NATIONAL UNIVERSITY OF SINGAPORE

EE3331C/EE3331E – FEEDBACK CONTROL SYSTEMS

Instruction Manual for Experiment 2

DC Motor Speed Control

Design and Implementation of Feedback Control

Objectives

1. To observe effect of disturbance under open loop control
2. To identify a transfer function model from step response
3. To implement P-control and to observe its effects on performance
4. To implement PI-control and to observe its effect on performance

1 Introduction

A motor is a rotating device which is widely used as prime mover in todays world. It finds its application in a variety of equipments and appliances, from rotating a load at a controlled angular velocity as in CD/DVD player to positioning a robotic arm.

Motor is a transducer that converts electric energy into mechanical energy (electro-mechanical energy conversion). The torque developed on the motor shaft depends on the magnetic field flux inside the motor and its armature current. A DC motor receives the electric energy from a DC voltage source where as an AC motor gets electric energy from an AC source.

Any engineering application of motor requires controlled operation of the mechanical motion, i.e., either controlled velocity or controlled displacement. AC motors are more difficult to control, especially for position control, and their characteristics are often non-linear. On the other hand, it is easier to control a DC motor.

In this hands-on exercise of the module EE3331C, you will learn about controlling speed of a DC-motor using feedback. For that, you will be required to identify a model of the motor and to implement the controller. You will also study the effects of feedback on steady-state error, transient, disturbance rejection etc.

2 Experimental Setup

a. Hardware: The experimental setup consists of the following apparatus.

- DC motor set
- PC installed with VI (virtual instrument) data acquisition card from National Instruments' (NI)
- Power supply for the DC motor set
- Printer

Do a physical inspection of the setup and identify the following components of the DC motor set.

(1) the motor

(2) the tachogenerator: this is the sensor. Its output is a voltage proportional to the angular velocity of the DC motor.

(3) digital display of RPM (revolution per minute): It shows speed of the motor in unit of RPM. It is for display only and is not a component of the feedback loop.

(4) the magnetic load arm: it is used to create loading effect on the motor. When the load arm is lowered, its interaction with the rotating disk generates a torque acting on the motor shaft. When the load arm is pulled up, the disturbance torque is removed.

b. Software: The software package used for implementing open loop and closed loop control is LabVIEW.

LabVIEW allows user to easily organize various control configurations. LabVIEW is a graphical programming language that has been widely adopted as the standard for data acquisition and instrument control software. It is windows-driven and various tasks can be performed by placing icons and connecting them appropriately.

For this laboratory experiment, you are not required to create the configurations. The feedback control configuration has already been programmed and a GUI is provided for you to manipulate different gains of the controller.

3 Familiarization with LabVIEW GUI

1. Power up the DC motor set.

2. Open the folder EE3331c and start LabVIEW GUI by double-clicking the appropriate file. [Seek help from GA if required.]

3. You are prompted to enter the last three (3) digits of your student ID number. After entering the number, you can use the GUI that is shown in Figure 1. You can switch between two windows:

   - 'Set parameter' window
   - 'Graphic Chart' window

   The 'set parameter' window allows you to do the following,

   - To choose open loop and closed loop control
   - To set different gains of controller
   - To choose between constant input and square wave input

   The signals from the DC motor set are displayed in the 'Graphic Chart' window. It shows input signal (reference input for closed loop mode) in blue, sensor (tachogenerator) output in red, and the control input in green.

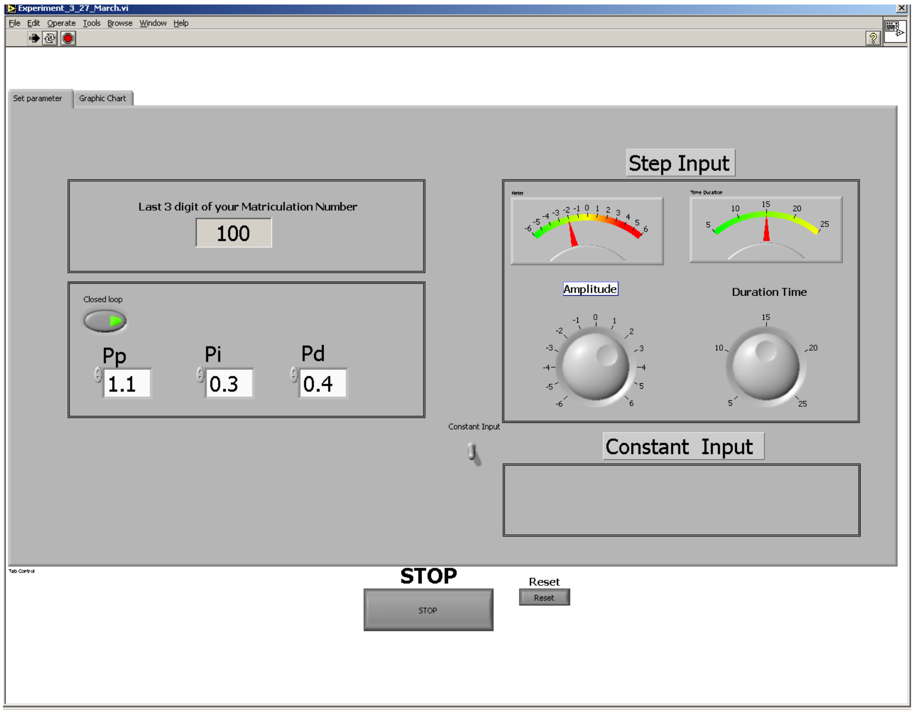

Figure 1: GUI for DC-motor experiment

4. You can toggle between open loop mode and closed loop mode by clicking the oval button at the left edge of the set parameter window.

5. You can switch between two types of input signal (constant or square wave) using the toggle switch labeled 'Constant input'.

   - In the constant input mode, a sliding bar is shown at the bottom-right corner. You can adjust the input voltage by sliding the bar. You will observe that DC motor speed is changing as you change the sliding bar position. You can also enter the input voltage level directly in the small box located just above the sliding bar.
   - Square wave input is used for experiments involving step input. A square wave represents a series of alternating step inputs. Amplitude of the square wave is set using the left dial labeled 'Amplitude' and period of the waveform is set using the right dial labeled 'Duration'. Set the amplitude to 2. Observe that the direction of motor spin changes at regular intervals.

6. In closed loop mode, you can choose any combination of the three-term controller: proportional, integral and derivative. Three gains can be entered using the three boxes labeled P_p, P_i, and P_d for proportional gain (K_p), integral gain (K_i) and derivative gain (K_d), respectively. If a term is not being used, set the corresponding value to 0. For example, to implement P-I control, set P_d to zero.

7. The graphic chart window displays different signals from the DC motor set. Typical graphic chart window is shown in Figure 2.

Figure 2: Graphic Chart Window

4 Experiment 1: Open Loop Control

In this part of the experiment, you will verify the following -

i. Motor speed can be varied by varying the input voltage.

ii. With open loop control, speed of the motor deviates from the desired level when load torque is changed. Change in load torque is emulated in the experimental setup using the magnetic load arm.

Block diagram representation of the hardware configuration for Experiment 1 is shown in Figure 3. Can you identify all the blocks in the DC-motor set hardware?

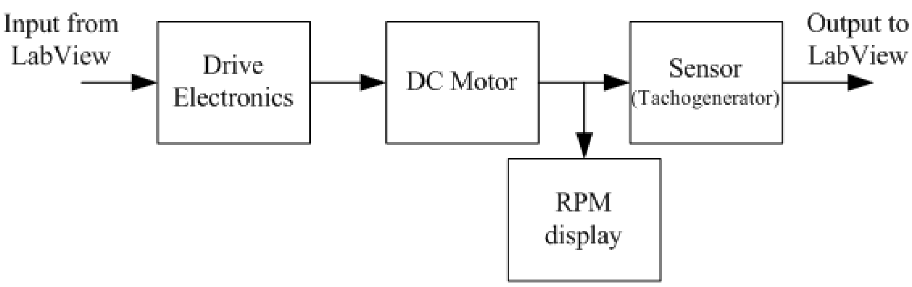

Figure 3: Open loop configuration

- Input voltage applied to the motor driver can be set to a specific level using the LabVIEW GUI.
- The RPM (revolutions per minute) of the motor is shown on an LED display.
- Motor shaft is attached to a tachogenerator that produces voltage proportional to motor speed. The output of the tachogenerator is a voltage signal. You will find a transfer function model of the motor setup in Experiment 2.
- Load disturbance is created by the load arm.

Carry out Experiment1 by executing following steps -

1. Make sure that the setup is in open loop mode and the load arm is in the up position. Choose 'Constant Input' for the input signal.

2. Change input voltage and observe the RPM display. Switch to signal display by clicking 'Graphic Chart'. Input voltage (blue line) and sensor output voltage (red line) as functions of time are displayed on the same graph.

3. Switch back to input GUI by clicking 'Set parameters'. Adjust the input voltage level to set the motor speed to any desired level, e.g., 100 RPM. Depending on the setup you use, this set speed may be different. Observe motor speed on RPM display while doing this.

4. Switch back to 'Graphic Chart'. Lower the load arm to emulate load torque applied to the motor. Observe the speed on RPM display as well as in the graphic chart. You can pause the graphic chart by clicking the 'Pause' switch (located in the top right area of the graphic chart window) when the change in output is observed and take a printout. Note down your observations.

Later you will repeat this test under closed loop control. However, designing a controller starts with a model of the plant. So, first you will find a model of the DC motor set by measuring its step response.

5 Experiment 2: Model Identification using Step Response

Instead of generating a step input, LabVIEW was programmed to create a square wave. Each transition of the square wave can be considered as a step input. A square wave input can be used to observe step response clearly if transient response of the system is shorter than half of the period of square wave. You can adjust the period of the square wave input to ensure this.

- Choose 'open loop' mode for Experiment 2.

- Toggle to 'Step Input' from 'Constant Input'.

- Use the amplitude dial to set the amplitude to 2V. This will make the input voltage switch between +2V and -2V at regular intervals. Depending on the motor set you are using, the voltage level may be different. Make sure that you can see clear step response in the graphic chart window. The interval is set by the second dial. The motor will rotate back and forth. Can you observe that?

- Observe traces of input signal and output signal in the graphic chart. Input signal is a square wave while the output signal should appear very much like the response of first-order dynamic system.

- Adjust the period of the square wave such that the output reaches its steady state before the input is reversed.

- The chart is continuously updated. Freeze it by clicking the 'Pause' button. Take a printout of the waveforms.

- Estimate the steady-state gain of the DC motor set using the following,

$$\begin{aligned} K_{ss} &\approx \frac{\Delta y}{\Delta u} \\ &= \frac{y_{final} - y_{init}}{u_{final} - u_{init}}. \end{aligned}$$

  where, u_{init} and u_{final} are the input voltage levels before and after the transition, respectively. Output voltage before the transition is y_{init} and steady-state output after transition is y_{final}. Refer to Figure 4.

- Estimate time constant (τ) of the DC motor: It is equal to the time elapsed between the start of transition and the time when output is $0.63\Delta y$. Use the step response printout to estimate this value. Refer to Figure 4.

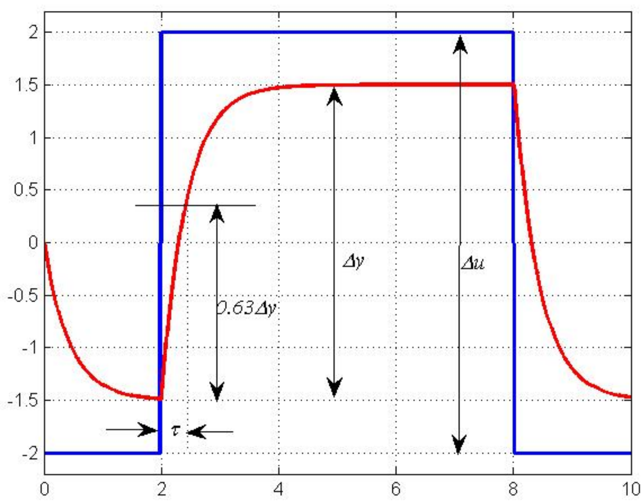

Figure 4: Model identification from step response

With K_{ss} and τ estimated, you have the following transfer function model of the DC motor.

$$G(s) = \frac{K_{ss}}{s\tau + 1}.$$

6 Experiment 3: Proportional Control

For Experiment 3 and Experiment 4, the hardware setup is configured in closed loop as shown in the block diagram of Figure 5. The button labeled 'Closed loop' in the 'Set parameter' window is used to toggle between open loop mode and closed loop mode.

1. Effect of Load Disturbance

   - Start with a small gain, for example, $K_p = 2.0$. Set other two gains (K_I and K_D) to zero.
   - Choose closed loop mode and constant input. The input signal generated by the LabView is applied as the reference input of the closed loop system.

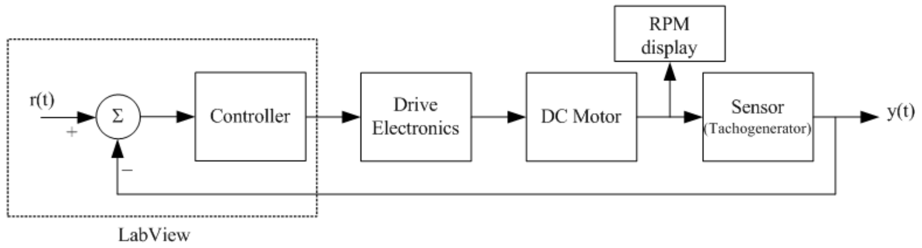

Figure 5: Closed loop configuration

- Adjust input level such that motor speed is at some desired level, e.g., 100 RPM. Observe the input and the output in the graphic chart
- Slowly lower the load arm and observe the effect of load disturbance.
- Keeping the load arm at the same position (so that the load disturbance is not changed), increase control gain. Do you see any difference? This is for a qualitative assessment to check whether increased gain of P-control reduces the effect of disturbance. There is no need to take printout here, but note down your observation which should be mentioned in the report.

2. Effect of proportional gain on steady-state error

   - Set the gain (K_p) to 2.0. Other two gains are still zero. Remove load disturbance by
   - Choose closed loop mode and square wave input. Adjust period of the waveform so that the output reaches steady-state before the input is reversed. You may adjust signal level as well to get reasonable response.
   - Pause the chart, take printout, and determine the steady state error.
   - Repeat the experiment with three (3) different values of the proportional gain.

   You will observe that the steady-state error is decreased with increasing gain of proportional control. In your report, answer these questions - Can the gain be increased to an arbitrarily high value? If not, why?

3. Effect of proportional gain on transient response

   - Set $K_p = 2$. Other two gains are still zero.
   - Choose closed loop mode and square wave input.
   - Observe the changes in transient response as the gain is increased gradually. Record the observation for three (3) different values of the gain.

7 Experiment 4: Proportional+Inegral Controller

In this part of experiment, you will implement a PI controller and will study effects of controller gains on closed loop performance. The PI controller is,

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

The transfer function of the controller is

$$C(s) = \frac{(K_p s + K_i)}{s}. \tag{1}$$

The plant model identified in Experiment 2,

$$G_p(s) = \frac{K_{ss}}{(\tau s + 1)}. \tag{2}$$

So the closed loop transfer function is,

$$G_{cl}(s) = \frac{\frac{K_{ss}}{\tau}(K_p s + K_i)}{s^2 + \frac{(K_{ss}K_p+1)}{\tau}s + \frac{K_{ss}K_i}{\tau}}. \tag{3}$$

7.1 Selecting PI Control Gains

The values of K_{ss} and τ are already known from the identified model of the DC-motor set. If the gains K_p and K_i are chosen such that the zero of the closed loop transfer function is far to the left compared to the closed loop poles, then the effects of the zero on step response can be assumed negligible. Keeping this condition in mind, find the gains K_p and K_i such that

- the closed loop's natural frequency (ω_n) is approximately 3.5 radians/sec, and
- damping factor is 0.5.

Several approximations are made while finding these gains. Model of the DC-motor set is an approximate model. We also assumed that the effect of closed loop zero is negligible. The experimental results with these gains may not be as good as you expect. However, they can be considered as the initial selection. Starting with these values, fine-tune the gains while performing the closed loop experiment.

An alternative approach is to fix the value of K_p first and set $K_i = 0$. This effectively means proportional control. Then gradually increase the value of K_i and observe the step response. Increasing K_i tends to make the step response oscillatory. Increase K_i up to a value which results in one or two cycles of oscillation in the step response. You may have to change the period of the reference square wave so that the transient response is seen clearly. If you find the response sluggish, change K_p to a higher value and repeat the process for choosing K_i.

7.2 Experimental Study of the P+I Control

Use the gains chosen and implement the controller to perform the following tests.

1. Step Response:
   Do this part of the experiment with load arm pulled up (no load disturbance).
   - Keep the controller gains as obtained after fine-tuning.
   - Choose closed loop mode and square wave input. Adjust period of the waveform so that the output reaches steady-state before the input signal is changed. You may adjust signal level as well to get response that is clearly visible.

- Take printout of the response.
- Keeping the integral gain unchanged, repeat this experiment for two other values of proportional gain. Take printout for both cases.
- Keeping the proportional gain set to the fine-tuned value, repeat the experiment for two different values of integral gains. Take printout for both cases.

2. Effect of Load Disturbance

   - Set the gains according to the fine-tuned values.
   - Choose closed loop mode and constant input.
   - Adjust input level such that motor speed is 100 RPM. Observe the input and the output on the graphic chart.
   - Lower the load arm and observe the response. Is the controller able to reject the effect of load disturbance?

8 Report

Write a report that must include your observations regarding the following aspects,

1. Accuracy of the model identified: Is the open loop step response exactly same as the step response of a first-order transfer function? What differences have you noticed?
2. Effect of load disturbance for three cases: (a) without feedback, (b) with P-control, and (c) with P+I control
3. Steady-state error for step input under proportional control and under P+I control
4. Effects of proportional and integral gains on closed loop performances

If you have observed anything in the results that is worth mentioning, include that as well in your report.

END OF MANUAL