Notes from my professor

You must use word processor to write all the lab reports. Handwritten reports are difficult to read. You must use computer programs for modeling, simulation, analysis and evaluation of the performance of different types of motors and generators.

You must attach computer outputs to demonstrate the outputs of motor and generators.

You should have the following format for writing a lab report:

1. Title of your experiment. You may have to select an appropriate title for the experiment under consideration.
2. Circuit Diagram(s) for the experiment and instruments used to measure speed, current and voltage.
3. Mathematical Model(s) – Equations describing each component of the complete circuit diagram.
4. Describe the simulation program used to carry out the experiment. If you use My Math Lab program to do the simulation, illustrate the simulation program(s).
5. Generate the results by executing the simulation program(s).
6. Computer outputs illustrate the performance of the simulation program. Computer output(s) indicate the results of the experiment. You must attach the computer outputs,
7. You must make comments on the computer-generated results.
8. Conclusion (describing the performance of the experiment under consideration). Are the results same as expected? If not, why not.

LAB 1

Problems 6.1 & 6.2

LAB 2

Problems 6.6 & 6.7

LAB 3

Problems 6.8 & 6.9

LAB 4

Problems 6.10 & 6.11

LAB 5

Problems 6.12 & 6.13

LAB 6

Problem 6.15

(amplifiers), issues such as saturation of the amplifier, friction in the motor, or backlash in gears will seriously affect the controller design. This chapter focused on problems involving dc motors including modeling, system identification, and controller design. We presented experiments on speed and position control of dc motors, followed by two controller design projects involving control of a simple robotic system and control of a single degree of freedom quarter-car model. The focus on dc motors in these experiments was intentional, because of their simplicity and wide use in industrial applications. Note that, in the design projects, aside from the speed and position control topics, other controllers such as PID and lead/lag were also discussed. You may wish to visit Chapter 9 to become more acquainted with these topics.

REFERENCE

1. F. Golnaraghi, "ENSC 383 Laboratory Experiment," Simon Fraser University, Mechatronic Systems Engineering Program, British Columbia, Canada, *Lab Manual*, 2008.

PROBLEMS

6-1. Create a model of the motor shown in Fig. 5-25. Use the following parameter values: $J_m = 0.0004$ kg-m^2; $B = 0.001$ Nm/rad/sec, $R_a = 2\ \Omega$, $L_a = 0.008$ H, $K_m = 0.1$ Nm/A, and $K_b = 0.1$ V/rad/sec. Assume that the load torque T_L is zero. Apply a 5-V step input to the motor, and record the motor speed and the current drawn by the motor (requires modification of SIMLab blocks by making current the output) for 10 sec following the step input.

(a) What is the steady-state speed?

(b) How long does it take the motor to reach 63% of its steady-state speed?

(c) How long does it take the motor to reach 75% of its steady-state speed?

(d) What is the maximum current drawn by the motor?

6-2. Set the viscous friction B to zero in Problem 6-1. Apply a 5-V step input to the motor, and record the motor speed and current for 10 sec following the step input. What is the steady-state speed?

(a) How long does it take the motor to reach 63% of its steady-state speed?

(b) How long does it take the motor to reach 75% of its steady-state speed?

(c) What is the maximum current drawn by the motor?

(d) What is the steady-state speed when the applied voltage is 10 V?

6-3. Set the armature inductance L_a to zero in Problem 6-2. Apply a 5-V step input to the motor, and record the motor speed and current drawn by the motor for 10 sec following the step input.

(a) What is the steady-state speed?

(b) How long does it take the motor to reach 63% of its steady-state speed?

(c) How long does it take the motor to reach 75% of its steady-state speed?

(d) What is the maximum current drawn by the motor?

(e) If J_m is increased by a factor of 2, how long does it take the motor to reach 63% of its steady-state speed following a 5-V step voltage input?

(f) If J_m is increased by a factor of 2, how long does it take the motor to reach 75% of its steady-state speed following a 5-V step voltage input?

6-4. Repeat Problems 6-1 through 6-3, and assume the load torque $T_L = -0.1$ N-m (don't forget the minus sign) starting after 0.5 sec (requires change of the disturbance block parameters in SIMLab).

(a) How does the steady-state speed change once T_L is added?

(b) How long does it take the motor to reach 63% of its new steady-state speed?

(c) How long does it take the motor to reach 75% of its new steady-state speed?

(d) What is the maximum current drawn by the motor?

(e) Increase T_L and further discuss its effect on the speed response.

6-5. Repeat Problems 6-1 through 6-3, and assume the load torque $T_L = -0.2$ N-m (don't forget the minus sign) starting after 1 sec (requires change of the disturbance block parameters in SIMLab).
(a) How does the steady-state speed change once T_L is added?
(b) How long does it take the motor to reach 63% of its new steady-state speed?
(c) How long does it take the motor to reach 75% of its new steady-state speed?
(d) What is the maximum current drawn by the motor?
(e) Increase T_L and further discuss its effect on the speed response.

6-6. For the system in Fig. 6-1, use the parameters for Problem 6-1 (but set $L_a = 0$) and an amplifier gain of 2 to drive the motor (ignore the amplifier voltage and current limitations for the time being). What is the steady-state speed when the amplifier input voltage is 5 V?

6-7. Modify the model in Problem 6-6 by adding a proportional controller with a gain of $K_p = 0.1$, apply a 10 rad/sec step input, and record the motor speed and current for 2 sec following the step input.
(a) What is the steady-state speed?
(b) How long does it take the motor to reach 63% of its steady-state speed?
(c) How long does it take the motor to reach 75% of its steady-state speed?
(d) What is the maximum current drawn by the motor?

6-8. Change K_p to 1.0 in Problem 6-7, apply a 10 rad/sec step input, and record the motor speed and current for 2 sec following the step input.
(a) What is the steady-state speed?
(b) How long does it take for the motor to reach 63% of its steady-state speed?
(c) How long does it take for the motor to reach 75% of its steady-state speed?
(d) What is the maximum current drawn by the motor?
(e) How does increasing K_p affect the response (with and without saturation effect in the SIMLab model)?

6-9. Repeat Problem 6-7, and assume the load torque $T_L = -0.1$ N-m starting after 0.5 sec (requires change of the disturbance block parameters in SIMLab).
(a) How does the steady-state speed change once T_L is added?
(b) How long does it take the motor to reach 63% of its new steady-state speed?
(c) How long does it take the motor to reach 75% of its new steady-state speed?

6-10. Repeat Problem 6-7, and assume the load torque $T_L = -0.2$ N-m starting after 1 sec (requires change of the disturbance block parameters in SIMLab).
(a) How does the steady-state speed change once T_L is added?
(b) How long does it take the motor to reach 63% of its new steady-state speed?
(c) How long does it take the motor to reach 75% of its new steady-state speed?

6-11. Insert a velocity sensor transfer function K_s in the feedback loop, where $K_s = 0.2$ V/rad/sec (requires adjustment of the SIMLab model). Apply a 2 rad/sec step input, and record the motor speed and current for 0.5 sec following the step input. Find the value of K_p that gives the same result as in Problem 6-7.

6-12. For the system in Fig. 6-3, select $K_p = 1.0$, apply a 1 rad step input, and record the motor position for 1 sec. Use the same motor parameters as in Problem 6-1.
(a) What is the steady-state position?
(b) What is the maximum rotation?
(c) At what time after the step does the maximum occur?

6-13. Change K_p to 2.0 in Problem 6-12, apply a 1 rad step input, and record the motor position for 1 sec.
(a) At what time after the step does the maximum occur?
(b) What is the maximum rotation?

6-14. Using the SIMLab, investigate the closed-loop position response using a proportional controller. For a position-control case, use proportional controller gains of 0.1, 0.2, 0.5, 1.0, and 2.0; record the step response for a 1 rad change at the output shaft; and estimate what you consider to be the best value for the proportional gain. Use the same motor parameters as in Problem 6-1.

6-15. Using the SIMLab, investigate the closed-loop position response using a PD controller. Modify the controller used in Problem 6-14 by adding derivative action to the proportional controller. Using the best value you obtained for K_P, try various values for K_D, and record the step response in each case.

6-16. Repeat Problem 6-15 and assume a disturbance torque $T_D = -0.1$ N-m in addition to the step input of 1 rad (requires change of the disturbance block parameters in SIMLab).

6-17. Repeat Problem 6-15 and assume a disturbance torque $T_D = -0.2$ N-m in addition to the step input of 1 rad (requires change of the disturbance block parameters in SIMLab).

6-18. Use the SIMLab and parameter values of Problem 6-1 to design a PID controller that eliminates the effect of the disturbance torque, with a percent overshoot of 4.3.

6-19. Use the SIMLab and parameter values of Problem 6-1 to design a PID controller that eliminates the effect of the disturbance torque, with a percent overshoot of 2.8.

6-20. Investigate the frequency response of the motor using the Virtual Lab Tool. Apply a sine wave with a frequency of 0.1 Hz (don't forget: 1 Hz $= 2\pi$ rad/sec) and amplitude of 1 V the amplifier input, and record both the motor velocity and sine wave input signals. Repeat this experiment for frequencies of 0.2, 0.5, 1.0, 2.0, 5.0, 10.0, and 50.0 Hz (keeping the sine wave amplitude at 1 V).

6-21. Using the Virtual Lab Tool, investigate the closed-loop motor speed response using a proportional controller. Record the closed-loop response of the motor velocity to a step input of 2 rad/sec for proportional gains of 0.1, 0.2, 0.4, and 0.8. What is the effect of the gain on the steady-state velocity?

6-22. Using the Virtual Lab Tool, investigate the closed-loop position response using a proportional controller. For a position-control case, use proportional controller gains of 0.1, 0.2, 0.5, 1.0, and 2.0; record the step response for a 1 rad change at the output shaft; and estimate what you consider to be the best value for the proportional gain.

6-23. Using the Virtual Lab Tool, investigate the closed-loop position response using a PD controller. Modify the controller used in Problem 6-15 by adding derivative action to the proportional controller. Using the best value you obtained for K_P, try various values for K_D, and record the step response in each case.

6-24. In Design Project 2 in Section 6-7, use the CarSim tool to investigate the effects of controlling acceleration $\ddot{X}$ on relative motion (or bounce) Z and vice versa.

(a) Use a PD controller in your investigation.

(b) Use a PI controller in your investigation.

(c) Use a PID controller in your investigation.

6-25. Using the Quarter Car Modeling Tool controlling,

(a) Set the simulation mode to "Passive Suspension" and set up the top axes to display $\ddot{y}(t)$. Select a step input with amplitude 0.02 m/s^2 and step time 0 seconds. Plot the response. Repeat this procedure for 0.2 and 0.5 m/s^2 input. Compare the results.

(b) Change the stiffness, k, to 15 N/m. With a step input of 0.02 m/s^2 and the lower axes configured to display $\ddot{z}(t)$, what is the frequency of the oscillatory response? This is the damped frequency of the system using default parameters (ω_d). How does the period of oscillation compare to the value that was observed in part (a)? Repeat the simulation several more times, gradually reducing the damping (variable c in the Model Parameters control window) to find the natural frequency of the system (ω_n).

(c) Obtain the effect of washboard bumps with an amplitude of 0.02 m/s^2 on the response of the system. Vary the frequency from 10 rad/s to 0.1 rad/s. What happens to the amplitude of relative displacement at the damped natural frequency, ω_d, measured in part (b)?

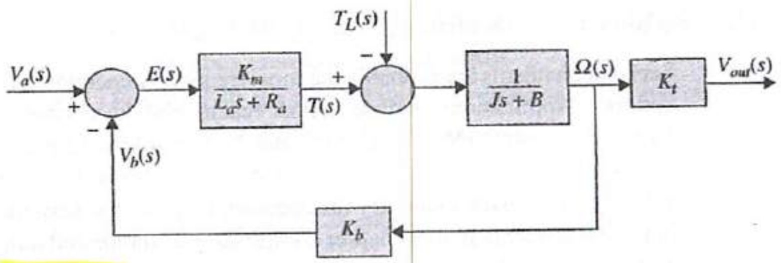

Figure 5-25 Block diagram of an armature-controlled dc motor.

As shown in Fig. 5-25, the armature-controlled dc motor is itself a feedback system, where back-emf voltage is proportional to the speed of the motor. In Fig. 5-25, we have included the effect of any possible external load (e.g., the load applied to a juice machine by the operator pushing in the fruit) as a disturbance torque T_L. The system may be arranged in input–output form such that $V_a(s)$ is the input and $\Omega(s)$ is the output:

$$\Omega(s) = \frac{\dfrac{K_m}{R_a J_m}}{\left(\dfrac{L_a}{R_a}\right)s^2 + \left(1 + \dfrac{BL_a}{R_a J_m}\right)s + \dfrac{K_m K_b + R_a B}{R_a J_m}} V_a(s) - \frac{\left\{1 + s\left(\dfrac{L_a}{R_a}\right)\right\}/J_m}{\left(\dfrac{L_a}{R_a}\right)s^2 + \left(1 + \dfrac{BL_a}{R_a J_m}\right)s + \dfrac{K_m K_b + R_a B}{R_a J_m}} T_L(s) \tag{5-114}$$

The ratio L_a/R_a is called the *motor electric-time constant*, which makes the system speed-response transfer function second order and is denoted by τ_e. Also, it introduces a zero to the disturbance-output transfer function. However, as discussed in Chapter 4, because L_a in the armature circuit is very small, τ_e is neglected, resulting in the simplified transfer functions and the block diagram of the system. Thus, the speed of the motor shaft may be simplified to

$$\Omega(s) = \frac{\dfrac{K_m}{R_a J_m}}{s + \dfrac{K_m K_b + R_a B}{R_a J_m}} V_a(s) - \frac{\dfrac{1}{J_m}}{s + \dfrac{K_m K_b + R_a B}{R_a J_m}} T_L(s) \tag{5-115}$$

or

$$\Omega(s) = \frac{K_{eff}}{\tau_m s + 1} V_a(s) - \frac{\dfrac{\tau_m}{J_m}}{\tau_m s + 1} T_L(s) \tag{5-116}$$

where $K_{eff} = K_m/(R_a B + K_m K_b)$ is the motor gain constant, and $\tau_m = R_a J_m/(R_a B + K_m K_b)$ is the motor mechanical time constant. If the load inertia and the gear ratio are incorporated into the system model, the inertia J_m in Eqs. (5-114) through (5-116) is replaced with J (total inertia).

RIPTION OF THE VIRTUAL EXPERIMENTAL SYSTEM

The experiments that you will perform are intended to give you hands-on (virtually!) experience in analyzing the system components and experimenting with various feedback control schemes. To study the speed and position response of a dc motor, a typical experimental test bed is shown in Fig. 6-1.

The setup components are as follows:

- A dc motor with a position sensor (usually an encoder with incremental rotation measurement) or a speed sensor (normally a tachometer or a differencing operation performed on encoder readings)
- A power supply and amplifier to power the motor
- Interface cards to monitor the sensor and provide a command voltage to the amplifier input and a PC running MATLAB and Simulink to control the system and to record the response (alternatively, the controller may be composed of an analog circuit system)

A simple speed control system is composed of a sensor to measure motor shaft speed and an amplifier with gain K (proportional control) in the configuration shown in Fig. 6-1. The block diagram of the system is also shown in Fig. 6-2.

To control the position of the motor shaft, the simplest strategy is to use a proportional controller with gain K. The block diagram of the closed-loop system is shown in Fig. 6-3. The system is composed of an angular position sensor (usually an encoder or a potentiometer for position applications). Note that for simplicity the input voltage can be scaled to a position input $T_{in}(s)$ so that the input and output have the same units and scale.

The components are described in the next sections.

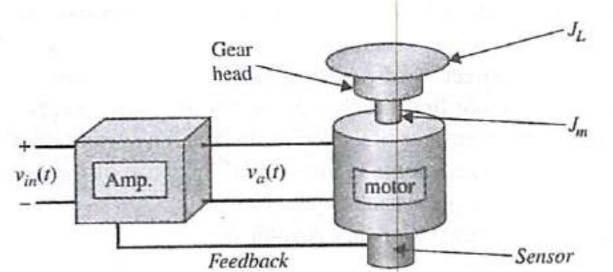

Figure 6-1 Feedback control of an armature-controlled dc motor with load inertia.

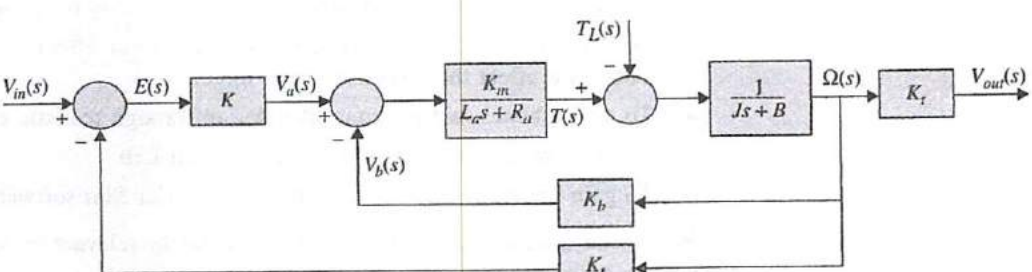

Figure 6-2 Block diagram of a speed-control, armature-controlled dc motor.

6-2-1 Motor

6-2-2 Position Sensor

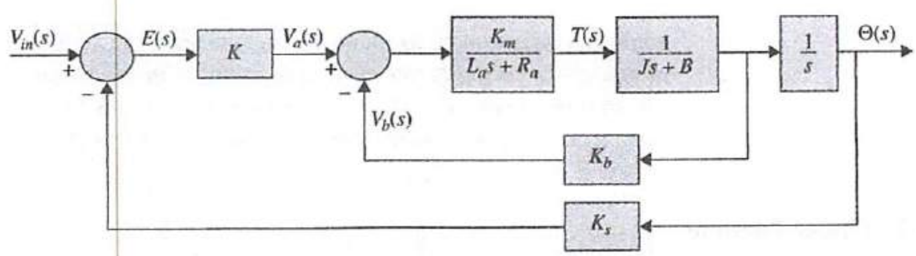

Figure 6-3 Block diagram of a position-control, armature-controlled dc motor.

6-2-1 Motor

Recall from Chapter 5 that for the armature-controlled dc motor shown in Fig. 5-24, the system parameters include

R_a = armature resistance, ohm
L_a = armature inductance, henry
v_a = applied armature voltage, volt
v_b = back emf, volt
θ = angular displacement of the motor shaft, radian
T = torque developed by the motor, N-m
J_L = moment of inertia of the load, kg-m^2
T_L = any external load torque considered as a disturbance, N-m
J_m = moment of inertia of the motor (motor shaft), kg-m^2
J = equivalent moment of inertia of the motor and load connected to the motor-shaft, $J = J_L/n^2 + J_m$, kg-m^2 (refer to Chapters 4 and 5 for more details)
n = gear ratio
B = equivalent viscous-friction coefficient of the motor and load referred to the motor shaft, N-m/rad/sec (in the presence of gear ratio, B must be scaled by n; refer to Chapter 4 for more details)
K_t = speed sensor (usually a tachometer) gain

The motor used in this experiment is a permanent magnet dc motor with the following parameters (as given by the manufacturer):

K_m = Motor (torque) constant 0.10 Nm/A
K_b = Speed Constant 0.10 V/rad/sec
R_a = Armature resistance 1.35 ohm
L_a = Armature inductance 0.56 mH
J_m = Armature moment of inertia 0.0019 kg-m^2
τ_m = Motor mechanical time constant 2.3172 E-005 sec

A reduction gear head may be attached to the output disk of the motor shaft. If the motor shaft's angular rotation is considered the output, the gear head will scale the inertia of the load by $1/n^2$ in the system model, where n is the gear ratio.

6-2-2 Position Sensor or Speed Sensor

For position-control applications, an incremental encoder or a potentiometer may be attached directly to the motor shaft to measure the rotation of the armature. In speed