ECE 203 – LAB 3
MOTOR SPEED CONSTRUCTION AND CHARACTERIZATION

BEFORE YOU BEGIN

PREREQUISITE LABS
• ECE 201 and 202 Labs

EXPECTED KNOWLEDGE
• Linear systems
• Transfer functions
• Step and impulse responses (at the level covered in ECE 222)
• Block diagram algebra (as covered in ECE 223)

EQUIPMENT
• Oscilloscope
• Programmable Power Supply
• Arbitrary Function Generator

MATERIALS
• Motor
• Generator
• Foam Pad
• Rubber Band
• Faceplate
• Coupling Hose
• Motor Mounting Screws
• Faceplate Mounting Screws
• TIP41 Power Transistor
• Large heat sink with screw and nut
• Assorted Resistors and Capacitors
• Operational Amplifiers

OBJECTIVES
In this lab you will gain knowledge of different ways to characterize the output of plants. You will learn how to determine the transfer function of a plant using step and impulse inputs and frequency response.

INTRODUCTION
Being able to characterize a plant is a skill all engineers must possess. Knowing how a plant works and how it will respond to different stimuli is a vital part of engineering. In this lab you
will characterize a plant that consist of a DC motor coupled to another DC motor that serves as a speed-dependent voltage generator

**PRELAB**

**PLANT ASSEMBLY**

The first step in this lab is to build the motor–generator plant. Figure 1 shows all the parts of the motor-generator kit. Your kit will also include a 2 x 4 x 12 board (not shown). If you are missing any parts contact your Lab TA. Two different motors are included in the kit. For this lab, the motor with the plastic end will be used as a motor and the other motor will be used as a generator.

![Figure 1. Plant Kit Inventory.](image)

1. Mount the motor to the faceplate with the motor mounting screws.

2. Mount the faceplate and motor assembly to the block of wood with the faceplate mounting screws so that the motor is extended from the edge of the board (see Figure 2).

3. Place the coupling hose over the long shaft of the generator and onto the long shaft of the motor.
4. Place the foam pad between the generator and the block of wood and loosely secure with the rubber band. Your plant should look like the plant shown in Figure 3.

![Figure 2. Attaching Motor Assembly to Board.](image)

![Figure 3. Finished Motor-Generator Plant.](image)
In this lab you will be using a TIP41 transistor. Figure 4 shows the pin-out for the TIP41 transistor as well as the schematic symbol. The transistor will be used as a voltage controlled current source. Attach a heat sink to the transistor by placing a small screw through the transistor, the heat sink, and then through the small nut. Tighten the screw while holding the nut in place with your finger. Be careful not to touch the transistor or heat sink during operation because it can become very hot.

![Figure 4. Pin-out for TIP41 Transistor.](image)

**CHARACTERIZING THE PLANT**

Before we can design a controller for the plant, we need a mathematical representation of the plant. In this lab we will assume that the plant is a linear dynamic system and can be completely modeled by a transfer function, $H(s)$. The transfer function is defined as the Laplace transform of the impulse response of the plant. The plant has a single input, the voltage driving the motor, and a single output, the voltage produced by the generator.

The transfer function of the plant depends on the speed at which the motor is operating. This constant (DC) speed is called the operating point.

**FULL SCALE CHARACTERIZATION**

In this section you will characterize the plant over a broad range of operating speeds. We will call this a full-scale characterization.

Connect your plant as shown in Figure 5. $V_S$ represents the output of the power supply. On the power supply, set the current limits to 1.5 A. The circuit will not need this much current, but will draw what it needs. If the current setting is too low the motor will not turn. On the generator, use the terminal next to the red dot as the reference point (ground). If you get negative values for $V_{OUT}$ after the generator starts rotating, switch the polarity of the leads on the motor.
When plotting the output versus the input of the plant you should find that as you slowly increase the voltage, the motor will remain stuck until it reaches a critical point. After the critical point, the speed should increase quickly to the steady-state operating speed. If you begin with the motor operating and slowly decrease the voltage, you should find that the motor stops at a lower speed than the voltage at which it starts. This nonlinear phenomenon is called hysteresis. Figure 6 shows the hysteresis of a similar motor-generator plant.
Answer Questions 1 – 3.

**Small Signal Characterization**

In the remaining sections of this lab you will be analyzing the dynamics of the plants near a fixed operating point (speed). You will begin by characterizing the plant while the plant is operating at a high speed. This will give you useful information about how quickly the plant can respond to small changes in the operating point. For this plant it is safe to assume that the small-signal model of the plant is linear and can be represented by first order transfer function

\[ H(s) = k \frac{\omega_0}{s + \omega_0} \]

where \( \omega_0 = \frac{1}{\tau} \) is the cutoff frequency and \( \tau \) is the time constant.

**Step Response**

In this section you will simulate a unit step input to the plant and use the oscilloscope to measure the response. From this response, you will be able to determine the gain \( k \) and time constant \( \tau \) that characterize the plant.

Connect the plant as shown in Figure 7. You will be using the function generator to simulate a unit step. Set the function generator to a pulse waveform with amplitude of 0.5 V. Set the frequency of oscillation to 3 Hz. This is slow enough to capture the response of the plant on the oscilloscope. Use channel 2 of the oscilloscope to capture the output of the plant. Set channel 2 to 10X attenuation with DC coupling and impedance of 1 M\( \Omega \). Set the oscilloscope probe to 10X attenuation as well. Set the horizontal scale to 200 mV/div and the vertical scale to 20 ms/div.

To view the step (pulse) signal from the function generator, connect a second oscilloscope probe to the node where the function generator and the power supply meet. Use channel 4 of the oscilloscope. Set channel 4 to 10X attenuation with DC coupling and impedance of 1 M\( \Omega \). Set the horizontal scale to 1.00 V/div and 10X attenuation.

![Figure 7. Schematic for Step Response.](image-url)
At such low frequencies you cannot get a standing waveform to appear on the oscilloscope. Instead, you will trigger the oscilloscope directly by a synchronizing signal from the function generator.

On the back of the function generator you will find a BNC terminal labeled SYNC OUT. Using a BNC to BNC cable, connect SYNC OUT to channel 1 of the oscilloscope. This will serve as the trigger signal. By connecting the function generator to the oscilloscope in this manner you force the oscilloscope to trigger synchronously with the output of the function generator. Set channel 1 of the oscilloscope to 1X attenuation with DC coupling and impedance of 1 MΩ.

Apply power to your circuit. You should see a waveform on the oscilloscope similar to the one in Figure 8. You may have to adjust the position of the signal on the oscilloscope screen.

Note that the waveform contains a periodic oscillation in addition to the slow first-order response due to the change in operating point (speed). This periodic waveform is called cogging and it is due to the finite number of stators (electromagnets) within the motor that are used to exert a rotational force on the rotor. This is a nonlinear effect that is not accounted for in our linear model. To separate the linear response from the cogging, you will need to configure the scope to average many different responses to a step input. Since the periodic part of the signal is not synchronous with the step input from the function generator, averaging the signal will effectively filter out the cogging.

To average the waveform on the oscilloscope, under the Acquire column select Menu⇒Average. Use the selector knob to adjust the number of acquisitions to 512. The oscilloscope will then average the output over 512 acquisitions. After a few seconds, the waveform should start to become smoother, as shown in Figure 9.

The gain $k$ can be measured directly from the averaged step response of the plant. For a small signal characterization, we treat the value before the step input as 0. The gain $k$ is therefore the difference between the average output voltage after the step and the steady-state average output voltage before the step was applied.

**Answer Question 4.**

We can also use the average step response to estimate the time constant of the plant $\tau$. When the time $t$ is equal to the time constant $\tau$, the response of the plant will be at $1 - e^{-1}$, or approximately 63% of its final value. Since the gain $k$ was estimated in the previous step, we can calculate the expected value of the output $\tau$ seconds after the step input is applied. Once you have calculated this value, you can use the cursors on the oscilloscope to help you find the time at which the output is equal to its expected value (see Figure 10). The difference between this time and the time at which the step input is applied is approximately equal to the time constant of the plant. Make sure to measure from the time when the step is applied.

**Answer Questions 5 – 9.**
Figure 8. Step Response to Plant.

Figure 9. Average Step Response of Plant.
An alternative method for estimating the plant gain \( k \) and the time constant \( \tau \) is by measuring properties of the impulse response. The amplitude of the impulse response is equal to \( k \omega_0 \) and the rate of response decay is proportional to \( \omega_0 \). Although we cannot generate a true impulse for the plant input, we can approximate an impulse by producing a short, large amplitude pulse. As with the step response, you must average many impulse responses to filter out the nonlinear cogging effect from the linear impulse response.

Connect the plant as shown in Figure 11. This is the same connection that you used for the step response except the power supply is reduced from 10 V to 4 V. You will be using the function generator to simulate an impulse. Configure the function generator with the same settings as you did for the step input and then adjust the duty cycle of the pulse to 5% (as opposed to 50% for the step input). You can adjust duty cycle to 5% by pressing \text{SHIFT} \Rightarrow \text{FUNC} \Rightarrow 5 \Rightarrow \text{ENTER} \Rightarrow \text{EXIT} on the function generator.

As with the step response, you will want to synchronize the triggering of the oscilloscope with the function generator. You may have to adjust the vertical and horizontal scales, as well as the position of the waveform, to get a good picture of the impulse response. Your impulse response should look similar to that of Figure 12.

**Answer Question 10.**
Unfortunately, averaging is less effective at eliminating the cogging effect for the impulse response than it was for the step response. We are also limited by practical constraints from producing a pulse that is of sufficient amplitude and short enough duration to obtain an accurate impulse response. For these reasons, we will not use the impulse response to estimate the parameters $k$ and $\tau$.

Figure 11. Schematic for Impulse Response.

Figure 12. Average Impulse Response of Plant.
**FREQUENCY RESPONSE**

In an earlier section you used the step response to estimate the gain and time constant of the plant at a specific operating point. This type of behavior is theoretically the same as a first order lowpass filter with a cutoff frequency \( \omega_c = \frac{1}{\tau} \). We can also estimate the properties of the plant by creating a bode plot. If the model is correct and the measurements are acquired carefully, these two estimates should match.

Connect the plant as shown in Figure 13. This time you will be using the function generator to supply a 1 V sine wave. Start with a frequency of 100 Hz. Since the output waveform will be periodic you will still want to synchronize the oscilloscope with the function generator.

![Figure 13. Schematic for Frequency Response.](image)

Unfortunately, the Bode VI used in the ECE 202 labs cannot be used to take these measurements automatically. Instead, you will record the measurements for each frequency manually. Use channels 2 and 3 of the oscilloscope to measure the RMS value of the output and input voltages. Make sure both channels are set to 10X attenuation with 1 M\( \Omega \) impedance. Since you will only want to record the periodic values of the input and output voltages you will want to use AC coupling to filter out the DC offset signal. Adjust the vertical scale of the oscilloscope to the highest value possible that allows for a standing wave. Adjust the horizontal scaling for each wave so that you get a good idea of what the wave looks like. You will still need to use averaging acquisition to eliminate the cogging effect. However, you can obtain sufficiently accurate measurements with the averaging of 128 samples, rather than 512 as was used earlier. Round the output voltage to the nearest milivolt.

Figure 14 shows the input (pink), and output (blue) voltages at 100 Hz. The square wave (yellow) is the synchronization signal from the function generator (this can be turned off). Figure 15 shows an example of a Bode magnitude plot for a similar plant. The red curve is from measured values and the blue curve is from a transfer function determined by the step response.

**Answer Questions 11 – 13.**
Figure 14. Average Frequency Response of Plant.

Figure 15. Bode Plot of Frequency Response of Plant.