Experiment M8
Dynamometers
Procedure

Deliverables: Checked lab notebook, Brief technical memo

Overview

Theoretical Background

A DC motor typically contains electromagnetic “rotor” coils mounted to the shaft, and permanent “stator” magnets mounted to the motor case. The torque output by a DC motor shaft depends on the magnetic field in the rotor coils, which is proportional to current. In most DC motors, the shaft torque τ is linearly related to the current I

$$\tau = K_T I \,, \tag{1}$$

where K_T is the motor torque constant.

The direction of current flow in the coils periodically switches as the shaft rotates. The inductance of the rotor coils prevents current from switching directions too quickly, and DC motors draw less current at higher speeds. The end result of all this is that the output torque τ increases with current I and decreases with shaft speed ω. Thus, the shaft torque decreases linearly with shaft speed

$$\tau = \tau_0 \left(1 - \omega/\omega_0\right), \tag{2}$$

where τ_0 is the stall torque and ω_0 is the no load speed. The stall torque depends on the applied voltage V and stator coil resistance R_c

$$\tau_0 = K_T \left(\frac{V}{R_c}\right). \tag{3}$$

Lastly, the rate of work done by the motor is known as the shaft power, and it can be calculated in units of Watts using the formula

$$P_{shaft} = \omega \tau \,, \tag{4}$$

where the shaft speed ω is in rad/s and the torque τ is in units of Nm. The motor efficiency is defined as the shaft power output divided by the electrical power input, $q = IV$.

Part I: Torque, Speed, Current, Voltage, Shaft Power and Efficiency

Experimental Procedure

You will experimentally measure the torque-speed curve and torque-current curve for a DC motor using the dynamometer pictured in Fig. 1. This data will then be used to calculate the torque-power curve and torque-efficiency curve.

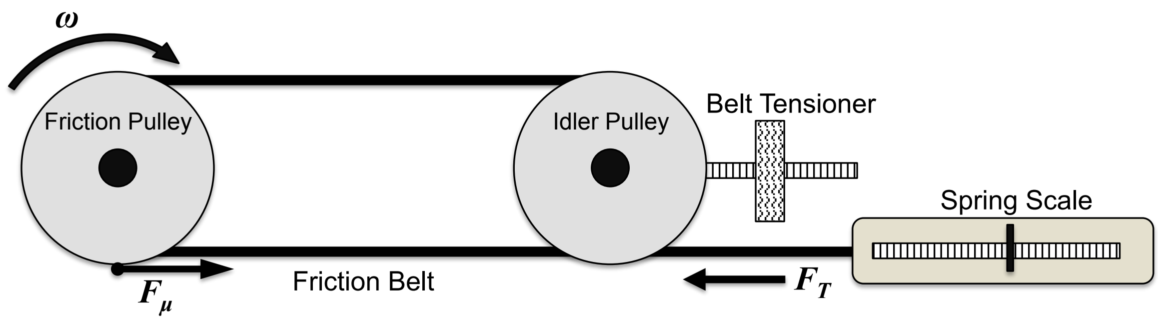

Figure 1 - A schematic of the dynamometer used to measure torque-speed curves. The friction pulley is mounted to the DC motor shaft and spins at an angular speed ω. The friction force from the belt provides a torque that can be adjusted using the belt tensioner and measured using the spring scale.

Safety First: If you have long hair, it must be tied in a ponytail or kept up in a hat or hairnet. Do not let it get tangled around the motor shaft!

1. Sketch a schematic of the experimental setup in your lab notebook.
2. Make sure the 550 RPM motor is mounted to the dynamometer. Ask the TA for help mounting it.
3. Measure the resistance across the terminals of the DC motor. This will give you the rotor coil resistance R_c.
4. Loosen the belt by turning the knob on the belt tensioner. Remove the belt from the friction pulley.
5. Use the calipers to measure the diameter of the friction pulley where the belt makes contact.
6. Set up the Keysight U8002A DC power supply:
    a. Press the "OVER VOLTAGE" button and make sure it is set to 14V. Press the "OVER VOLTAGE" button again to save the setting.
    b. Press the "OVER CURRENT" button and make sure it is set to 4 A. Press the "OVER CURRENT" button again to save the setting.
    c. Press the "Output ON/OFF" button. You should see a value for voltage and current show up on the screen.
    d. Toggle the "Voltage/Current" button and turn up the voltage to 12V.
    e. Press the "Output ON/OFF" button. The screen should say "OFF".

7. Sketch the circuit in Fig. 2 in your lab notebook. Note that this is the same circuit used for in hydraulic pump lab.
8. Connect the motor to the DC power supply + and – outputs with the handheld DMM in series to measure current on the 10A scale, as shown in Fig. 2. **Make sure you are connected to the 10A banana plug on the DMM.**
9. Press the "Output ON/OFF" button on the DC motor to energize the motor. Make sure the motor and friction pulley are spinning clockwise as shown in Fig. 1. If not, flip the cables around on the DC power supply + and – outputs

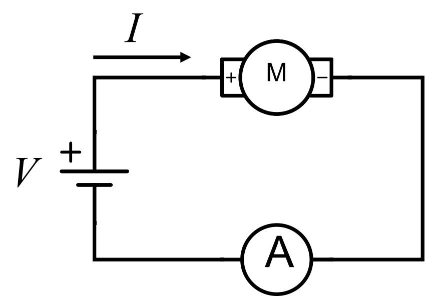

Figure 2 - The motor is connected to a DC power supply and an ammeter for measuring current.

10. When the motor is running without the belt, the applied torque is effectively zero and it will spin at the "no load speed" ω_0. With the motor spinning clockwise, use the handheld tachometer to measure the angular speed in RPM. Hold the tachometer close to the pulley so the red laser beam reflects back into the tachometer. **Think about how the optical tachometer works.**
11. Measure the motor current with no load.
12. Turn off the motor. Place the belt back on the friction pulley and tighten it up a bit using the belt tensioner.
13. Turn the motor back on. Tighten the belt using the belt tensioner, and you should see the motor slow down, the force on the spring scale increase, and the current increase.
14. Create a table in your lab notebook with three columns for angular speed ω, the motor current I, and the force F_T on the spring scale.
15. Start with a low torque (loose friction belt) and measure the angular speed ω, the motor current I, and the force F_T on the spring scale. Increase the tension in the belt and measure these three parameters again. Repeat this procedure until the motor stalls (stops spinning).
16. When the motor stalls, *quickly* record the motor current I and the force on the spring scale F_T. Then, turn off the DC power supply. **Do NOT leave the motor stalled for more than a few seconds.**
17. Loosen the belt tensioner and remove the belt. Then, remove the pulley from the motor by loosening the set screw.

18. Unscrew the two M3 screws holding the motor in place, and replace the 550 RPM motor with the 200 RPM motor.
19. Create a new table in your lab notebook, and repeat the measurement of the angular speed ω, the motor current I, and the force F_T on the spring scale. Be sure to get all the data points from no-load to stall.
20. When you are finished collecting data for the 200 RPM motor, replace the motor with the 550 RPM motor.
21. Use the measured diameter of the pulley to calculate torques from the measured forces.
22. Turn off the power supply, tachometer, and handheld DMM. Disconnect the cables.

Part II: Pulse Width Modulation (PWM)

Theoretical Background

In this part of the lab, you will use *pulse width modulation* (PWM) to control the electrical power going into the motor. The motor will be powered by a pulsed square wave, and the percentage of time that the square wave is ON is known as the *duty cycle*. Adjusting the duty cycle will adjust the average voltage $\langle V \rangle$ applied to the motor.

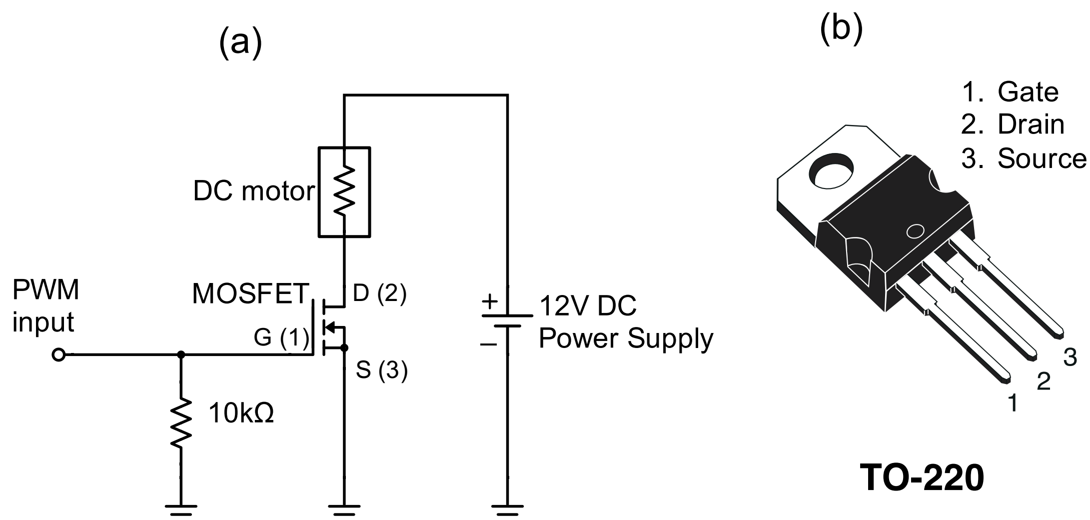

Figure 3 – (a) The PWM MOSFET circuit is used to control the speed of a DC electric motor. (b) The pin-out for the TO-220 N-channel MOSFET.

Microcontrollers and function generators are very good at producing PWM signals. However, the PWM output of a microcontroller or function generator is very low power, and it cannot provide enough current to drive the motor. Thus, we must use the MOSFET transistor circuit shown in Figure 3 to amplify the PWM signal.

Experimental Procedure

You will now construct the PWM MOSFET circuit in Fig. 3 and measure the relationship between duty cycle and the torque speed curve.

Safety First: If you have long hair, it must be tied in a ponytail or kept up in a hat or hairnet. Do not let it get tangled around the motor shaft!

1. Sketch the PWM MOSFET circuit and MOSFET pin-out shown in Fig. 3 in your lab notebook.
2. The DC power supply should say "OFF" on the display. If it does not, press the blue "Output ON/OFF" button to turn it off.
3. Loosen the belt by turning the knob on the belt tensioner. Remove the belt from the friction pulley.
4. Use the breadboard to construct the circuit shown in Fig. 3a.
   a. Designate one of the blue vertical bus lines on the breadboard as common ground, and connect the – terminal of the DC power supply to it. Importantly, anything with a ground symbol in the circuit should be connected to this common ground.
   b. Connect the + terminal of the DC power supply to the – terminal of the DC motor.
   c. Connect the + terminal of the motor to the drain of the MOSFET.
   d. Connect a 10k "pull-down" resistor from the gate to the common ground.
5. Use the function generator to produce the PWM signal via the "Pulse" function with a frequency of 500 Hz, a high value of 5V and low value of 0V.
   a. Select the function type to be "Pulse" by pressing the "Pulse" button.
   b. Press the "Amplitude/High" button. Set the "High Level" to 5V and the "Low Level" to 0V.
   c. Press the "Frequency/Period" button, and set the frequency to 500 Hz.
   d. Press the "Duty/Width" button and set the duty cycle to 10%.
6. Use the BNC T to split the PWM signal coming from the function generator, with one side of the T going to Channel 1 on the oscilloscope and the other side of the T going to drive the gate of the MOSFET. Remember, **the black mini-grabber always goes to ground.**
7. Press the "ON" button on the bottom of the function generator to enable its output.
8. Press the "Autoset" button at the top of the oscilloscope. You should see a square wave.
9. Turn on the DC power supply by pressing the blue "Output ON/OFF" button.
10. Press the "Duty/Width" button on the function generator, and turn the big wheel knob to adjust the duty cycle.
11. Vary the duty cycle or pulse width on the function generator, and observe how it affects the motor speed. Increasing the duty cycle on the function generator should increase the motor speed. The motor shaft should be spinning clockwise.

12. Measure a torque-speed curve at 99% duty cycle using the same technique as Part I. (Be sure to include the no load speed.) Note that you will not be measuring current this time.
13. Measure a second torque-speed curve at 75% duty cycle using the same technique as Part I. (Be sure to include the no load speed.) Note that you will not be measuring current this time.
14. You do NOT have to repeat this for the 200 RPM motor.
15. Disconnect the motor and disassemble the MOSFET circuit from the breadboard.

Data Analysis and Deliverables

Using LaTeX or MS Word, make the following items and give them concise, intelligent captions. **Additionally, write 1 – 3 paragraphs separate from the caption describing what you did in lab and how it relates to the plot/table. Any relevant equations should go in this paragraph.**

1. Use the 'yyaxis' command to make a plot of the torque-speed and torque-current curves for the 12V data from Part I. (Be sure to include data from the stall torque and no load speed measurements in your curve.) Use the '-o' and '-*' options to connect the measured data points with lines.
    - On the left y-axis, plot the angular speed in units of RPM as a function of the torque in units of Nm.
    - On the right y-axis, plot the motor current in units of Amperes as a function of the torque in units of Nm.
    - Make two plots like this—one for the 550 RPM motor and another for the 200 RPM motor.
2. Use the 'yyaxis' command to make a plot of the torque-power and torque-efficiency curves for the 12V data from Part I. (Be sure to include data from the stall torque and no load speed measurements in your curve.) Use the '-o' and '-*' options to connect the measured data points with lines.
    - On the left y-axis, plot the shaft power in units of Watts as a function of the torque in units of Nm.
    - On the right y-axis, plot the percent efficiency as a function of the torque in units of Nm. The efficiency is defined as the shaft power divided by electrical power IV.
    - Make two plots like this—one for the 550 RPM motor and another for the 200 RPM motor.
3. Make a plot of the torque-speed curves for the two different duty cycles from Part II. Both data sets should be on the same plot.
    - Plot the angular speed in units of RPM as a function of the torque in units of Nm for both of the duty cycles.
    - Be sure to include the stall torque and no load speed as data points in your curve.
    - Use the '-o' and '-*' options to connect the measured data points with lines.
    - Include a legend to denote the duty cycle of the various data sets.

Talking Points – Discuss/answer these in your paragraphs.

- Compare the ratio of the stall torques to the ratio of no-load speed for the 550 and 200 RPM motors.
- Compare the peak power and peak efficiency for the 550 and 200 RPM motors. Which one is more efficient? Why do you think this is?
- Describe how the PWM duty cycle affected the no-load speed and stall torque of the motors.

Appendix A

Equipment

Part I

- Dynamometer (stored in cabinet above lab bench)
- 12V DC gear motors, 550 RPM and 200 RPM – Amazon Part #s B072R5G5GR and B071GTTSV3
- Red banana-to-banana cable
- Red and black banana-to-minigrabber cables
- Extech handheld DMM
- Handheld tachometer
- Dial calibpers
- Keysight U8002A DC Power Supply

Part II

- Dynamometer (stored in cabinet above lab bench)
- Red banana-to-banana cable
- Red and black banana-to-minigrabber cables
- Black minigrabber cable
- Extech handheld DMM
- Handheld tachometer
- N-Channel MOSFET TO-220AB (Digikey Part # 497-2765-5-ND)
- Small breadboard
- Jumper wire kit