$2F_f + \frac{4}{3}ml\ddot{\phi} - mg\phi = m\ddot{x}$$

Above formula is the simplified differential equation for linear 1-stage inverted pendulum system. When the values are applied, the differential equation is shown as formula below.

$$\ddot{\theta} = 29.4\theta + 3\ddot{x} - 2\frac{F_f}{m}$$

When F_f is ignored, such equation may be simplified as formula given below.

$$\ddot{\theta} = 29.4\theta + 3\ddot{x}$$

The linear 1-stage inverted pendulum system is a single-input and double-output fourth-order system without considering the disturbing force and a double-input and double-output fourth-order system considering the disturbing force. The 4 internal state variables is *X*, the cart's position, $\dot{x}$. , the cart's speed, θ, the angle of the pendulum bar, and $\dot{\theta}$, the angular velocity of the pendulum bar. The observed variety of the system output is, X the cart's position, and θ, the angle of the pendulum bar. The control variable is $\ddot{x}$, the cart's accelerated speed. F_f is the sum of all disturbing factors occurred in the motion of linear 1-stage inverted pendulum system, it is equivalent to the disturbing force.

Experiment Procedures

1. Establish the system transfer function

According to system differential equation (Formula 1.10), the formula can be transformed into the transfer function as regards the input of accelerated speed and output of angle.

$$\frac{\theta(s)}{R(s)} = \frac{3}{s^2 - 29.4}$$

2. Stability analysis for closed-loop system of linear 1-stage inverted pendulum Constitute the closed-loop system as shown in Fig. 1.4, and the closed-loop poles are (-5.1381) and (5.1381).

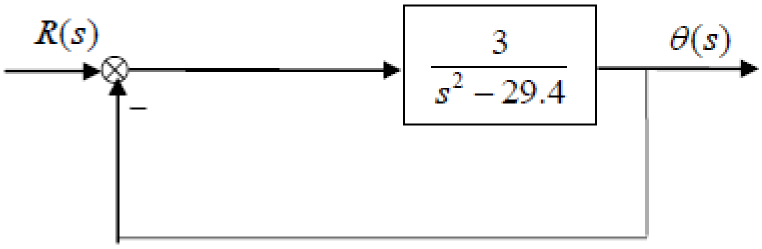


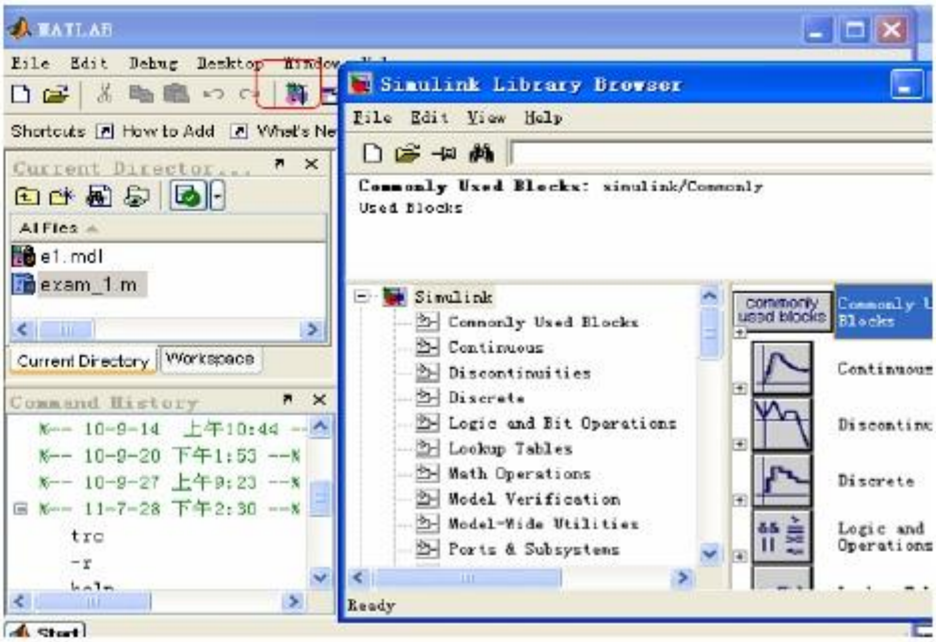
Fig. 13.4: Closed-loop Diagram

As the pole owns a positive value in the real part, the closed-loop is unstable, and a controller is necessary for the stability of the system.

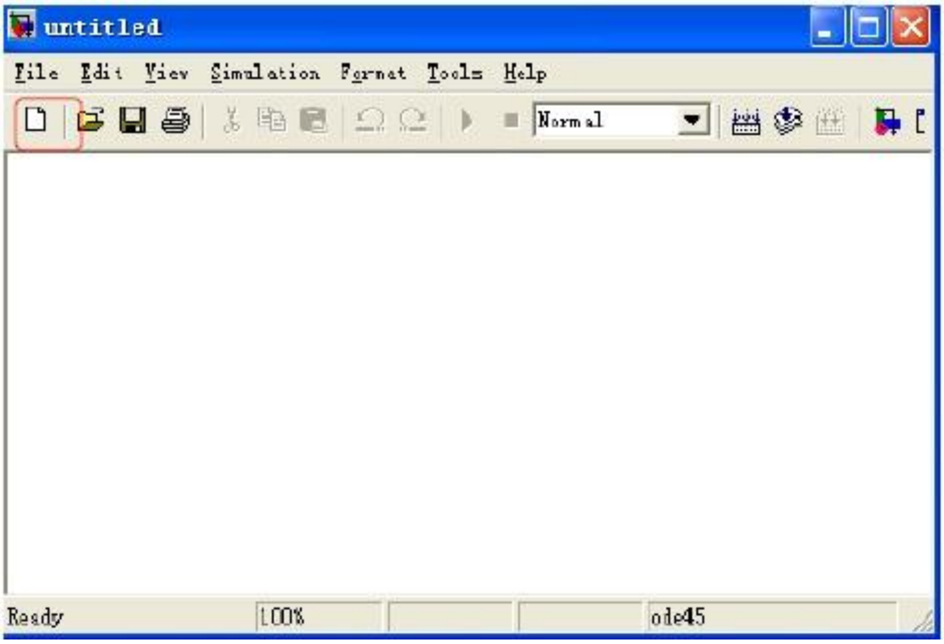
3. Simulation

Establish the simulation program e1 as shown in Fig. 1.4 in the MATLAB Simulink, and add the step signal at 1m/s2, the procedures are listed below.

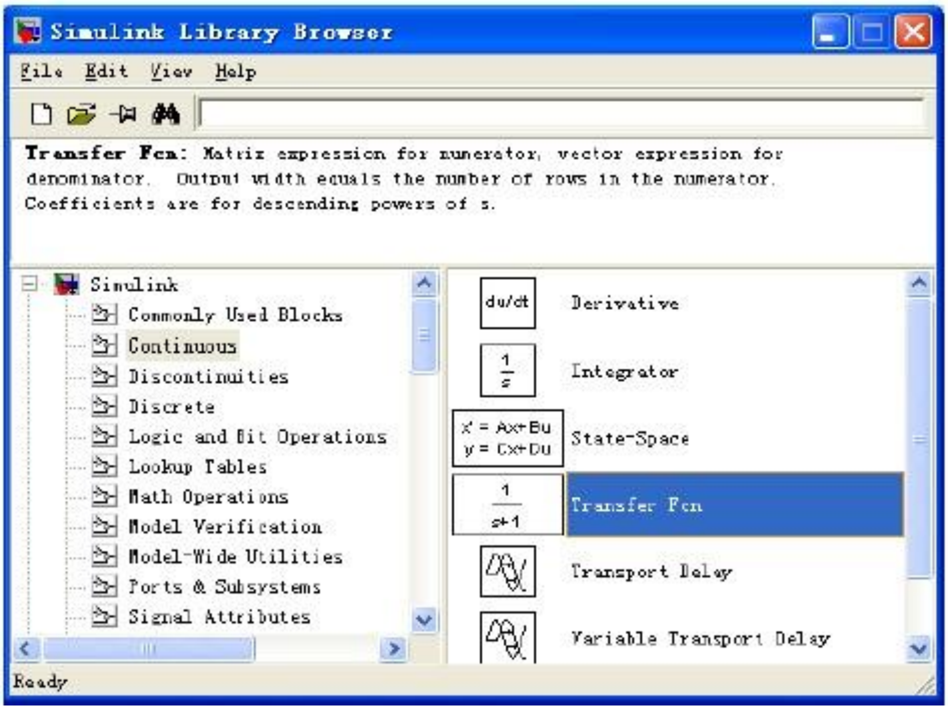
1) Open the MATLAB/Simulink simulation environment.



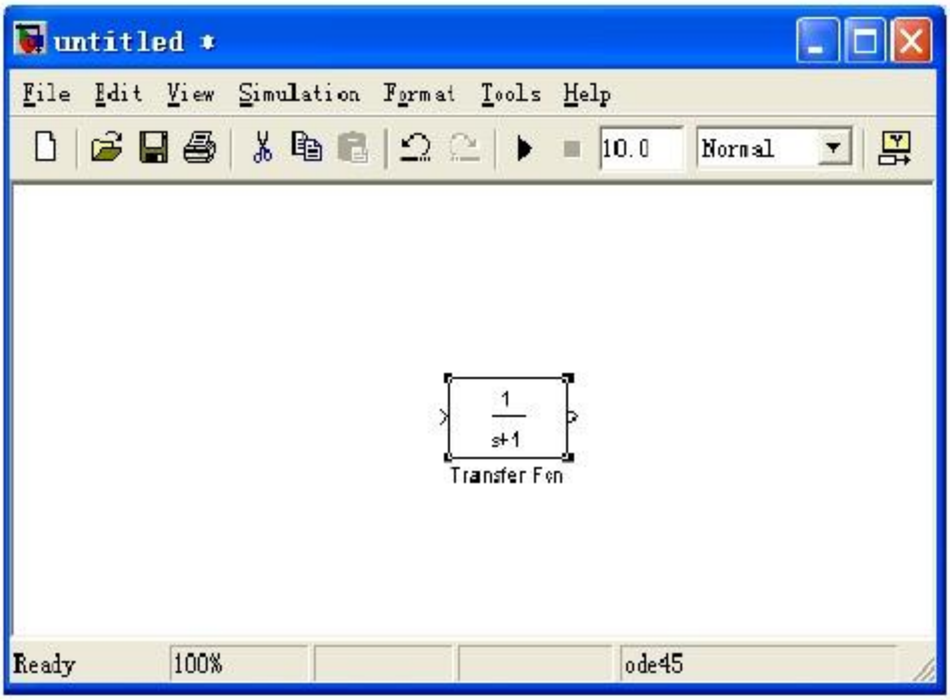
2) Click on the "" icon on the top left of the window to open a new "Model"window.



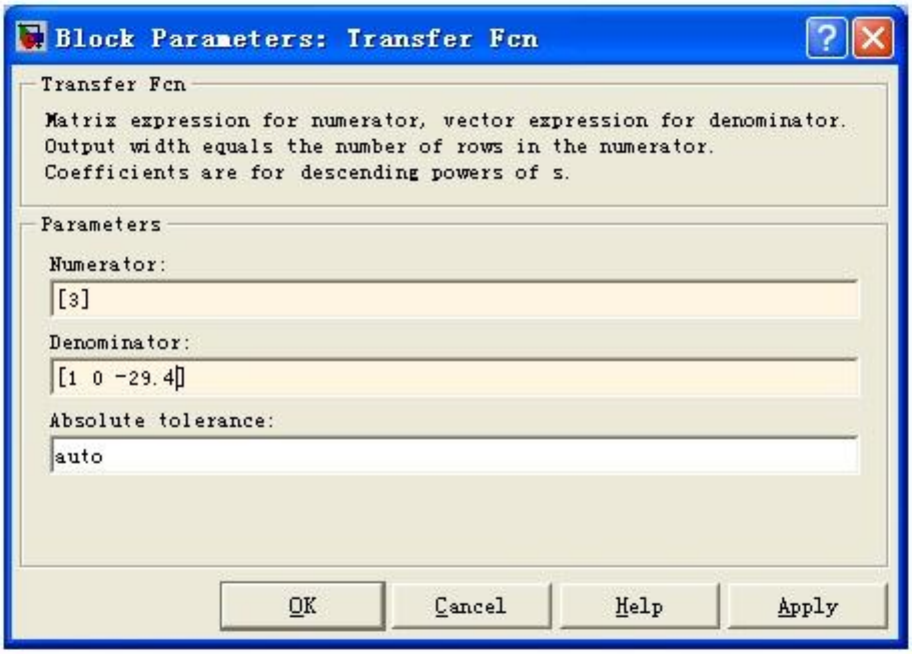
3) Open the “Simulink\Continuous “window as shown below in the “Simulink Library Browse “window.



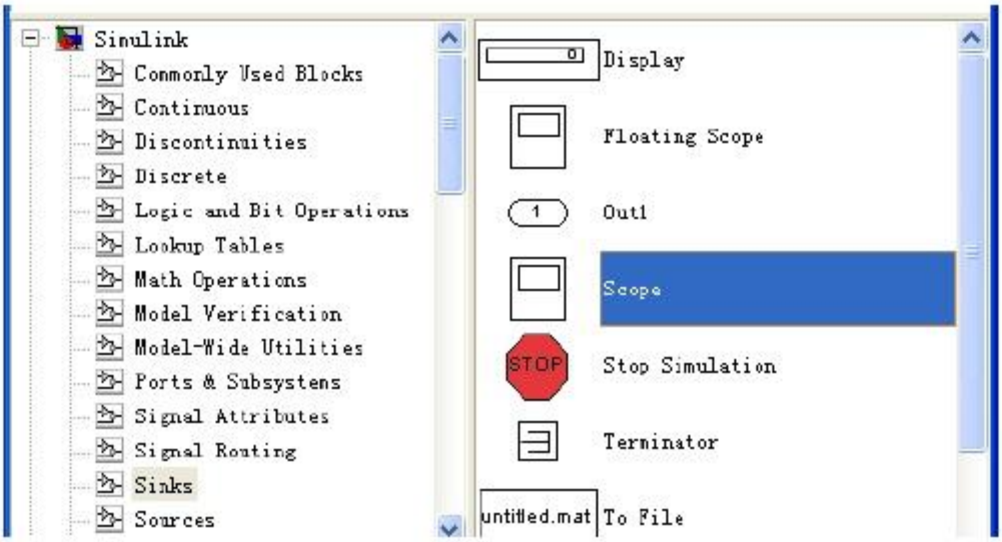
4) Drag the “Transfer Fcn”module into the newly build window named “untitled”.



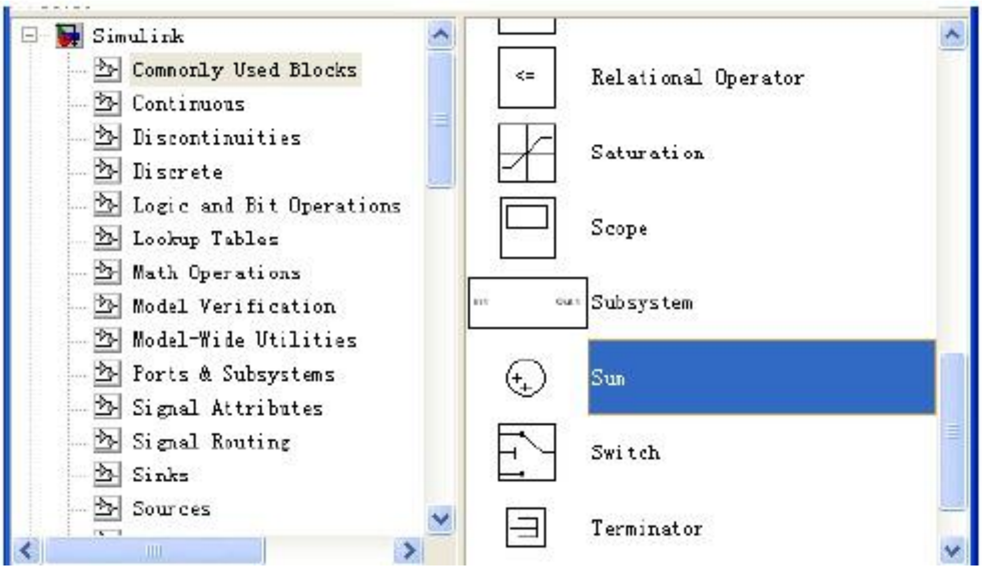
5) Double click on the “Transfer Fcn” module to open the window below, and come to parameters settings page.



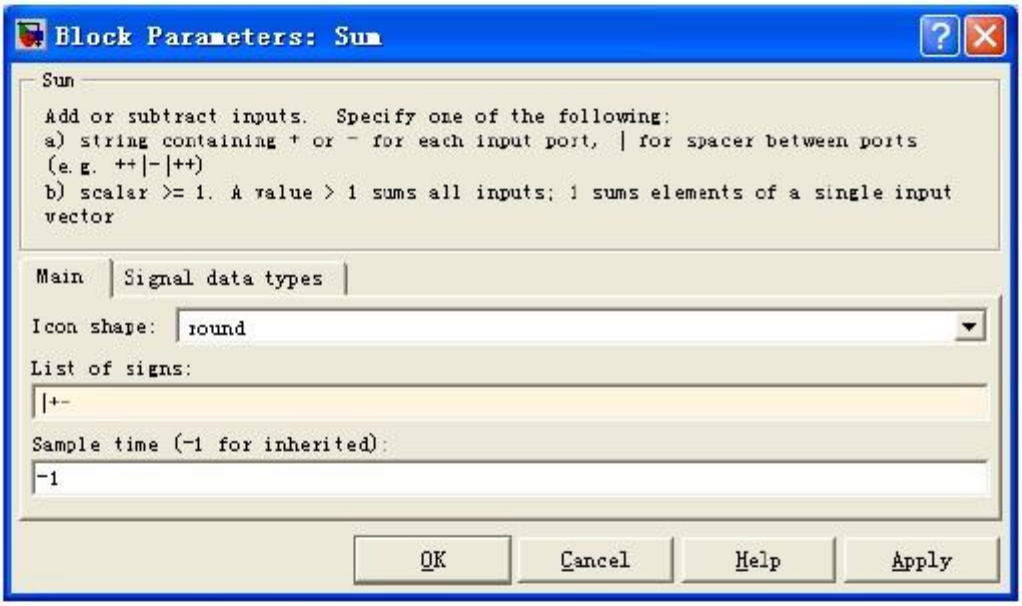
6) Drag a “Scope”from the “Simulink\Sinks”into the “untitled”window.



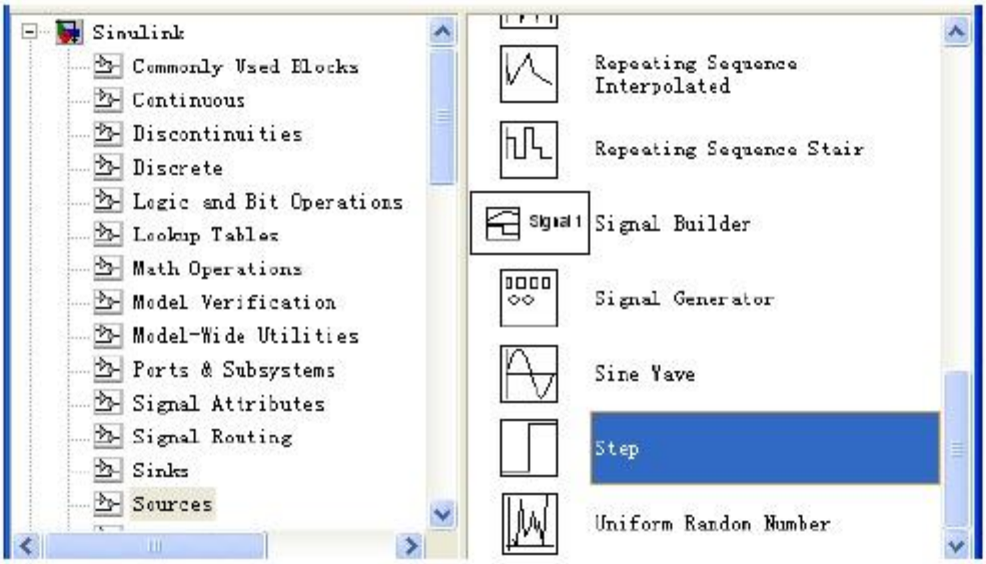
7) Drag a “Sum” from “Simulink\Commonly Used Blocks “to the “untitled “window.



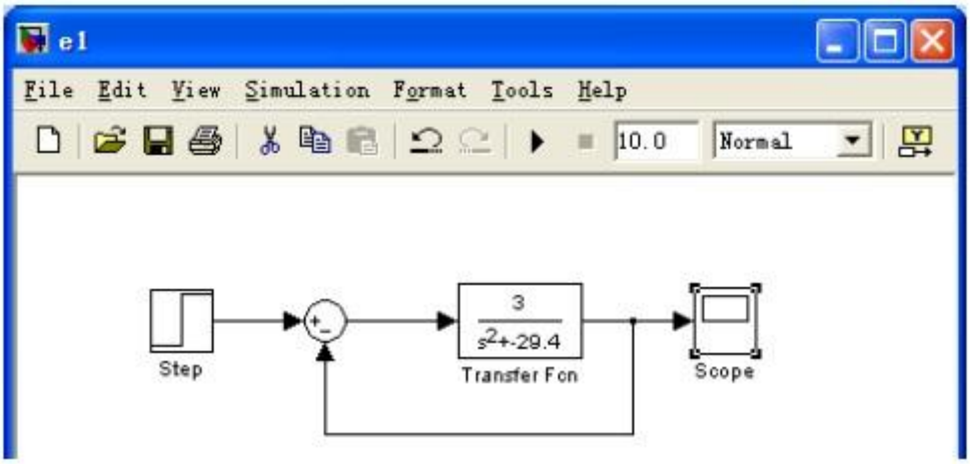
8) Double click on the “Sum” module and open the window below, then the feedback settings is presented.



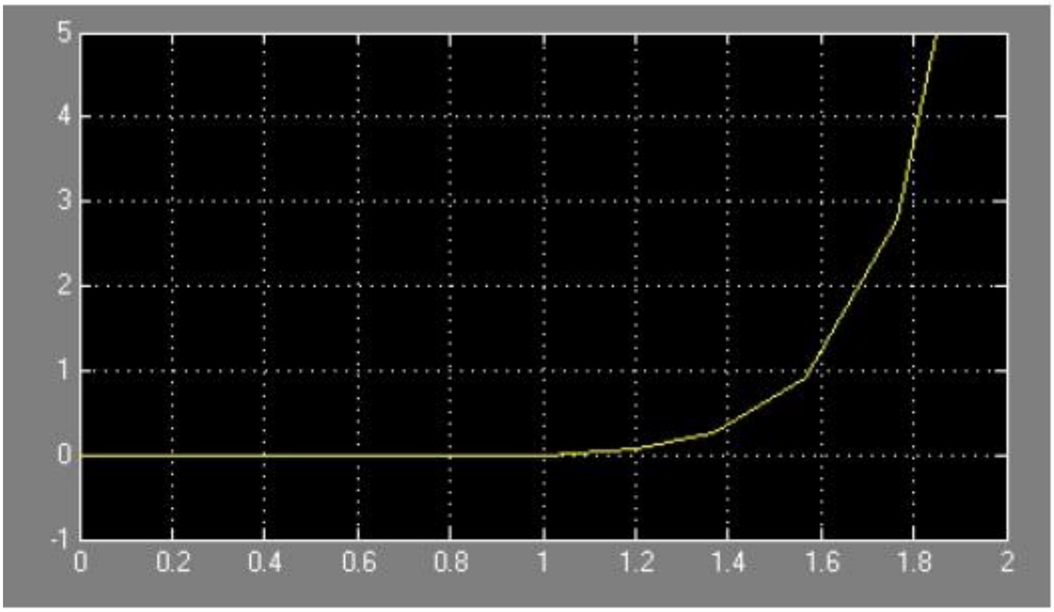
9) Drag a “Step” from “Simulink\Sources” to the “untitled” window.



10) Link the four modules following the instructions listed below and then save the file in the name of "e1", and the format of mdl.



11) Click on button "" then double click on "Scope" module, we will obtain the simulation curve. As the system at this moment is unstable, the curve is in the form of divergence.



Experiment Records

Fill the values obtained from simulation experiment into the table below:

Content	Values
Transfer function of the open-loop system	$\frac{\theta(s)}{R(s)} =$
Input signal of closed-loop system	
Output signal of closed-loop system	

Experiment Analysis and Questions

It is the pole position of the closed-loop system that affects the system stability. The system would be unstable if any pole locates at the s right half plane. One of the methods to measure the system stability is to add into step signal in appropriate size, and the system stability and other performances could be analyzed based on the output step response.

Questions: Summarize the basic procedures for modeling with mechanism methods based on the modeling

Procedures of linear 1-stage inverted pendulum.

1. Compose equation based on the physical laws of system motion;
2. Simplify it into differential equation;
3. Simplify it into transfer function of linear system based on linear theory about tiny deviation.

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

EXPERIMENT #14

PID Control of Inverted Pendulum

Experiment Purpose

1. Master the method to analyze system stability with root locus method.
2. Correct the linear 1-stage inverted pendulum with PID control.

Experiment Requirements

1. Analyze the stability of linear 1-stage inverted pendulum system with root locus method;
2. Correct the linear 1-stage inverted pendulum system with PID control;

Experiment Equipment

1. Linear 1-stage inverted pendulum.
2. Computer MATLAAB platform.

Experiment Principles

1. Analyze the stability of linear 1-stage inverted pendulum system with root locus method

The open-loop transfer function of linear 1-stage inverted pendulum system is:

$$\frac{\theta(s)}{U(s)} = \frac{3}{s^2 - 29.4}$$

The closed-loop root locus is mapped out as Fig. 14.1:

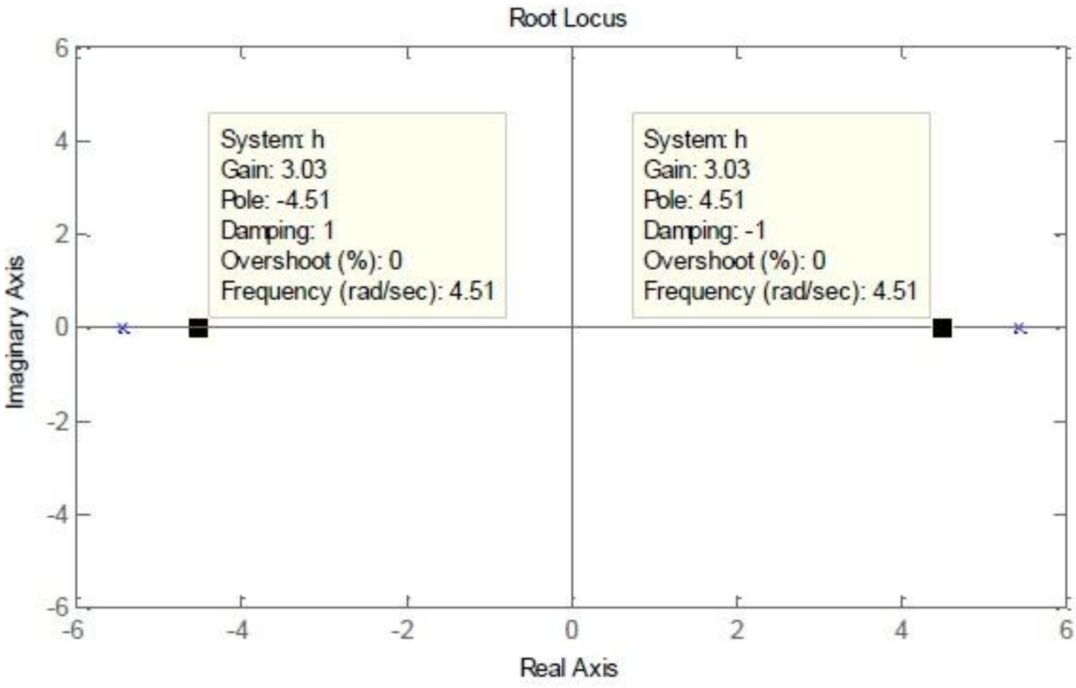


Fig. 14.1(a) Closed-loop Root Locus Diagram

Seen from the root locus, we can draw that one of the open-loop poles of the closed-loop transfer function is located at the right half plane, and the root locus of the closed-loop system is imaginary axis symmetric, which means that the closed-loop root will maintain at the positive real axis or imaginary axis no matter how the root locus gains change, i.e. the system is unstable or in critical stability.

2. Correct linear 1-stage inverted pendulum system with PIC control

(1) Introduction to PID

A great number of PID control algorithms have their own application ranges. Three different algorithms are given respectively in Fig. 14.1, Fig. 14.2 and Fig. 14.3.
In simulated control system, the PID control is the most commonly used one. The principle block diagram of the simulated control system is shown in Fig. 14.1. The system is composed of simulated PID controller and the controlled object.

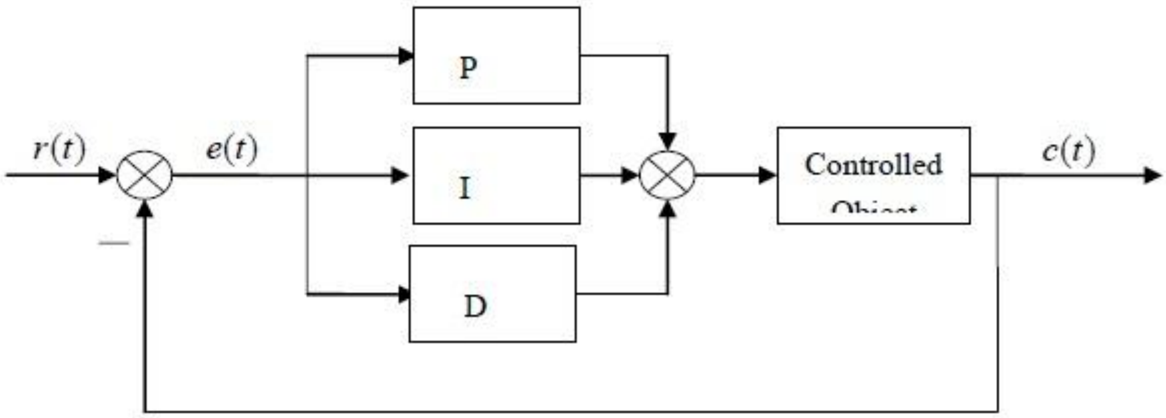


Fig. 14.1(b) Principle Block Diagram of Simulated PID Control System

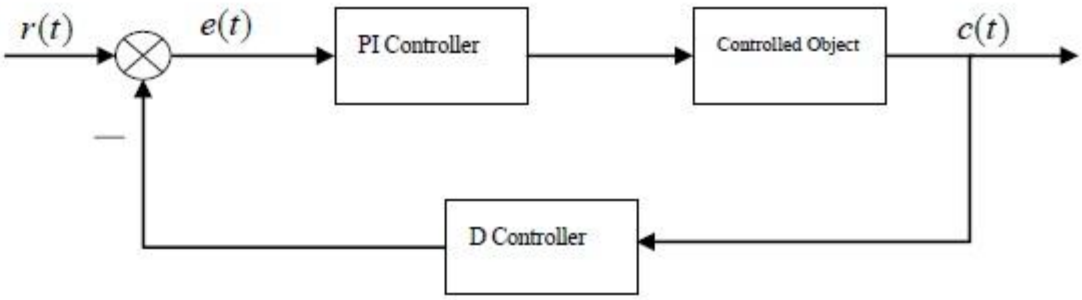


Fig. 14.2: Differential Antecedent PID Control Schematic Diagram

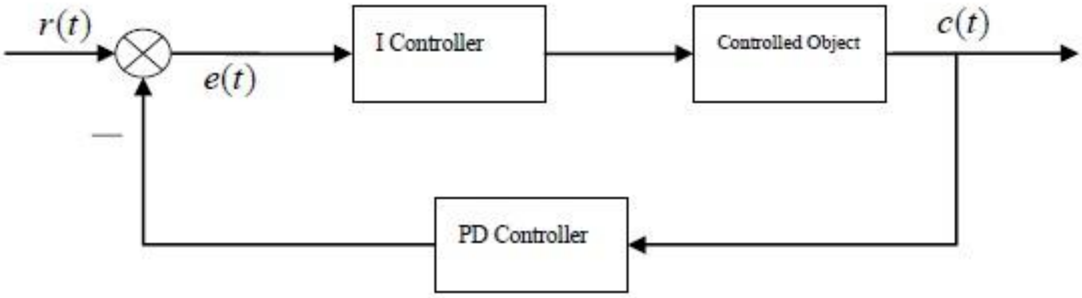


Fig. 14.3: Puppet PID Control Schematic Diagram

As a kind of linear controller, the PID controller shall constitute control deviation e (t) between the given value r (t) and actual output value.

$$e(t) = r(t) - c(t)$$

The PID controller is so called because it combines Proportion P, Integral I with Differential D of the deviation via linear means, and constitutes the control variable to have the object controlled. The law is:

$$r(t) = K_P\left[e(t) + \frac{1}{T_I}\int_0^t e(t)dt + T_D\frac{de(t)}{dt}\right]$$

Or in the form of transfer function:

$$G(s) = \frac{R(s)}{E(s)} = K_P\left(1 + \frac{1}{T_I s} + T_D s\right)$$

Where, K_P means proportion coefficient T_I, integral time constant T_D and differential time constant. In control system design and simulation context, the transfer function is also written in the form of:

$$G(s) = \frac{R(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_p s + K_I}{s}$$

Where, K_p means proportion coefficient, K_I integral coefficient, and K_D differential coefficient. Seen from the standpoint of root locus, formula (3.5) is equivalent to adding a pole located at base point and two null points with variable location to the system.

To be simple, each calibration sector of the PID controller works as below:

A. Proportion sector: it reflects the deviation signal *e* (*t*) of the control system in proportion; the controller shall work as soon as the occurrence of the deviation to reduce it.

B. Integral sector: It is mainly used to eliminate the static error and improve system type level. The role of integral is negatively correlated to the integral time constant T_I, i.e. the larger the T_I, the weaker the integral's role.

C. Differential sector: It reflects the change trend (change rate) of the deviation signal, introduces an effective early correction signal into the system before the deviation signal enlarges, so as to speed up the process and shorten tuning time.

(2) Determination method for PID parameters

A. Determination of PID parameters with root locus method.

The mathematical model of PID can be transformed into:

$$G(s) = \frac{K_D s^2 + K_p s + K_I}{s}$$

It is equivalent to adding an open-loop pole located at base point and two open-loop null points with variable location to the system, therefore, the root locus method is applicable to the determination of PID parameters, which is based on the expected performance index as regards the system with known low-order mathematical model.

B. Determination of PID parameters with frequency response method

As regards the system with known frequency characteristic curve, the PID controller is equivalent to adding an integral link and a second-order differential link to such curve, which can, through the adjustment of PID parameters, change the frequency characteristic of the PID controller, so as to further change the frequency characteristic of the closed-loop system.

C. Determination of PID parameters with trial-and-error method

During the adjustment process of PID parameters, it is desirable to determine such parameters with theories; however, it is more common to determine such parameter with trial-and-error method in actual application in consideration of various factors.
In general, the increase of proportion coefficient P can accelerate the system response, which is favorable to offset reduce, while over-large P value would result into large overshoot, which is accompanied with oscillation, and would deteriorate the system stability.
The increase of integral time I can reduce overshoot and oscillation, and improve the system stability, which however will require longer time to eliminate the offset.
The increase of differential time D can shorten system response, reduce overshoot and improve the system stability, which however will undermine system capability to inhibit disturbance.
During the progress of trial-and-error, the adjustment sequence of proportional, integral and differential may be imposed on the parameters in reference of the influence trend on system control by parameters listed above.
The increase of integral time I can reduce overshoot and oscillation, and improve the system stability, which however will require longer time to eliminate the offset.
The proportion link shall be firstly adjusted. To be specific, the proportion coefficient shall be changed from small to large, accompanied with observation of corresponding system response till the curve characterized by fast response and little overshoot is obtained. If the system has no or little to the allowed range offset, and the response curve is satisfied, then the regulator is the only one required.
If the system offset has a gap to the satisfactory value on the basis of proportional adjustment, the integral link is necessary. Prior to the adjustment process, the integral time shall be set at a large value, followed by that, the regulated proportion coefficient shall be lessen slightly (generally80% of the original value), with the reduction of the integral time, which would eliminate the offset under constant fair system dynamic performance. During such progress, the system response curve may be based to repeatedly change the proportion coefficient and the integral time, in the aim to get satisfactory control process and adjustment parameters.
However, if the process listed above fails to lead to the satisfactory result, then the differential link shall be added in. firstly, the differential time D shall be set a0, then increase the D

gradually and alter the proportion time and integral time at the same time. Such process shall be done in a trial and error manner till the obtaining of a satisfactory result.

(3) Instances for determination of PID controller parameters with root locus

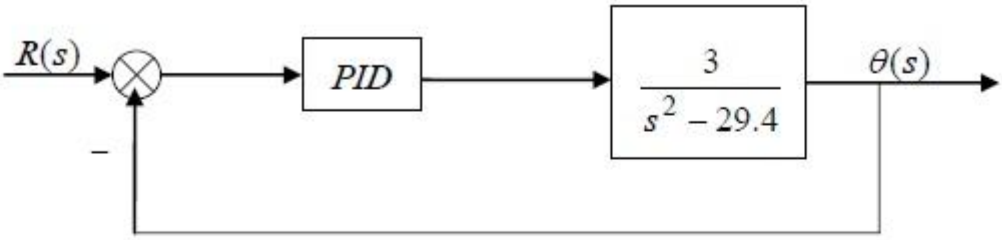


Figure 14.4: linear 1-stage inverted

The open-loop transfer function for angle control system is

$$G(s)=\frac{3k_d\left(s^2+\frac{k_p}{k_d}s+\frac{k_i}{k_d}\right)}{s\left(s^2-29.4\right)}$$

The open-loop pole is -5.42, 0, and 5.42.
The open-loop null point is

$$-\frac{k_p}{k_d}+\sqrt{\left(\frac{k_p}{k_d}\right)^2-4\frac{k_i}{k_d}} \qquad -\frac{k_p}{k_d}-\sqrt{\left(\frac{k_p}{k_d}\right)^2-4\frac{k_i}{k_d}}$$

The PID link adds a pole located at base point and two null points with variable location to the system, and the system would have two null points and three poles. The third-order system may apply the root locus method to determination of PID parameters. While the root locus may be divided into eight categories based on the relative location of the two null points, see the Fig. 14.4 to Fig. 14.12.

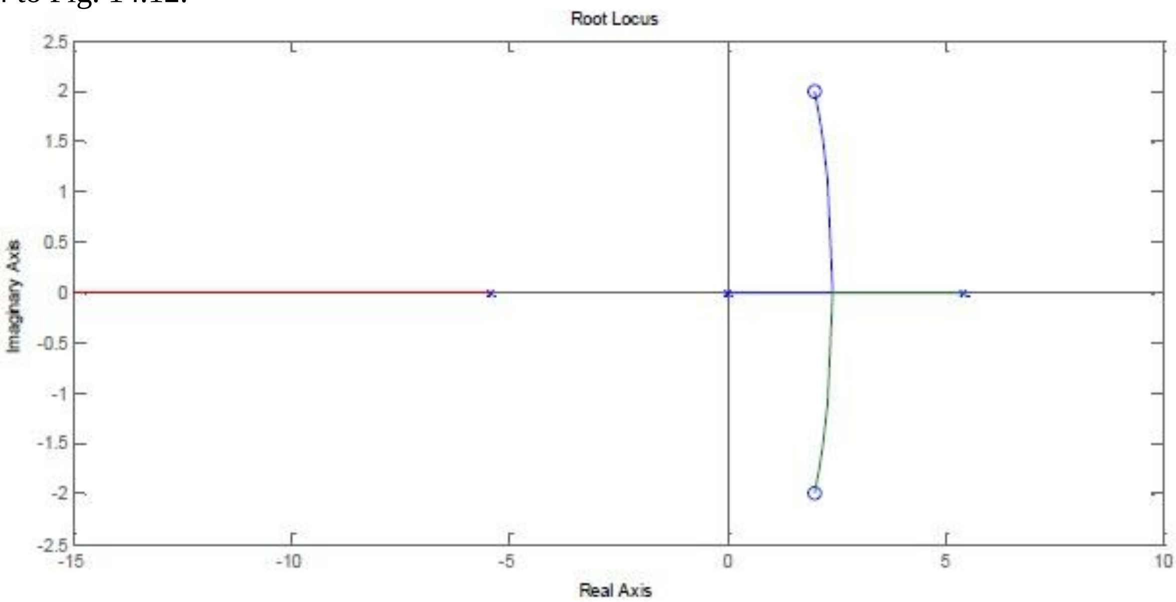


Figure. 14.4: Two Conjugated Null Points of (e3_1.m) Located at the Right Half Plane

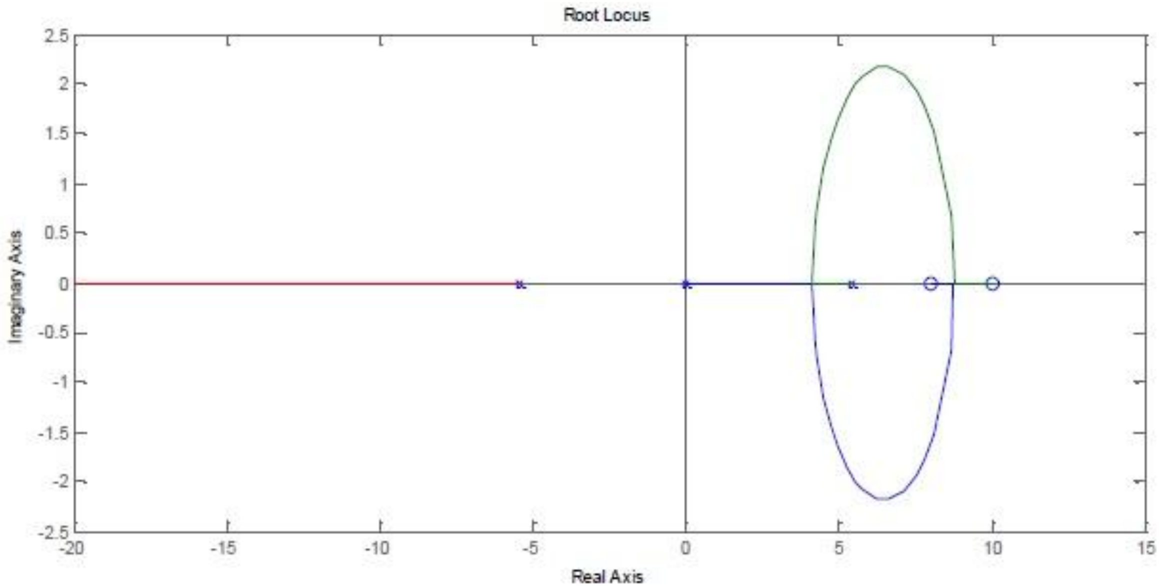


Figure 14.5: Two Null Points of (e3_2.m) on the Positive Real Axis Located at the Right of the Positive Pole

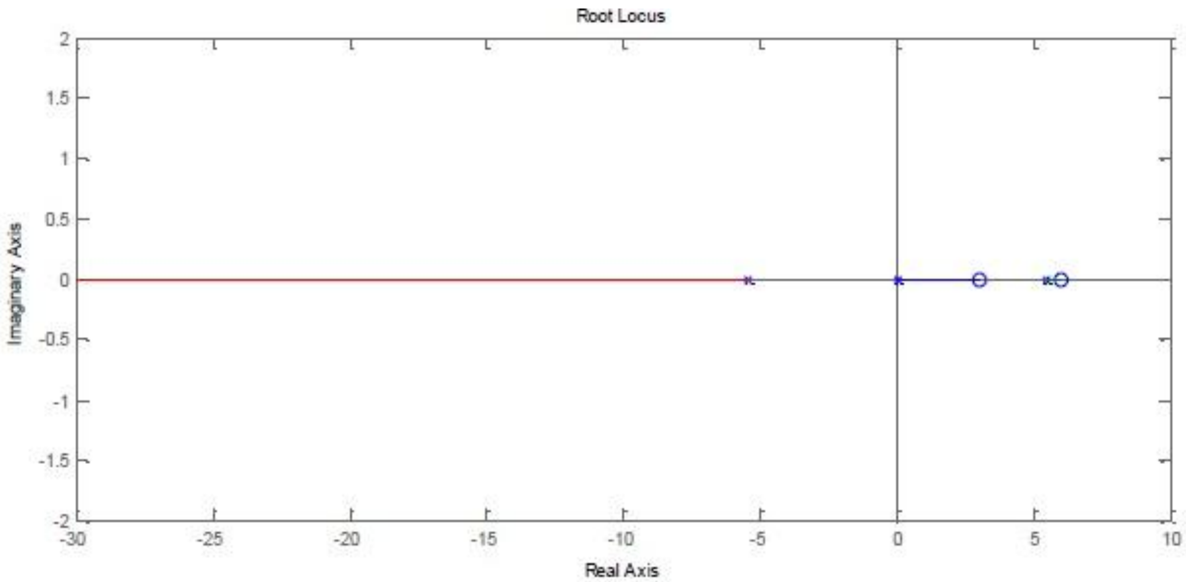


Figure. 14.6: Two Null Points of (e3_3.m) on the Positive Real Axis with One Located at the Right of the Positive Pole

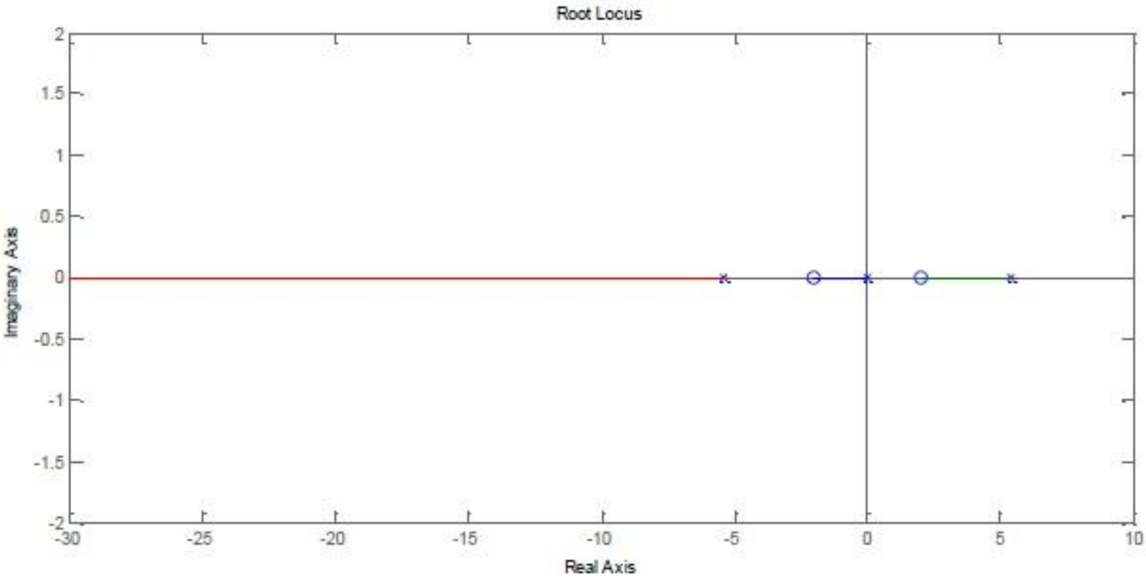


Figure. 14.7: One Null Point of (e3_4.m) Located at the Positive Real Axis and the Other the Negative Real Axis

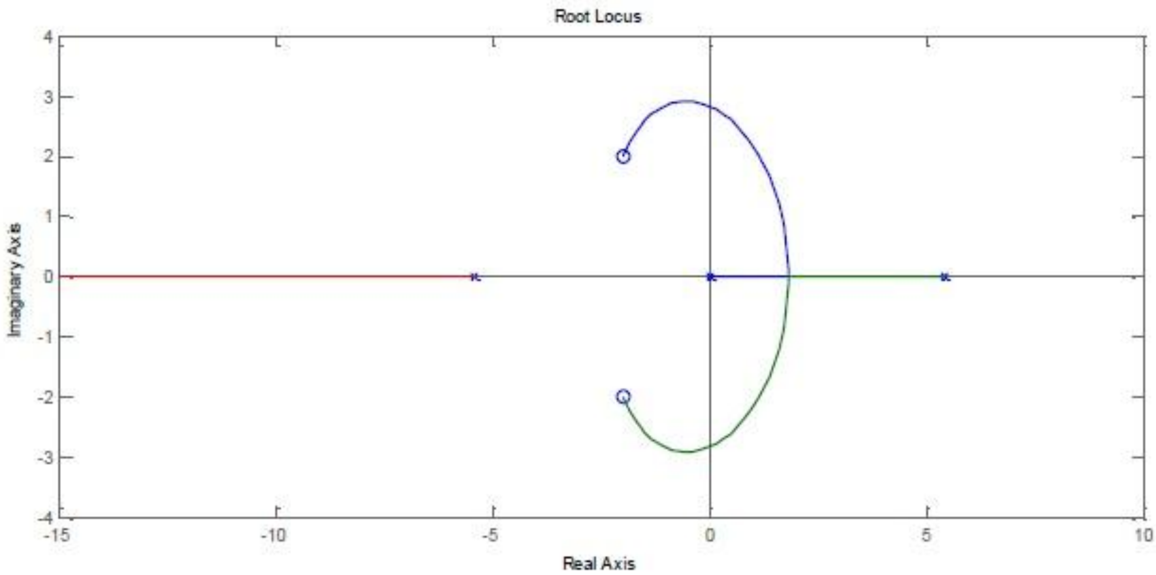


Figure. 14.8: Negative Real Links of Two Conjugated Null Points of (e3_5.m) Located between Negative Pole and the Base Point

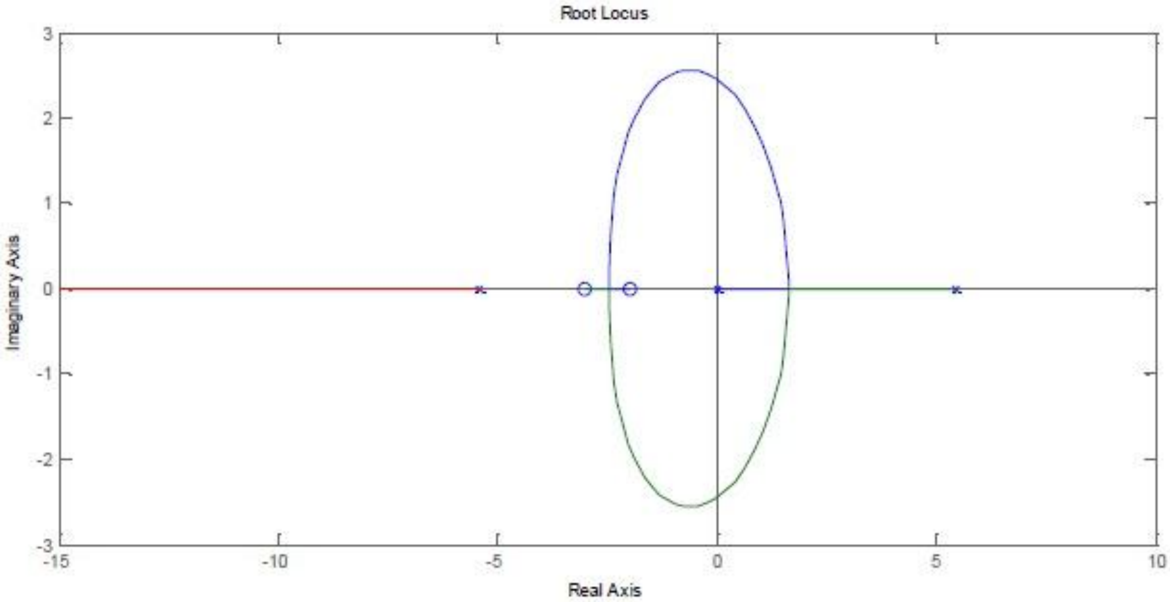


Figure. 14.9: Two Negative Real Null Points of (e3_6.m) Located between Negative Pole and the Base Point

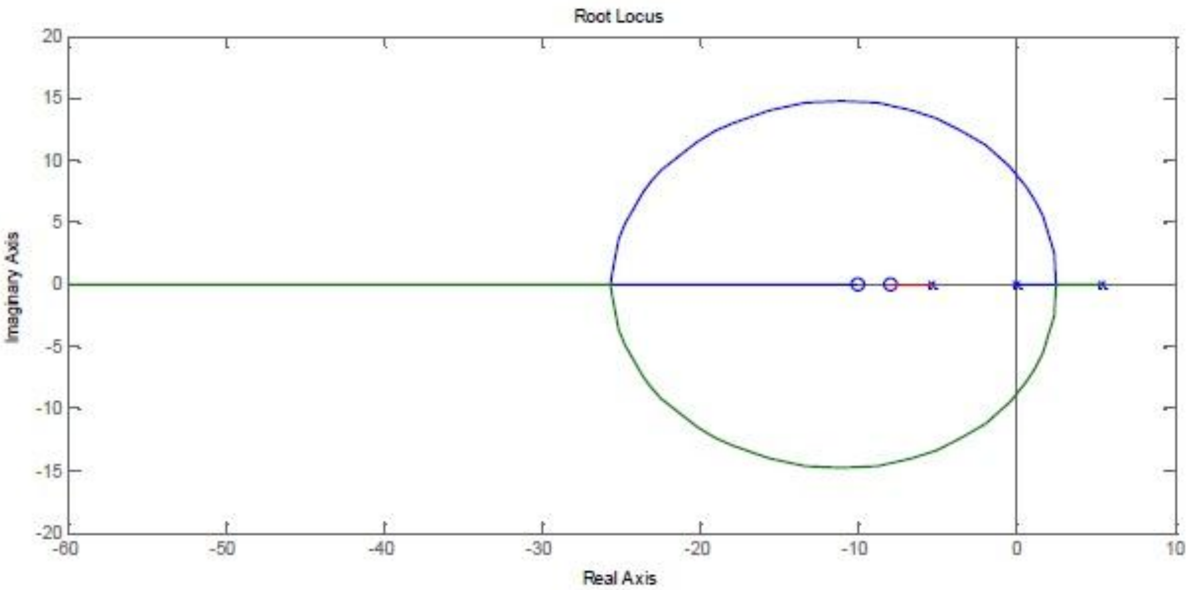


Figure. 14.10: Two Negative Real Null Points of (e3_7.m) Located on the Left of the Negative Pole

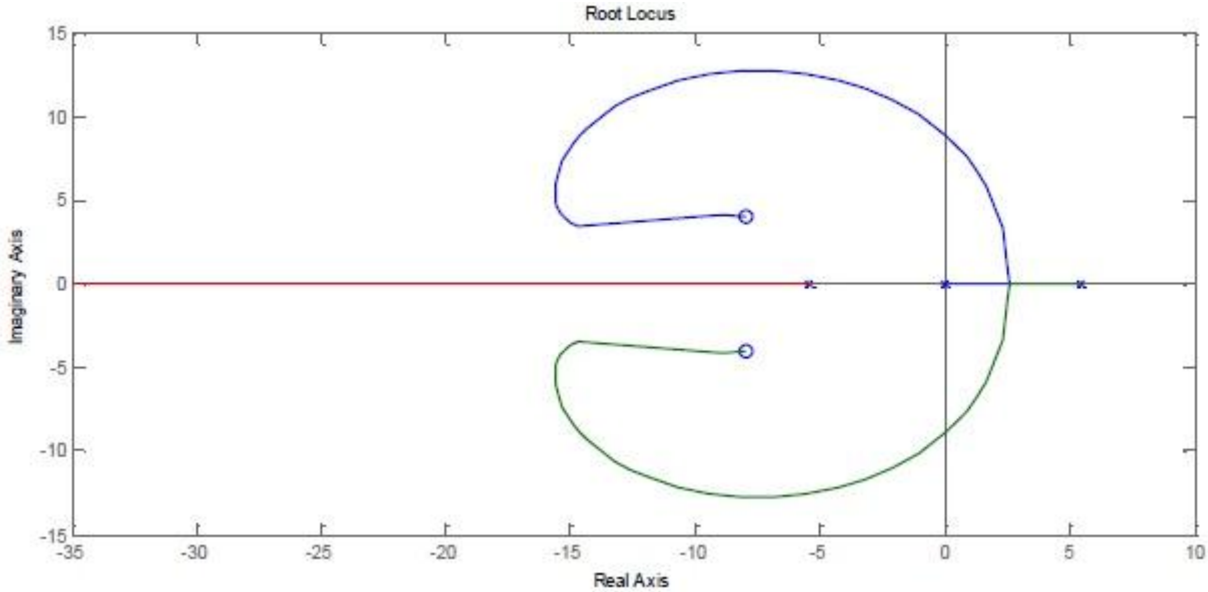


Figure. 14.11: Two ConjugatedNull Points of (e3_8.m) with the Negative Real LinkLocated on the Left of the Negative Pole in a Short Distance to the Negative Pole

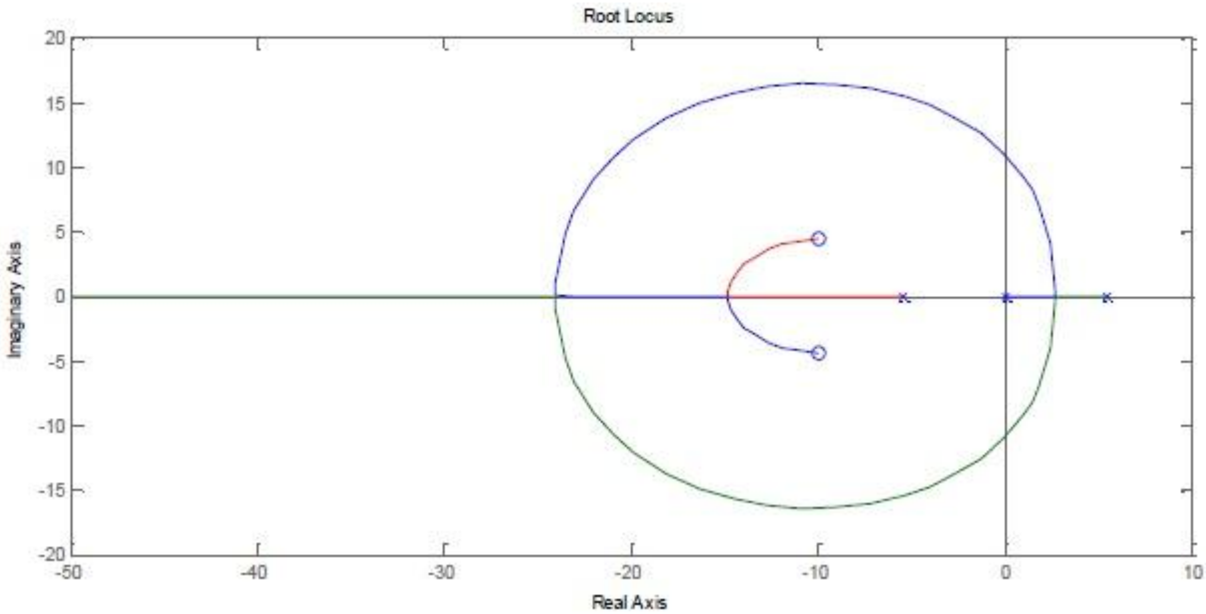


Figure. 14.12: Two Conjugated Null Points of (e3_9.m) with the Negative Real Link Located on the Left of the Negative Pole in a Far Distance to the Negative Pole

Drawn from the eight figures listed above, the four types of root locus shown in Fig. 14.4, Fig. 14.5, Fig. 14.6 and Fig. 14.7 means that there is a right pole to the closed-loop system, which is unstable. Fig. 14.8 and Fig. 14.9 show that there are at least two closed-loop poles located between the left pole and the base point, which is bad to system speed ability. Fig. 14.10 shows three closed-loop poles located at the left of the left pole, but one pole has a short root locus branch, which means that the system speed ability is hard to improve largely even under great change to the root locus gain. Fig. 14.11 and Fig. 14.12 manifest that the closed-loop pole may be, through the adjustment of the root locus gain, located at the left of the left open-loop pole, proximate to the negative real axis, all of which would lead to the system with good speed ability and stability.

Assume that kp=200, kd=10, ki=1090, when the conjugated null points of the system are located at the $-10 \pm 3i$, and the root locus gain is 30, then the system closed-loop pole is -8.4、$-10.8 \pm 16.5i$, which means the root locus gain may be kept enlarging to reduce system overshoot and the regulation time. The root locus is shown as Fig. 14.13.

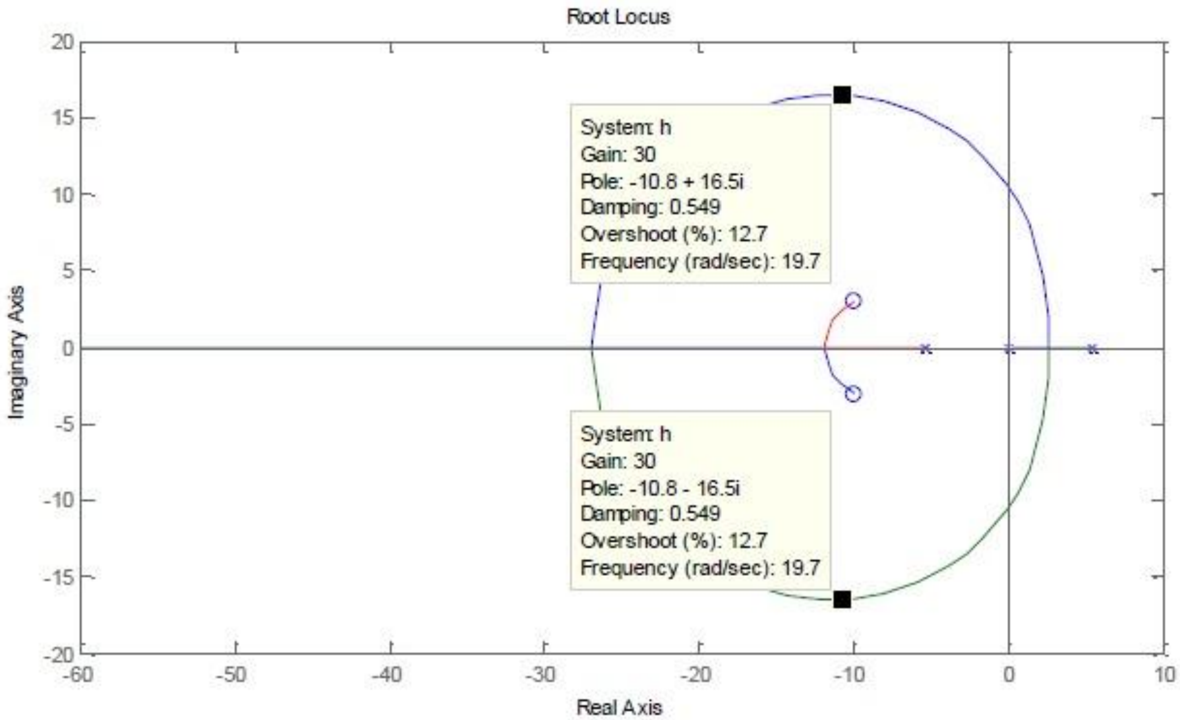


Figure. 14.13: Root Locus Diagram

The simulated diagram for angle output is shown as Figure. 14.14.

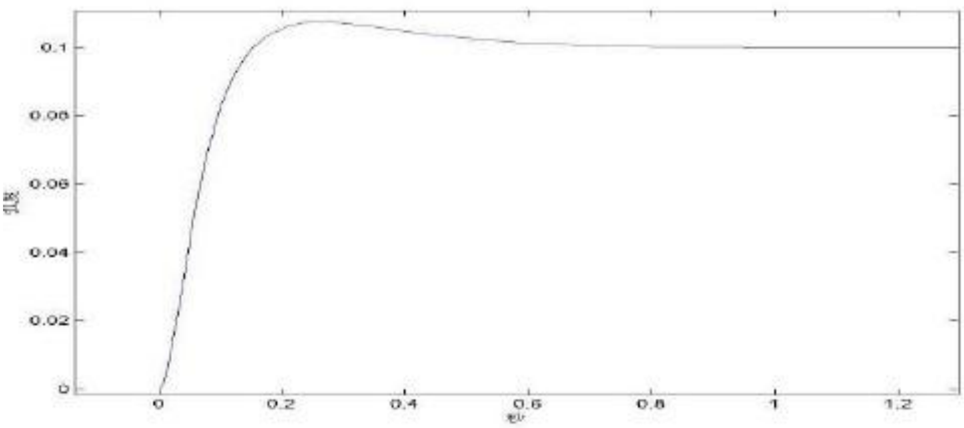


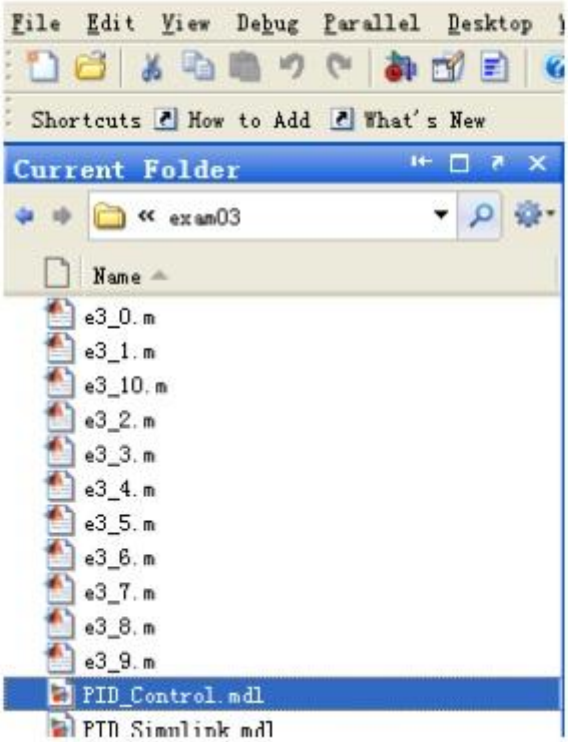
Figure. 14.14: Simulated Diagram for Step Response of Angle Output

The angle overshoot is 11.5%, regulation time s0.5 s, and the angle output is stable.

Experiment Procedures

1) Switch on the power button on the electric cabinet of the inverted pendulum, then place the inverted pendulum cart at the mid of the guide rail.

2) Open file “PID_Control.mdl”in MATLAB/Current Folder, then the real control page as shown in Fig. 14.15 will pop up.



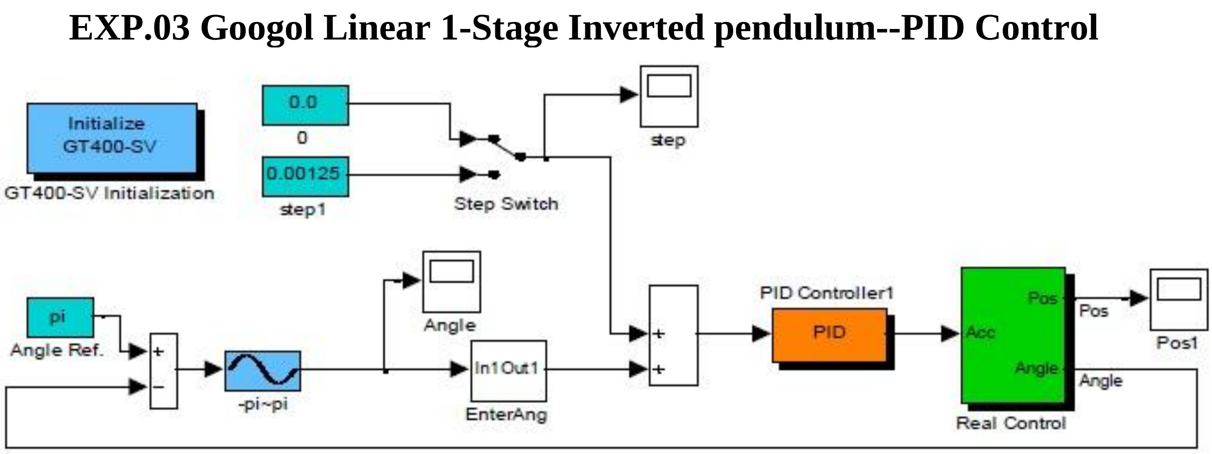


Figure 14.15: PID Control Simulink

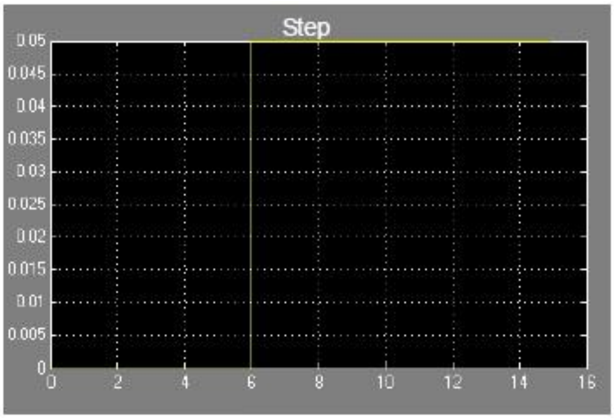
3) Click on “” to start real-time workshop build procedures.

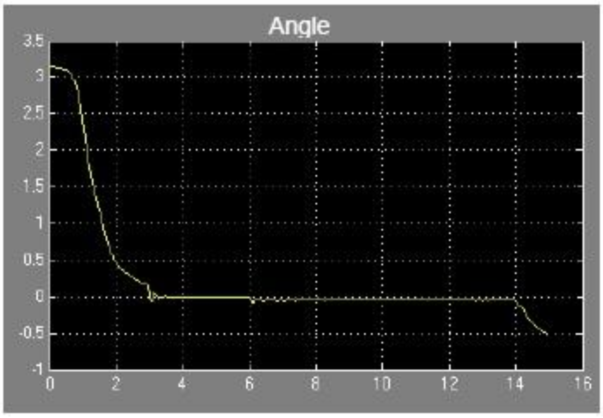
4) Click on  icon to link the programs, when the buzzing generated from the motor after servo would be heard.

5) Click on  button to operate the program, then manually place the pendulum bar to the straight up position, when the program would enter control state. Hold the pendulum bar and maintain it at the mid of the guide rail.

6) Double click on the “Step Switch1”to stimulate the input signal to the $0.05 m/s^2$ end, hold the pendulum bar still for 10s, and then observe the motion with hands off.

7) Click on  button to stop the program, and double click on the "Step" and "Angle" oscilloscopes to observe the response of system output in Angle when the signal in Step in switched into $0.05 m/s^2$.





Experiment Records

1. Fill the values obtained from experiment into the table below,

Content	Values
Controller Forms and Parameters	
Input Signal	
Output Signal	

2. Describe the motion of the inverted pendulum cart.

Experiment Analysis and Questions

1. Reason analysis for system instability

The linear 1-stage inverted pendulum system is composed of a cart moving along a smooth guide rail, with a pendulum bar linked on the cart with hinge. When the pendulum bar is controlled, the position of the cart is limited by the length of the guide rail. Therefore, the output covers the angle of the pendulum bar and the position of the cart. The relation between theposition and the input -the accelerated speed of the cart is:

$$\frac{X(s)}{R(s)} = \frac{1}{s^2}$$

The structure of the control system is shown as Fig. 14.16:

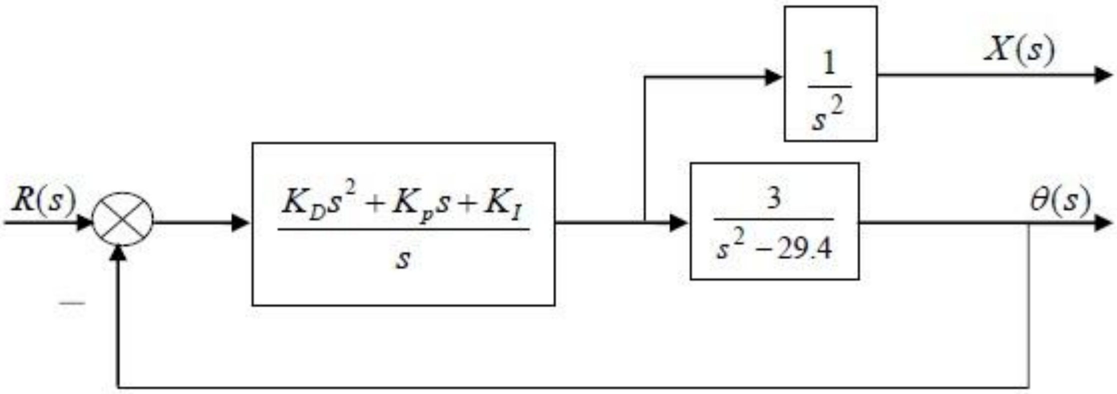


Figure. 14.16: Structural Diagram with Controller

At this moment, the simulation diagram for position output is shown as Fig. 14.17 (unit: Abscissa axis is s, and the ordinate axis is m).

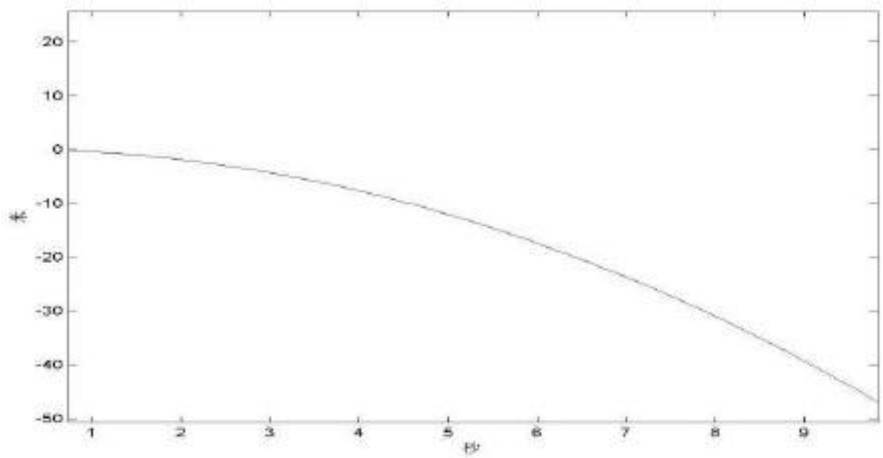


Figure. 14.17: Step Response for Displacement Output

The cart is in accelerated movement to the other end, it will knock into the wall, and the pendulum bar is unstable.
The inverted pendulum's motion will inevitably disturbed by various factors, and the angle and position will fluctuate within certain range even under balanced state. Hence, a constant tiny step signal may be added on the input end to compensate the disturbance upon the inverted

pendulum's stability, i.e. static compensation to have the inverted pendulum in static stability state.
Note: The value of static compensation is dependent on the velocity, direction and guide rail's friction of the holding of the inverted pendulum bar, which requires repeated trial as deviations will occur each time.
2. Realization of static compensation

The static compensation experiment requires two people's joint effort. And the procedures are listed as below:
1) Switch on the power button on the electric cabinet of the inverted pendulum, then place the inverted pendulum cart at the mid of the guide rail.

2) Open file "PID0.mdl"in MATLAB/Current Folder, then the real control page as shown in Fig. 3.18 will pop up.

EXP.03 Googol Linear 1-Stage Inverted pendulum--PID Control

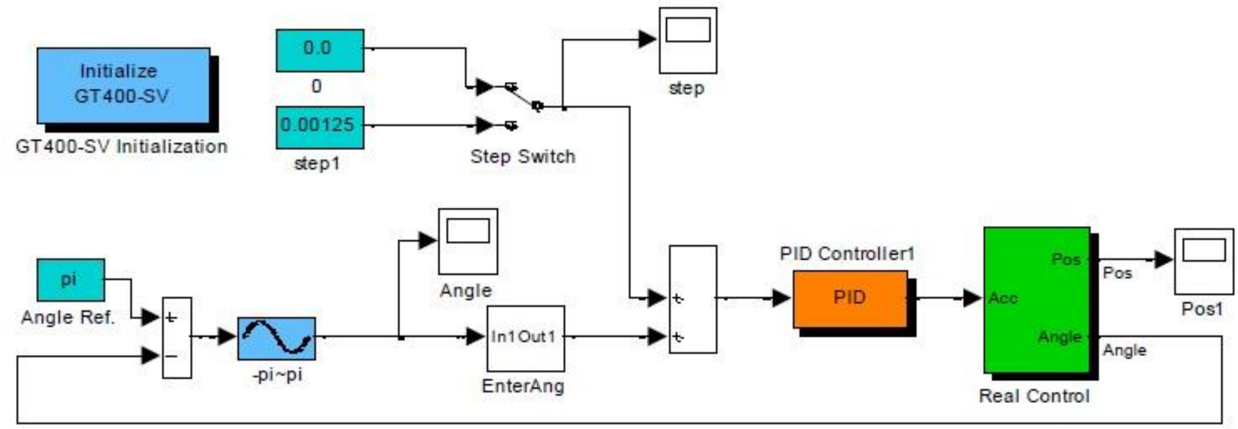


Fig. 3.18 Real Control Diagram for Static Compensation of Displacement

Click on "" to start real-time workshop build procedures.

4) Click on "" icon to link the programs, when the buzzing generated from the motor after servo would

be heard. Then Click on "" button to operate the program.

5) **Experimenter1** shall swiftly lift the pendulum bar to the straight up position, and release its lowly after the program is under control. Hold the pendulum bar still at the same time.
6) **Experimenter2** shall double click on the "Step Switch" to stimulate the input signal to the 0.05m/s2end.
7) **Experimenter1** shall slowly release the pendulum bar. If the cart is unable to stand still, then observe the motion direction and speed of the cart.
8) **Experimenter2** shall adjust the input signal value at the software page as shown in Fig. 14.19. The method is to place the input signal reverse to the motion direction of the cart; if the motion speed is too fast, then reduce the input signal value appropriately.

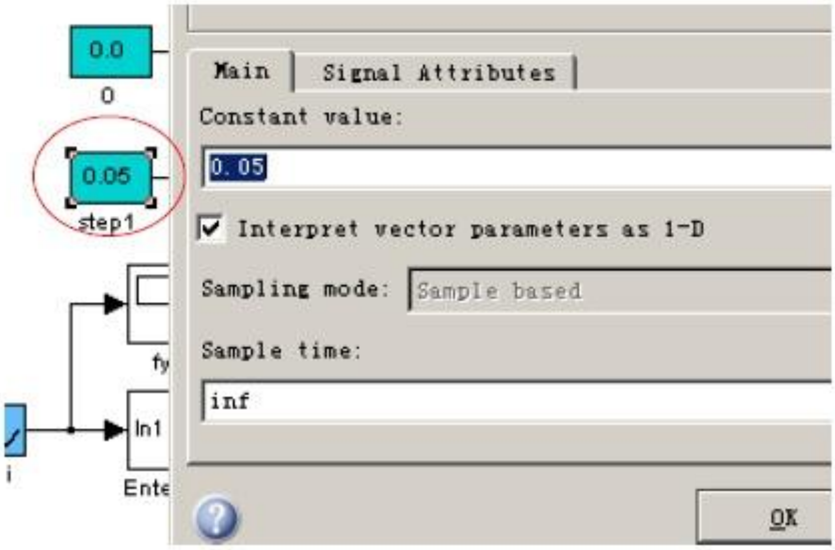


Figure. 14.19: Parameter Adjustment of the Static Compensation

9) Repeat procedures 8)-9) till the balance of the cart with hands off.

10) Record the static compensation value and fill it into the Experiment Records table.

3. Questions

A. How to determine the parameters of PID controller?

B. Whey PID control is widely used in industries?

TASK: Submit a separate report according to the format given in appendix C.

Registration Number------------------------------

Student Name------------------------------

Teacher Signature ------------------------------

EXPERIMENT #15

Frequency Response Control of Inverted Pendulum

Experiment Purpose

1. Master the method to analyze system stability with frequency response method.
2. Correct the linear 1-stage inverted pendulum with frequency response control.

Experiment Requirements

1. Analyze the stability of linear 1-stage inverted pendulum system with frequency response method.
2. Correct the linear 1-stage inverted pendulum system with frequency response control.

Experiment Equipment

1. Linear 1-stage inverted pendulum.
2. Computer MATLAB platform.

Experiment Principles

1. Analyze the stability of linear 1-stage inverted pendulum system with frequency response method

The transfer function of linear 1-stage inverted pendulum system is:

$$\frac{\theta(s)}{R(s)} = \frac{3}{s^2 - 29.4}$$

The Bode Diagram for open-loop system is shown as Fig. 15.1:

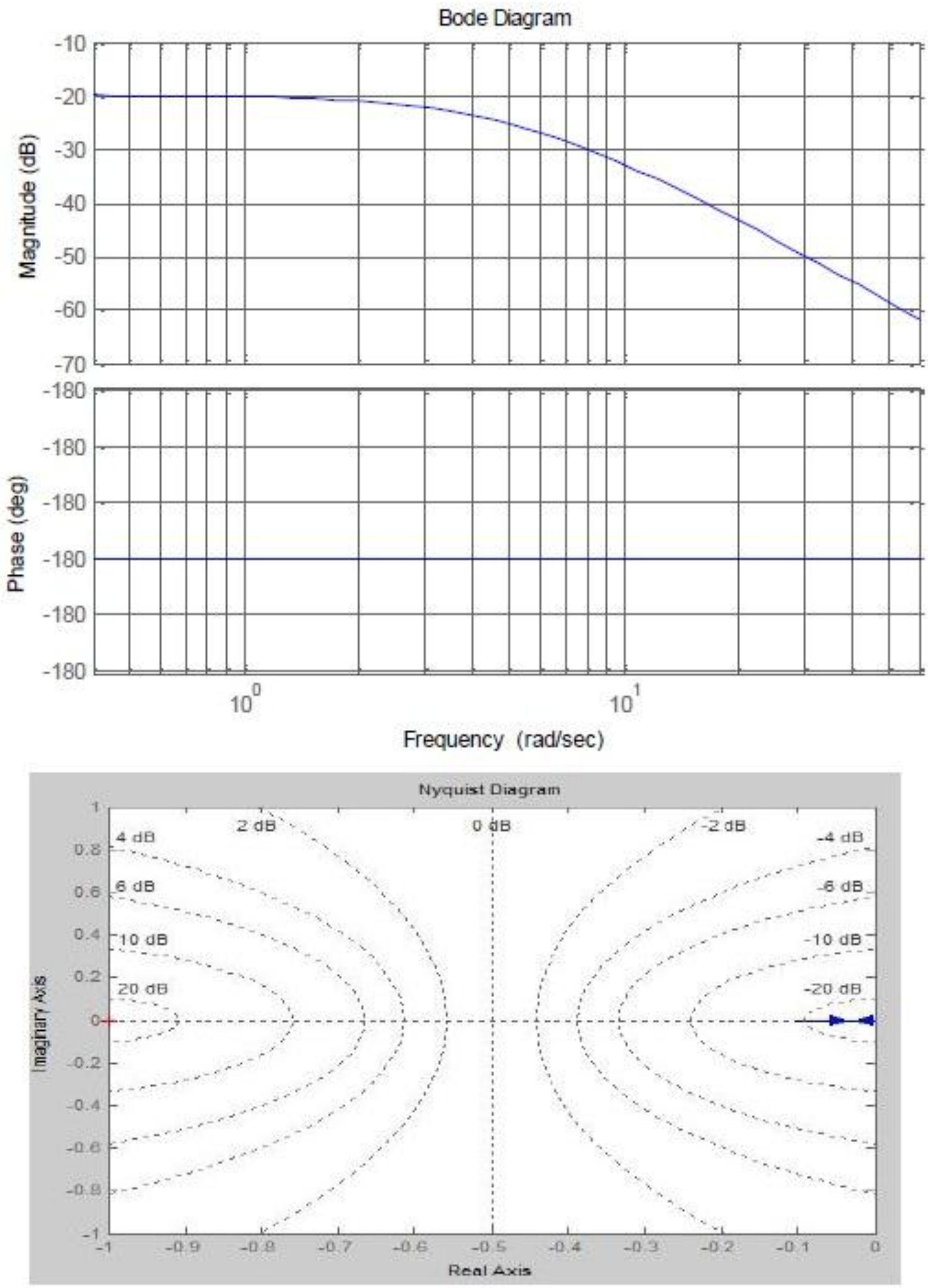


Figure. 15.1: The Bode Diagram and Nyquist Diagram for Open-loop System

The Nyqiust Criterion shows that the system is unstable, and a controller is required to stabilize the system.

2. Correct the linear 1-stage inverted pendulum with frequency response control

The control refers to adding some institutes or devices into the system to change the system characteristics, so as to satisfy the expected performance index. The control device can be linked through such means as series control, feedback control and composite control. The series control is used in main feedback circuit, generally after error detection and before amplifier. In general, the low frequency range of the open-loop frequency characteristic manifests the steady performance of the closed-loop system, the mid frequency range the dynamic performance, and the high frequency range the complexity and noise suppression ability. Therefore, the basic idea of frequency response is to have the open-loop frequency characteristic after control characterized by that:

A. The gain of the low frequency range is large enough to meet the steady-state precision;

B. The slope of the mid frequency range is -20db/dec, and the phase margin is around 45°with wide frequency band so as to endow the closed-loop with good dynamic performance;

C. The high frequency range requires fast attenuation in magnitude to reduce the influence of the noise.

The series control devices are divided into two categories, one is phase lead control. It utilizes the phase lead characters of the lead control device to enlarge the system phase margin and improve the system dynamic performance. Therefore, the requirement to control the largest phase lead angle occurs at the point of shear frequency.

The other one is the frequency lag control, which functions in two areas. The first one is to improve the low frequency response gain to reduce system steady-state error and maintain the transient performance at the same time; the second one is to utilize the low-pass filtering characteristic of the lag control device to attenuate the gain of high frequency response, and to decrease the shear frequency, so as to improve the system phase angle stability margin and enhance the system stability and some certain transient performance.
Assume that the open-loop transfer function of the uncorrected second-order system is shown as Fig. 15.1.
Then the structural diagram of such uncorrected closed-loop system is shown as Fig. 15.2.

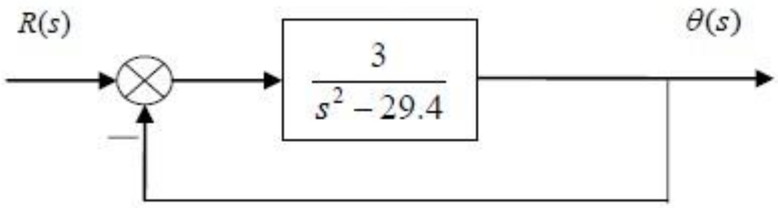


Figure. 15.2: Structural Diagram of Uncorrected Closed-loop System

The closed-loop system is unstable, and its open-loop frequency characteristics are shown in Fig. 15.3.

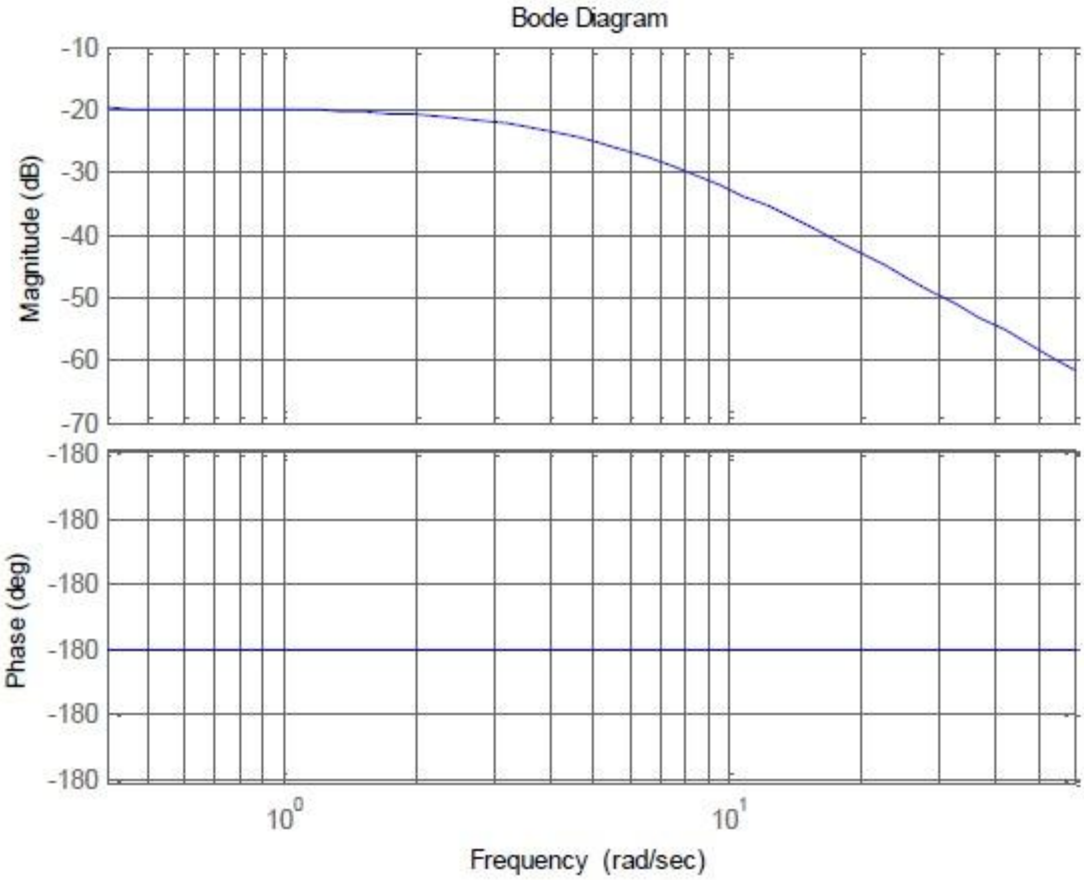


Figure. 15.3: (Freq0.m) Open-loop Frequency Characteristic Diagram for the Uncorrected System

It is observable that the uncorrected system is unstable. Now it comes to the design of the series lead control link, and the

The system analysis result is: $\delta_p \leq 25\%$, $t_s \leq 1s$.

Drawn from the empirical relationship formula corresponding to the open-loop frequency response index and time domain index:

$$\sigma = 0.16 + 0.4(\frac{1}{\sin\gamma} - 1), \quad 35° \leq \gamma \leq 90°$$

$$t_s = \frac{K_0 \pi}{\omega_c}$$

Where, $K_0 = 2 + 1.5(\frac{1}{\sin\gamma} - 1) + 2.5(\frac{1}{\sin\gamma} - 1)^2, \qquad 35° \leq \gamma \leq 90°$

We conclude the stability margin and cutoff frequency after control based on the δp-performance index overshot, and ts-regulation time.

Simplify the formula, we obtain

$$\gamma = \arcsin(\frac{0.4}{\sigma + 0.24}),$$

$$\frac{0.4}{\sigma + 0.24} \le 1,$$

As a result, $\sigma \ge 0.2$.

Let the overshoot $\sigma = 20\%$, then $\gamma \approx 65° = 1.14 rad/s$, $K_0 = 2.176$.

Assume that the regulation time t_s =0.5s, then $\omega_c = \frac{K_0 \pi}{t_s} \approx 14$, if $\omega_c = \omega_m = 14$, $\gamma_0 = 0°$.

If the series lead correction link is

$$\alpha G_c(s) = \frac{1 + \alpha T s}{1 + T s}, \text{ then}$$

$$\alpha = \frac{1 + \sin \varphi_m}{1 - \sin \varphi_m}, \quad T = \frac{1}{\omega_m \sqrt{\alpha}}$$

Where, the phase overshoot $\varphi_m = \gamma - \gamma_0 + \varepsilon$, ε refers to the compensation correction value used to compensate the phase lag value due to shear frequency increased through lead correction. In general, if the slope of the uncorrected system's open-loop frequency characteristic curve at the point of shear frequency is -40db/dec, then the compensation value is $\varepsilon = 5 \sim 10°$, or if the slope is $-60 dB/dec$, then $\varepsilon = 15 \sim 20°$.

Therefore, as the slope is $-40 dB/dec$, then $\varepsilon = 5°$.

$\varphi_m = 65° - 0° + 5° = 70° = 1.22 rad/s$

$\alpha = 32.05$

$T = 0.0126$

The correction part is:

$$\alpha G_c(s) = \frac{1 + 0.4038s}{1 + 0.0126s}$$

The closed-loop transfer function of the system after correction is:

$$G_c(s)G(s) = \frac{1 + 0.4038s}{1 + 0.0126s} \times \frac{3}{s^2 - 29.4}$$

And the corresponding open-loop frequency characteristic curve is shown as Fig. 15.4.

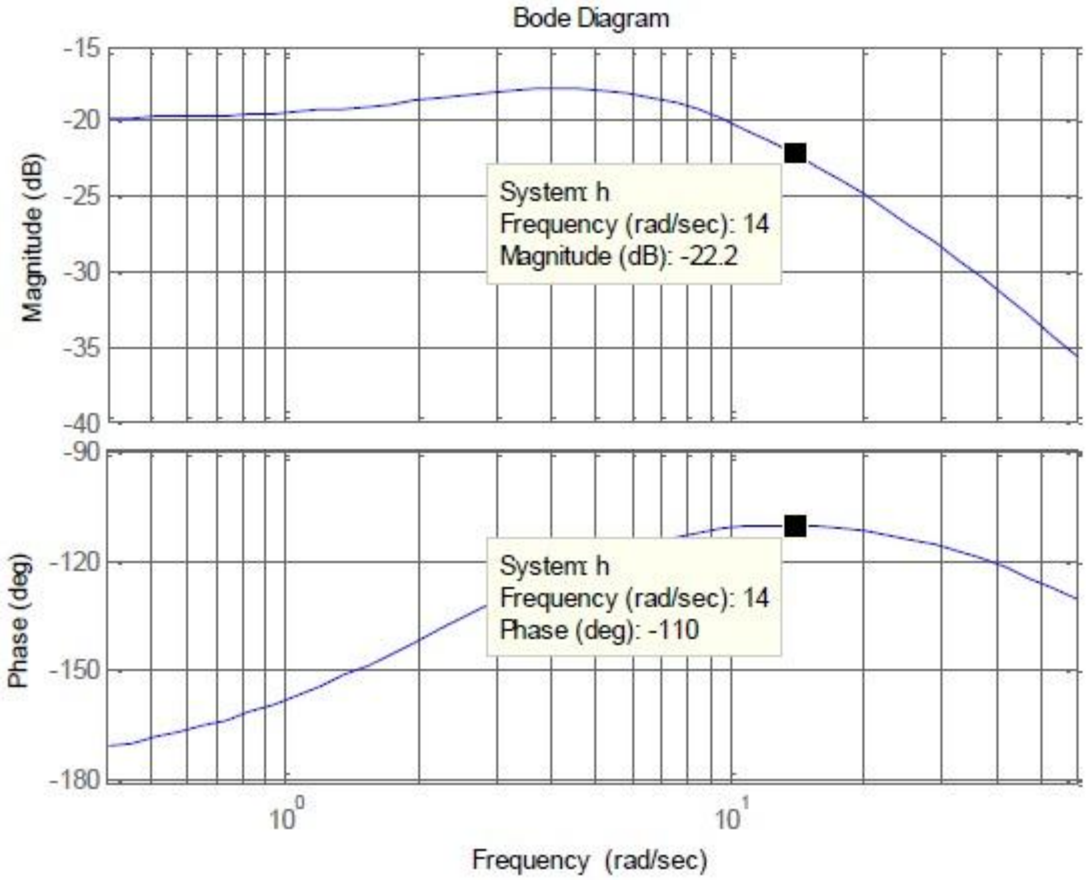


Fig. 15.4: (FreqR1.m) Open-loop Frequency Characteristic Diagram for the Corrected System

The system shear frequency is 22.8 rad, and stability margin 67 degree, and the system is stable. Therefore, the structural diagram after compensation and correction is shown in Fig. 15.6:

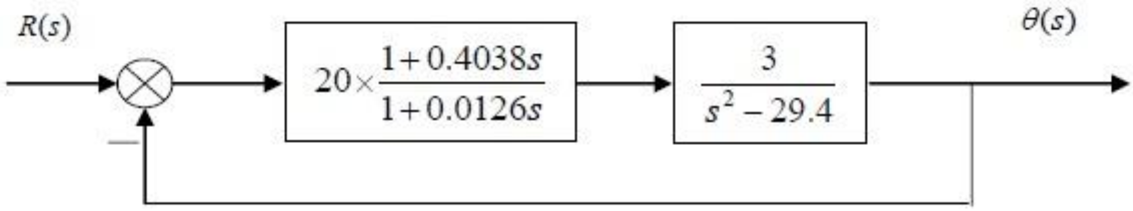


Figure. 15.6: Structural Diagram for Closed-loop System after Compensation

And the step response curve (FreqR_Simulink.mdl) of the system is shown in Figure. 15.7:

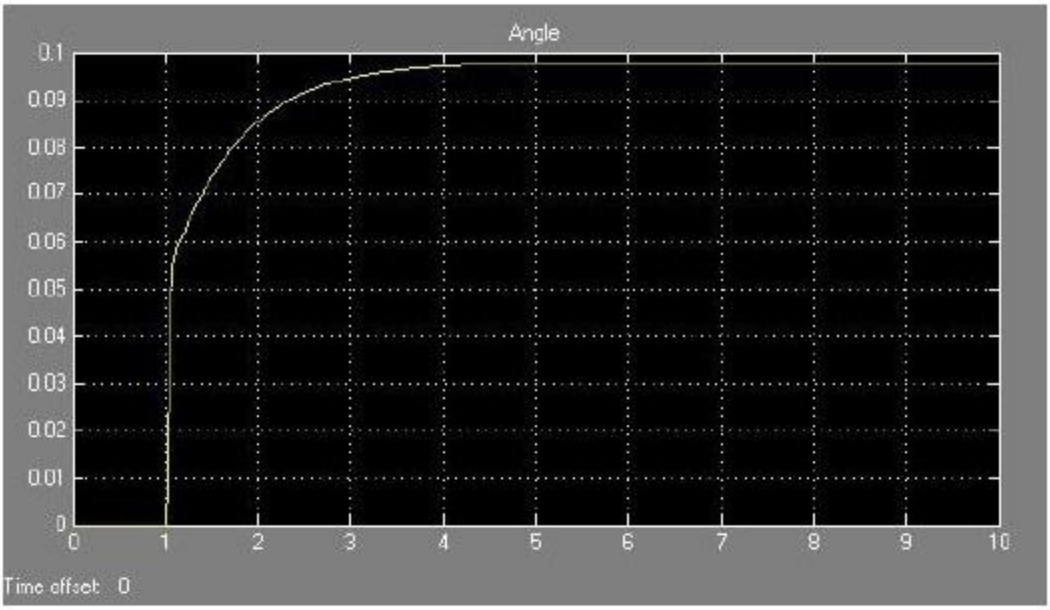


Figure. 15.7: System Bode Diagram after Compensation

The regulation time is 4s and overshoot is 0.

Experiment Procedures

1) Switch on the power button on the electric cabinet of the inverted pendulum, then place the inverted pendulum cart at the mid of the guide rail.

2) Open file “FreqR Control.mdl” in MATLAB/Current Folder then the real control page as shown in Fig. 4.8 will pop up.

EXP.04 Googol Linear 1-Stage Inverted Pendulum--Frequency Response Control

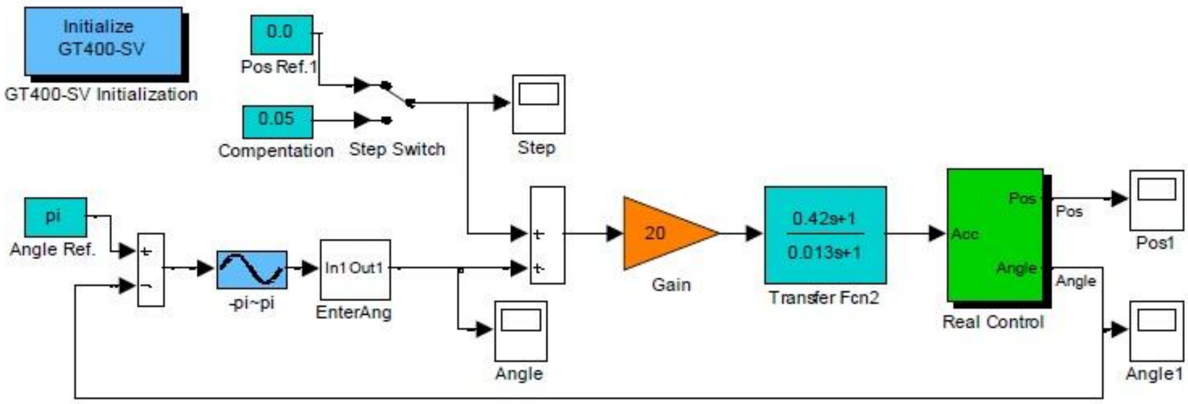


Figure. 15.8: Real Control Diagram

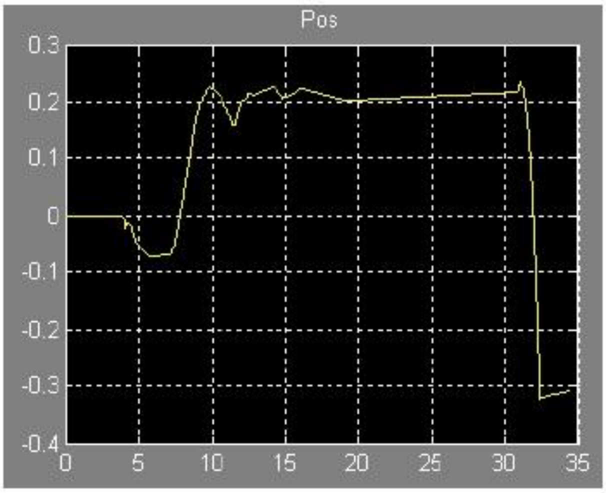
3) Click on “ ” to start real-time workshop build procedures.

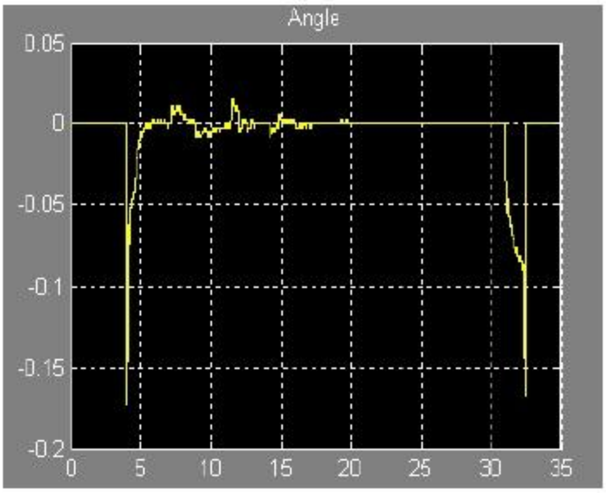
4) Click on “ ” icon to link the programs, when the buzzing generated from the motor after servo would be heard.

5) Click on “ ” button to operate the program, then manually place the pendulum bar to the straight up position, when the program would enter control state. Hold the pendulum bar and maintain it at the mid of the guide rail.

6) Double click on the “Step Switch1”to stimulate the input signal to the 0.05m/s^2 end, hold the pendulum bar still for 10s, and then observe the motion with hands off.

7) Click on button to stop the program, and double click on the "Angle" and "Pos1" oscilloscopes to observe the response of system output when the signal is switched into 0.05m/s^2.





Experiment Records

Fill the values obtained from experiment into the table below:

Content	Values
Controller Forms and Parameters	
Input Signal	
Output Signal	

Experiment Analysis and Questions

1. Reason analysis for system instability

The linear 1-stage inverted pendulum system is composed of a cart moving along a smooth guide rail, with a pendulum bar linked on the cart with hinge. When the pendulum bar is controlled, the position of the cart is limited by the length of the guide rail. Therefore, the output covers the angle of the pendulum bar and the position of the cart. The relations between the position and the input -the accelerated speed of the cart is

$$\frac{X(s)}{R(s)} = \frac{1}{s^2}$$

The structure of the control system is shown as Fig. 15.9:

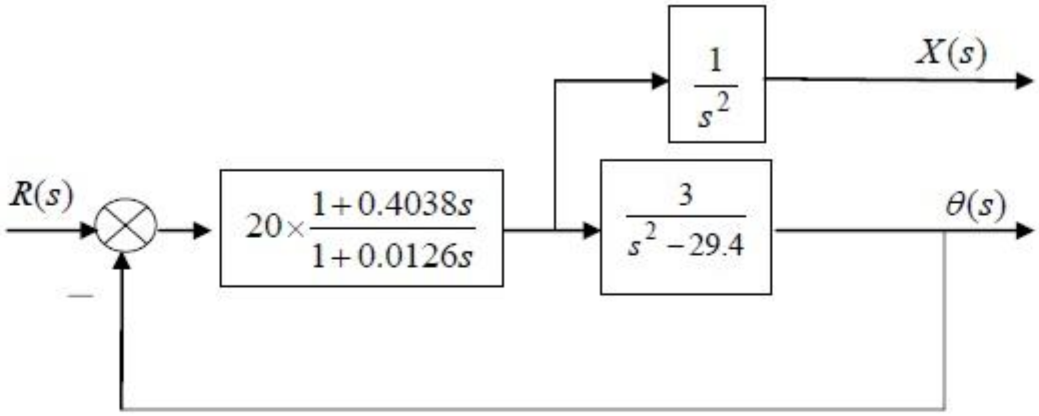


Figure. 15.9: Structural Diagram with Position Output

At this moment, the simulation diagram for position output is shown as Fig. 10 (unit: Abscissa axis is s, and the ordinate axis is m).

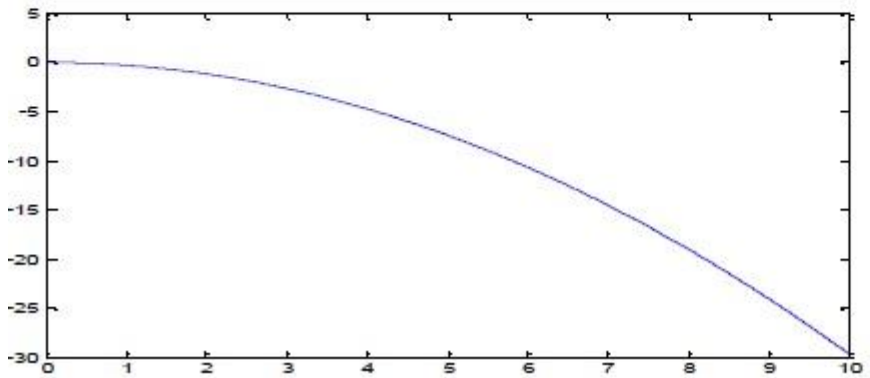


Figure. 15.10: Simulated Diagram for Position Output

The cart is in accelerated movement to the other end, it will knock into the wall, and the pendulum bar is unstable.

The inverted pendulum's motion will inevitably disturbed by various factors, and the angle and position will fluctuate within certain range even under balanced state. Hence, a constant tiny step signal may be added on the input end to compensate the disturbance upon the inverted pendulum's stability, i.e. static compensation to have the inverted pendulum in static stability state.

Note: The value of static compensation is dependent on the velocity, direction and guide rail's friction of the holding of the inverted pendulum bar, which requires repeated trial as deviations will occur each time.

2. Realization of static compensation

The static compensation experiment requires two people's joint effort. And the procedures are listed as below:
1) Switch on the power button on the electric cabinet of the inverted pendulum, then place the inverted pendulum cart at the mid of the guide rail.

2) Open file "FreqR_Control.mdl" in MATLAB/Current Folder, then the real control page as shown in Fig. 4.11 will pop up.

EXP.04 Googol Linear 1-Stage Inverted Pendulum--Frequency Response Control

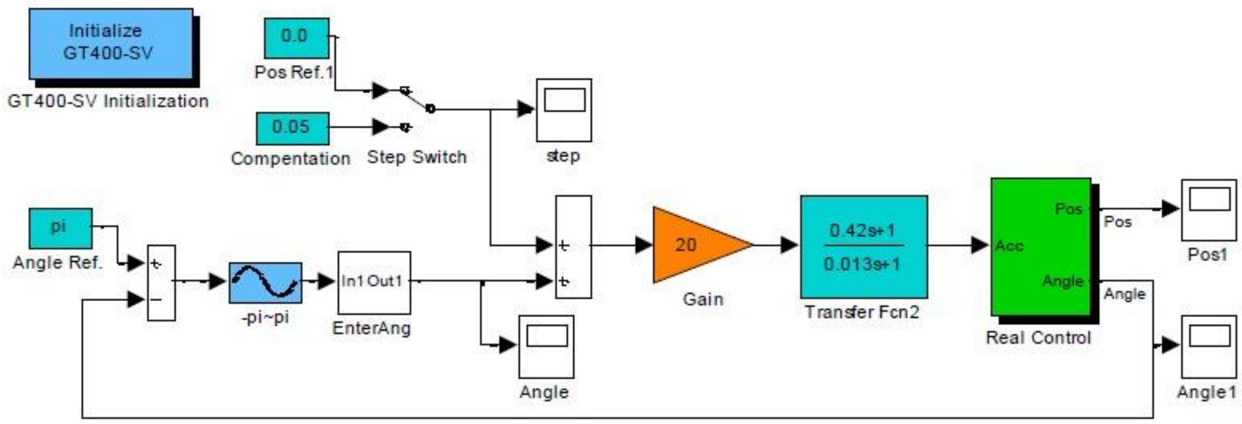
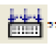


Figure. 15.11: Real Control Diagram for Static Compensation of Position

3) Click on "" to start real-time workshop build procedures.

4) Click on "" icon to link the programs, when the buzzing generated from the motor after servo would be heard. Then Click on "" button to operate the program.

5) **Experimenter1** shall swiftly lift the pendulum bar to the straight up position, and release it slowly after the program is under control. Hold the pendulum bar still at the same time.

6) **Experimenter2** shall double click on the "Step Switch" to stimulate the input signal to the 0.05m/s2end.

7) **Experimenter1** shall slowly release the pendulum bar. If the cart is unable to stand still, then observe the motion direction and speed of the cart.

8) **Experimenter2** shall adjust the input signal value at the software page as shown in Fig. 4.12. The method is to place the input signal reverse to the motion direction of the cart; if the motion speed is too fast, and then reduce the input signal value appropriately.

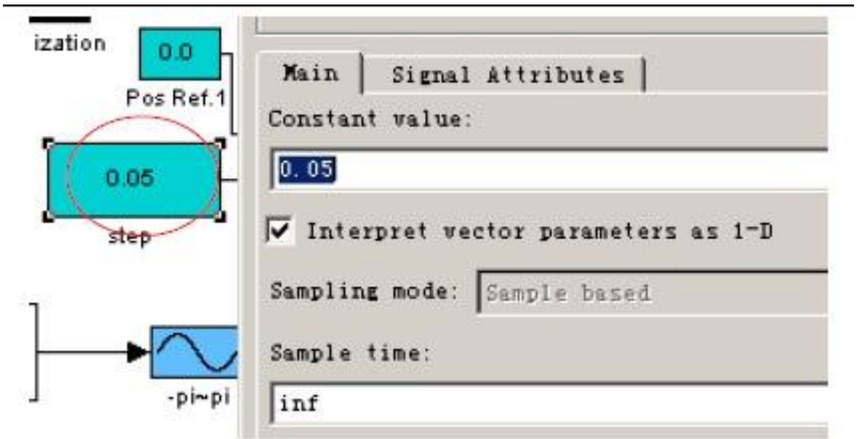


Figure. 15.12: Parameter Adjustment of the Static Compensation

9) Repeat procedures 8)-9) till the balance of the cart with hands off.

10) Record the static compensation value and fill it into the Experiment Records table.

3. Questions:

Beside lead control device, are there any other kinds of frequency response control devices? What are their features and difference? How shall we select the right control device?

TASK: Submit a separate report according to the format given in appendix C.

Registration Number-------------------------------

Student Name-------------------------------

Teacher Signature -------------------------------

Linear Control System Lab Design Project

Title: Modelling and Simulation of DC Motor Drive Using PI and PID Controllers

Objective: To select a suitable controller to get precise speed control, stable operation in complete range of speed, good transient response (minimum percentage overshoot, less rise, peak and settling time) and minimum (zero) steady state error.

Requirements with controller:
Rise Time = 3 sec
Settling Time = 8 sec
Percent overshoot = 10%
Steady state error = ±2%

Task to be performed:
1) Modelling of separately excited DC motor.
2) State space representation of model.
3) Selection of suitable controller.
4) Implementation and simulation results without controller.
5) Design PI and PID controller using root locus & frequency response techniques
6) Implementation and simulation results with controller (PI & PID).

Given Data:
A separately excited DC motor is given with the following specifications and parameters:
3 hp, 230 V, 11 A, 1500 rpm
R_a = 1 Ω for EA2, 2 Ω for EC2 and 3 Ω for EB1
L_a = 0.15 for EA2, 0.25 for EC2 and 0.35 for EB1
J_a & D_a = Consult with instructor
J_L = Last two digits of your own reg. #
D_L = Last digit of your own reg. #
K_b = 3.
K_m = 1.

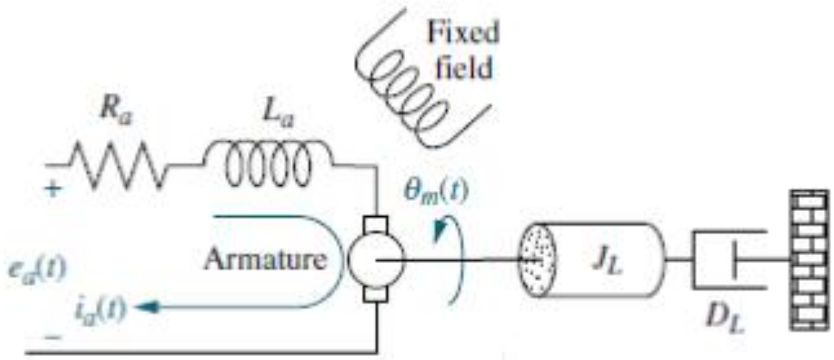


Figure 1: Motor and Load.

Project Description.

- Students grouping is not allowed.
- Each student is required to model and implement it according to the “task to be performed”.
- Each student have to select the above said values of parameters on the basis of his/her own Lab section (e.g. EB1, EA2, EC2) and reg.#.
- Each student is free to choose any value of PI and PID controller to meet the above mentioned requirements of response. However the student who will get better transients and steady state performance results with controller will get benefit over others.
- Marking Criteria: (Total 15 Marks)
  Modelling in frequency (transfer function) and time domain (state space) = 5
  MATLAB Simulation = 2.5
  Accuracy of Result / desired results = 2.5
  Project Report (Soft and Hard copy) = 5
- Project Report Format:
  a) Title Page, must mention Name & Registration number, Section and Date of submission.
  b) Introduction of the project.
  c) Complete modelling in frequency and time domain.
  d) MATLAB Simulink implementation without controller must include screenshots of model & properly labeled waveform of output response.
  e) Selection of controller.
  f) Design of PI & PID controller using root locus and frequency response techniques
  g) MATLAB Simulink implementation with controller must include screenshots of model & properly labeled waveform of output response.
  h) Mention the values of PI and PID controllers to meet the given requirements.
  i) Observations.
  j) Discussion
  k) Conclusions.
- Submission Dates: The projects implemented on MATLAB Simulink along with complete Project Report are required to be submitted in the week starting from **Date, Month 2018**. Each student must submit its project in its respective lab session. Late submissions will not be entertained under any circumstances.
- Viva will also be conducted with the submission of project. Each student is required to be fully prepared otherwise he/she will lose marks even if the project is perfectly modeled and implemented.

Appendix A: Lab Evaluation Criteria

Labs with projects

1. Experiments and their report 50%
    a. Experiment 60%
    b. Lab report 40%
2. Quizzes (3-4) 15%
3. Final evaluation 35-%
    a. Project Implementation 60%
    b. Project report and quiz 40%

Labs without projects

1. Experiments and their report 50%
    a. Experiment 60%
    b. Lab report 40%
2. Quizzes (3-4) 20%
3. Final Evaluation 30%
    i. Experiment. 60%
    ii. Lab report, pre and post experiment quiz 40%

Notice:

Copying and plagiarism of lab reports is a serious academic misconduct. First instance of copying may entail ZERO in that experiment. Second instance of copying may be reported to DC. This may result in awarding FAIL in the lab course.

Appendix B: Safety around Electricity

In all the Electrical Engineering (EE) labs, with an aim to prevent any unforeseen accidents during conduct of lab experiments, following preventive measures and safe practices shall be adopted:

- Remember that the voltage of the electricity and the available electrical current in EE labs has enough power to cause death/injury by electrocution. It is around 50V/10 mA that the “cannot let go” level is reached. “The key to survival is to decrease our exposure to energized circuits.”
- If a person touches an energized bare wire or faulty equipment while grounded, electricity will instantly pass through the body to the ground, causing a harmful, potentially fatal, shock.
- Each circuit must be protected by a fuse or circuit breaker that will blow or “trip” when its safe carrying capacity is surpassed. If a fuse blows or circuit breaker trips repeatedly while in normal use (not overloaded), check for shorts and other faults in the line or devices. Do not resume use until the trouble is fixed.
- It is hazardous to overload electrical circuits by using extension cords and multi-plug outlets. Use extension cords only when necessary and make sure they are heavy enough for the job. Avoid creating an “octopus” by inserting several plugs into a multi-plug outlet connected to a single wall outlet. Extension cords should ONLY be used on a temporary basis in situations where fixed wiring is not feasible.
- Dimmed lights, reduced output from heaters and poor monitor pictures are all symptoms of an overloaded circuit. Keep the total load at any one time safely below maximum capacity.
- If wires are exposed, they may cause a shock to a person who comes into contact with them. Cords should not be hung on nails, run over or wrapped around objects, knotted or twisted. This may break the wire or insulation. Short circuits are usually caused by bare wires touching due to breakdown of insulation. Electrical tape or any other kind of tape is not adequate for insulation!
- Electrical cords should be examined visually before use for external defects such as: Fraying (worn out) and exposed wiring, loose parts, deformed or missing parts, damage to outer jacket or insulation, evidence of internal damage such as pinched or crushed outer jacket. If any defects are found the electric cords should be removed from service immediately.
- Pull the plug not the cord. Pulling the cord could break a wire, causing a short circuit.
- Plug your heavy current consuming or any other large appliances into an outlet that is not shared with other appliances. Do not tamper with fuses as this is a potential fire hazard. Do not overload circuits as this may cause the wires to heat and ignite insulation or other combustibles.
- Keep lab equipment properly cleaned and maintained.
- Ensure lamps are free from contact with flammable material. Always use lights bulbs with the recommended wattage for your lamp and equipment.
- Be aware of the odor of burning plastic or wire.

- ALWAYS follow the manufacturer recommendations when using or installing new lab equipment. Wiring installations should always be made by a licensed electrician or other qualified person. All electrical lab equipment should have the label of a testing laboratory.
- Be aware of missing ground prong and outlet cover, pinched wires, damaged casings on electrical outlets.
- Inform Lab engineer / Lab assistant of any failure of safety preventive measures and safe practices as soon you notice it. Be alert and proceed with caution at all times in the laboratory.
- Conduct yourself in a responsible manner at all times in the EE Labs.
- Follow all written and verbal instructions carefully. If you do not understand a direction or part of a procedure, ASK YOUR LAB ENGINEER / LAB ASSISTANT BEFORE PROCEEDING WITH THE ACTIVITY.
- Never work alone in the laboratory. No student may work in EE Labs without the presence of the Lab engineer / Lab assistant.
- Perform only those experiments authorized by your teacher. Carefully follow all instructions, both written and oral. Unauthorized experiments are not allowed.
- Be prepared for your work in the EE Labs. Read all procedures thoroughly before entering the laboratory. Never fool around in the laboratory. Horseplay, practical jokes, and pranks are dangerous and prohibited.
- Always work in a well-ventilated area.
- Observe good housekeeping practices. Work areas should be kept clean and tidy at all times.
- Experiments must be personally monitored at all times. Do not wander around the room, distract other students, startle other students or interfere with the laboratory experiments of others.
- Dress properly during a laboratory activity. Long hair, dangling jewelry, and loose or baggy clothing are a hazard in the laboratory. Long hair must be tied back, and dangling jewelry and baggy clothing must be secured. Shoes must completely cover the foot.
- Know the locations and operating procedures of all safety equipment including fire extinguisher. Know what to do if there is a fire during a lab period; “Turn off equipment, if possible and exit EE lab immediately.”

Appendix C: Guidelines on Preparing Lab Reports

Each student will maintain a lab notebook for each lab course. He will write a report for each experiment he performs in his notebook. A format has been developed for writing these lab reports.

C.I: Hardware Lab Report Format

For hardware based labs, the format of the report will include:

1. **Introduction**: Introduce area explored in the experiment.
2. **Objective**: What are the learning goals of the experiment?
3. **Measurements**: In your own words write how the experiment is performed (Do not copy/paste the procedure).
    a. **Issues**: Which technical issues were faced during the performance of the experiment and how they were resolved?
    b. **Graphs**, if any
4. **Conclusions**: What conclusions can be drawn from the measurements?
5. **Applications**: Suggest a real world application where this experiment may apply.
6. Answers to post lab questions (if any).

Sample Lab Report: Hardware Experiments

Introduction

An RC circuit is a first order circuit that utilizes a capacitor as an energy storage element whereas a resistor as an energy wastage element. RC circuits are building blocks of electronic devices and their thorough understanding is important in comprehending advance engineering systems such as transistors and transmission lines.

An RC circuit can be operated with both DC and AC sources. In this lab we study transient response of RC circuits with a square wave as a DC source. During the DC operation of an RC circuit the voltage across the capacitor or the resistor show energy storing (capacitor charging) and dissipating (capacitor discharging via resistor) mechanisms of the circuit. The capacitor charging or discharging curves then lead to determine time constant of the circuit where the time constant signifies time required by the RC circuit to store or waste energy.

Objective:

To study transient response of a series RC circuit.

Measurements:

The circuit used for the experiment is shown in Fig. 1. Both input (a square wave) and output (voltage across capacitor) waveforms are monitored on an oscilloscope. The capacitor charging is observed during "on" part of the square waveform whereas the capacitor discharging is observed during "off" part of the square waveform (Fig. 2). We measure the time constant from the capacitor charging or discharging curve. While keeping the capacitor value constant, we also measure time constants with various resistor values (Table 1).

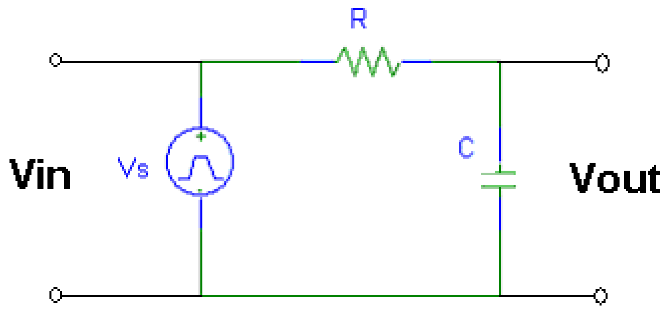


Fig.1. The circuit used in the experiment

Issues:

Mention any issue(s) you encountered during the experiment and how they were resolved.

Conclusions:

From the measurements following conclusions can be drawn:

a) The capacitor charging and discharging curves are exponential.

b) The time constant is directly proportional to the resistor value.

Both of the above conclusions are also easily verifiable by solving differential equation for the RC circuit.

Applications:

An RC circuit can be employed for a camera flash. The capacitor discharges through the flash light during a picture taking event.

INPUT VOLTAGE **VOLTAGE ACROSS A CAPACITOR**

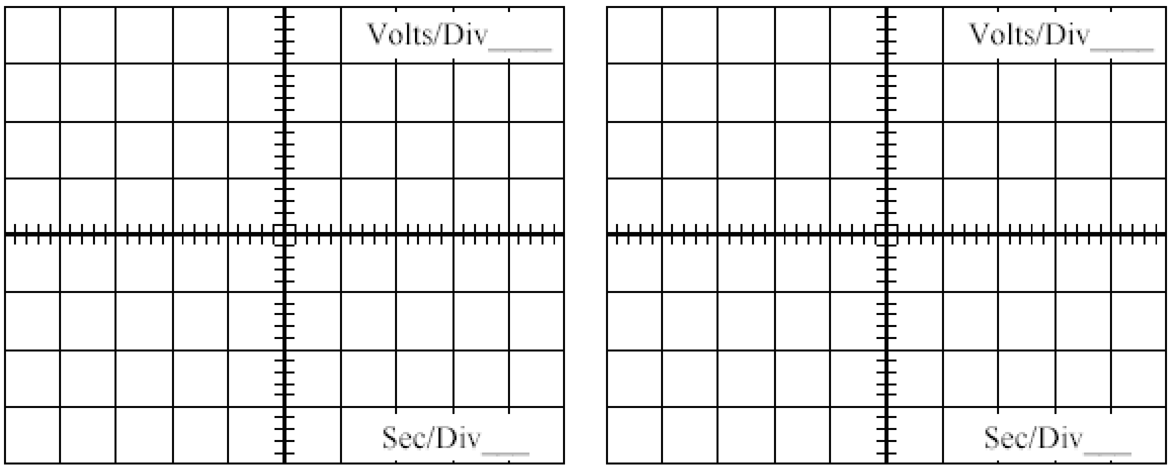


Fig. 2. Input and Output waveforms

TABLE I. Time constant as a function of the resistor values

Resistance (Nominal)	270 Ω	330 Ω	470 Ω	1 kΩ	2.2 kΩ	3.3 kΩ
Resistance (Measured)						
Time constant (Calculated)						
Time constant (Measured)						
Capacitance (Measured)						

C.2: Programming Stream Lab Report Format

For programming streams, the format of the report will be as given below:

1. **Introduction**: Introduce the new constructs/ commands being used, and their significance.
2. **Objective**: What are the learning goals of the experiment?
3. **Design**: If applicable, draw the flow chart for the program. How do the new constructs facilitate achievement of the objectives; if possible, a comparison in terms of efficacy and computational tractability with the alternate constructs?
4. **Issues**: The bugs encountered and the way they were removed.
5. **Conclusions**: What conclusions can be drawn from experiment?
6. **Application**: Suggest a real world application where this exercise may apply.
7. Answers to post lab questions (if any).

Sample Lab Report for Programming Labs

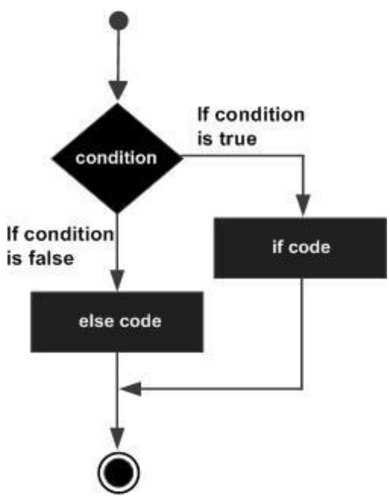
Introduction

The ability to control the flow of the program, letting it make decisions on what code to execute, is important to the programmer. The if-else statement allows the programmer to control if a program enters a section of code or not based on whether a given condition is true or false. If-else statements control *conditional branching*.

if (expression)
  statement1

else
  statement2

If the value of *expression* is nonzero, *statement1* is executed. If the optional **else** is present, *statement2* is executed if the value of *expression* is zero. In this lab, we use this construct to select an action based upon the user's input, or a predefined parameter.



Objective:

To use if-else statements for facilitation of programming objectives: A palindrome is a number or a text phrase that reads the same backward as forward. For example, each of the following five-digit integers is a palindrome: 12321, 55555, 45554 and 11611. We have written a C++ program that reads in a five-digit integer and determines whether it is a palindrome.

Design:

The objective was achieved with the following code:

```
#include<iostream>

usingnamespace std;

int main()

{

int i,temp,d,revrs=0;

   cout<<"enter the number to check :";

      cin>>i;

   temp=i;

while(temp>0)

   {

      d=temp%10;

      temp/=10;

      revrs=revrs*10+d;

      }

if(revrs==i)

   cout<<i<<" is palindorme";

else

   cout<<i<<" is not palindrome";

   }

}
```

Screen shots of the output for various inputs are shown in Figure 1:

Fig.1. Screen shot of the output

The conditional statement made this implementation possible; without conditional branching, it is not possible to achieve this objective.

Issues:

Encountered bugs and issues; how were they identified and resolved.

Conclusions:

The output indicates correct execution of the code.

Applications:

If-else statements are a basic construct for programming to handle decisions.