Lab 10: Motors and Gears

NOTE: To rent lockers in the Innovation Studio, please talk to a volunteer. Only lockers in MEL 2325 are left.

Overview

The objective of this lab is to gain an intuitive understanding of motors and gears in mechanisms and the limits on power output and transmission in a non-ideal system. In the prelab, you will learn how motors work. During the lab, we will perform a set of systematic tests to characterize the performance of a DC motor and disassemble a drill to find the gear ratio. At the end of session, you will be familiar with the torque-speed and power-speed response of the motor. In the post-lab, you will analyze the data and answer some questions to build your understanding of the load response.

Procedure

1. **Prelab:**

   1.1. Read the entire lab manual (prelab, in-lab, post-lab sections) and familiarize yourself with how DC motors work and the planned in-lab activities. Watch these three videos below. It will save you a lot of time to finish the lab.
   - How does an Electric Motor work?
   - How cordless drill works
   - How to assemble and disassemble an cordless electric screwdriver

   1.2. Read the prelab materials (Prelab Reading Materials: How DC motors work, page 2 ~ 4)

   1.3. Take the online quiz. See Gradescope.

2. **In Lab:**

   There will be three stations. Each group should spend about 15-20 minutes at each station.

   1. **Station A:** No-load Testing: Measure the speed versus applied voltage on an electric motor.

   2. **Station B**: Load Testing: Measure the slowing speed under different applied torque for a fixed voltage on the same electric motor.

   3. **Station C:** Drills & Planetary Gear Systems: Disassemble and reassemble an inexpensive electric drill to see how it incorporates a planetary gear system. Measure the gear ratio.

3. **Postlab (60 points):**

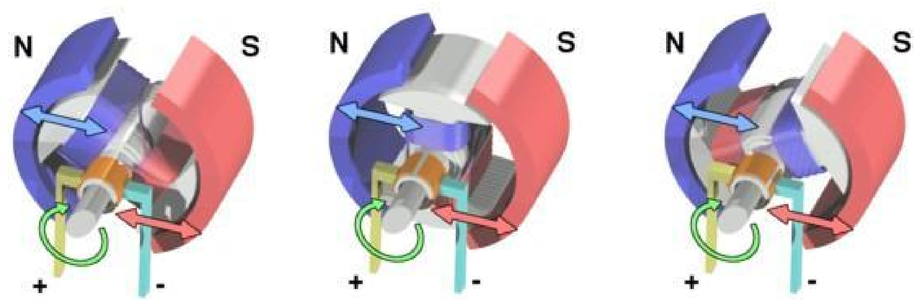
   Analyze and plot the collected data to quantitatively characterize the response of the motors.

About the motor

In stations A and B, we will test an electrical motor (34:1 Gearmotor 12V) from Pololu. This motor has been frequently used in ME 370 final projects. **For this lab, the motors being tested will be similar to the motor for the mechanism that your team will design with in Project 2**. It is a small, brushed DC motor, with a diameter of 25mm and a nominal operating voltage of 12V.

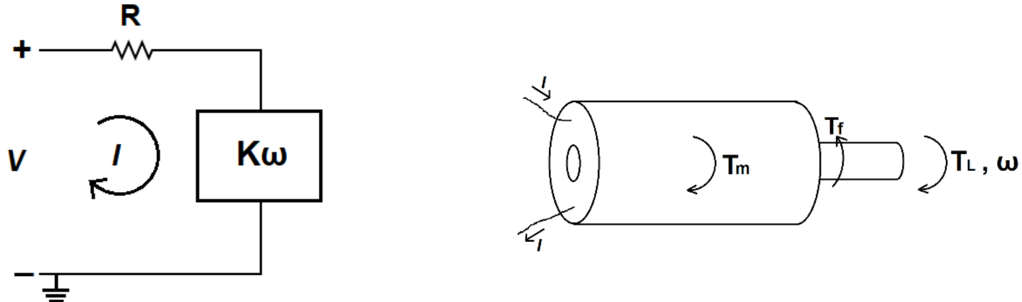
Prelab Reading Material: How DC motors work

Permanent magnet direct current (PMDC) motors are popular equipment in applications from robots to automobiles, due to their efficiency and the recent availability of powerful rare-earth magnets (e.g., neodymium iron boron and samarium cobalt). The high-end PMDC motors are brushless, with digital commutation. At the lower end, we find brush-type motors, which can range in cost from a couple dollars to a few hundred dollars (Maxon). In each case, the basic principle is essentially the same, as illustrated in Figure. 1. The basic torque arises from the Lorentz force, F, for a current, I, flowing in a magnetic field, B, such that $F = I \times B$, where the right-hand rule applies, taking B from north to south.



<u>Prelab Figure 1: Stages in the cycle of an electric motor</u>
http://en.wikipedia.org/wiki/Brushed_DC_electric_motor

To analyze a DC motor, we need to consider it from two perspectives: as a magnetic actuator (Prelab Fig. 1), and as an electrical circuit (Prelab Fig. 2 left). The electrical diagram (Prelab Fig. 2) shows that an applied voltage, V, can be considered to drop through the resistance in the motor coils, R, and the back EMF, $k\omega$. Back EMF is a voltage generated by the motor as it turns. Every motor is also a generator; every generator is also a motor. The *back EMF* is a function of the angular velocity, ω, and a constant, k, which is a function of the motor design and, especially, of the permanent magnets. The current passing through the coils generates (via the Lorenz force) a torque, T_m (m for motor), which acts against friction, T_f, and the output or load torque, T_L (Prelab Fig. 2 right).



<u>Prelab Figure 2.</u> Left: electrical circuit for motor. Right: The electrical and mechanical inputs and outputs of the motor.

Essential motor equations

Summarizing the two diagrams, we get the two essential motor equations. *Everything else can be derived from these equations:*

$$V_{in} = R_w i - k_v \omega \tag{1}$$

$$T_m = k_T i \tag{2}$$

We assume $k_T = k_v$ and $\frac{di}{dt} = 0$ in an ideal motor model. Notice from Eq. 1 that the current i and the angular velocity ω are always inversely coupled; if we know one under any operating condition, we can always find the other. Notice from Eq. 2 that torque is always linearly proportional to current. The combination of these two factors means that as angular velocity increases, torque decreases. Conveniently, if we use MKS units, the motor constant, k, is the same for the electrical and mechanical aspects of the problem. (Consider $P = Vi = T_m\omega = ki\omega$).

By equating the current in the two equations, we arrive at a relationship between torque, velocity, and input voltage.

$$T = \frac{k_T}{R_w} V_{in} - \frac{k_T^2}{R_w}\omega \tag{3}$$

Two special conditions are of particular interest in defining the properties of the motors: Stall and No-Load.

Stall

At stall, the load is so large that the motor stops rotating, i.e., when $\omega = 0$. i_{stall} is typically given by the motor manufacturer. We can also find it from equation 1.

$$V_{in} = R_w i_{stall} - k_v 0 \tag{4}$$

Equation 2 gives us the definition for the stall torque, T_{stall}:

$$T_{stall} = k_T i_{stall} \tag{5}$$

The stall current and stall torque are the maximum possible values of current and torque, respectively. (To prevent overheating and excessive power consumption, you usually don't want to hold a motor at stall for long.)

No-Load

When the output is not attached to anything, the motor will spin with the fastest rotational velocity, ω_{NL}, under this condition, the motor has no external load (i.e. $T_L = 0$), and the only residual torque is the friction torque, T_f. In this situation, Equation 1 becomes:

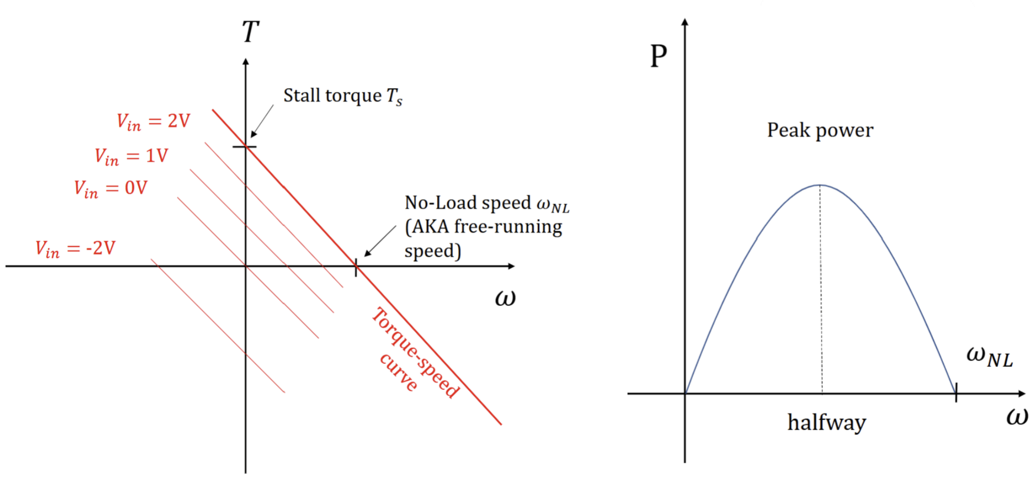
$$\omega_{NL} = \frac{V - i_{NL} R_w}{k_v} \tag{6}$$

In practice, it is usually most accurate to measure ω_{NL} directly with a tachometer, which is one of the activities in the lab.

The left plot of Prelab Figure 3 shows the Torque-Speed ($T - \omega$) plot of the motor at various voltages (T is the shaft load T_L in the equations). Each line represents the characteristic curve relating torque and angular velocity at a particular voltage. These plots show that load torque and speed are linearly related to one another. Moreover, when the drive voltage of the motor increases, the curve will shift outward. The point that intersects the torque axis corresponds with the stall torque, while the point that intersects the speed axis corresponds with the no-load speed.

The right plot in Prelab Figure 3 shows the relationship between output power and rotational velocity of a motor, over the range from 0 to ω_{nl}. The electric power flowing into the motor is $P_{in} = V\ i$, while the mechanical power flowing out from the motor shaft is $P_{out} = T\ \omega$. You can think of the mechanical power as the area of a rectangle for a given point on the ($T - \omega$) plot. This power output will be variable depending on operating speed and torque load on the shaft, and will be a maximum when the area under the curve is largest. As seen in the plot, the maximum occurs at 0.5 ω_{nl}. Mathematically, we can derive this relationship by multiplying equation 3 by ω to get an expression for power:

$$P_O = \left(k_t i\right)\omega - \left(\frac{k^2}{R}\right)\omega^2 \tag{7}$$



Prelab Figure 3: Left: Typical torque versus speed characteristic curve of a motor at two different voltages. Right: Power versus speed.

In-lab Activities

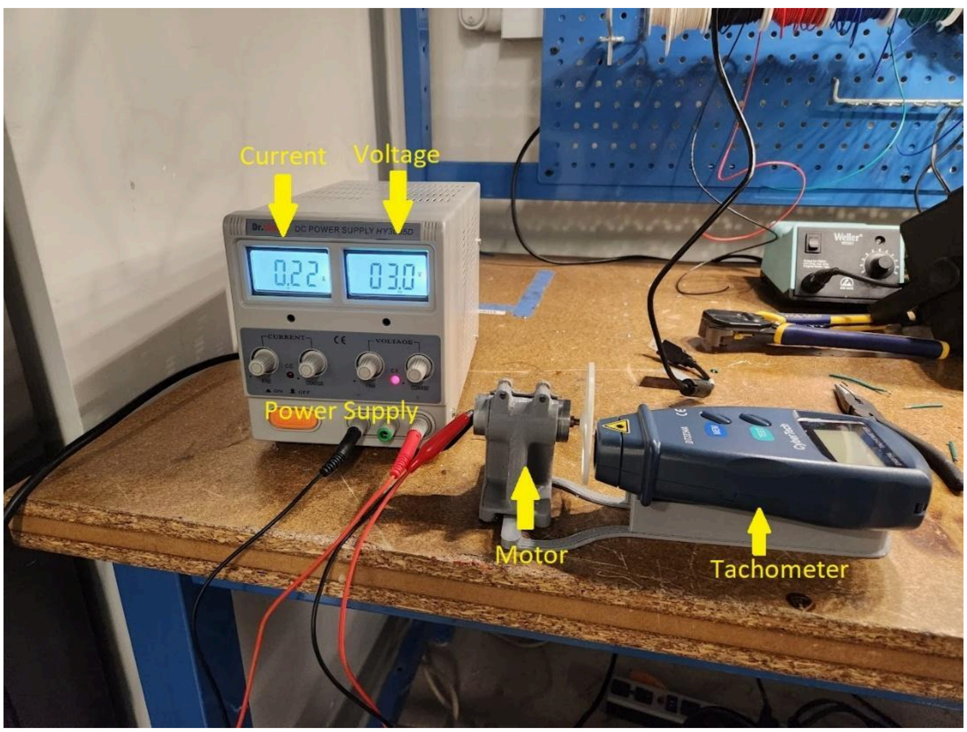
Station A: No-Load Testing

Purpose

The goal of this station is to measure the speed of a DC motor at various voltages while the motor shaft rotates freely (No-Load). The data results from this station allow us to observe the variation motor speed as a function of input power ($V\ i$), which is due to internal frictions (T_f) and self-induction response of rotor ($k\ \omega$). In addition, these data also serve to characterize V-ω or P-ω behavior of the motor at the full range of motor speed.

Setup

In-lab Figure 1 shows the setup for measuring motor speed at different voltages. Rather than hooking up to a battery, the motor should be wired to a power supply which allows simultaneous measurement of voltage and current.



In-lab Figure 1: The power supply, motor, and optical tachometer for counting the motor shaft revolutions.

Procedures
Use the lab worksheet at the end of the document to tabulate results.

a) Clamp the motor on the table and connect to the DC power supply.
b) Insert the indexing wheel (with the reflective tape on it) to the motor shaft. You will use a tachometer to measure the angular speed of the motor via the reflective tape on the wheel.
c) Starting with 2 Volts, read the current (A) and measure angular speed (rpm) of the motor. Calculate the shaft speed (ω) in the units of [rad/sec].

NOTE: Do NOT change the current dial, as there is a chance that the motor will be overloaded and subsequently break.

d) Repeat by measuring the speed 3 times for each voltage. You should vary the voltage from 2 V to 12V in increments of 2V (total of 18 measurements). Write down the **current and speed** at every voltage.
e) Tabulate all data (current and speed for at 2, 4, 6, 8, 10 and 12V) in the worksheet on the last page.

f) Discussion questions.
   - From these data, how fast should the motor turn when hooked up to a 9.6V battery? Note that 9.6 V is the maximum voltage produced by the rechargeable batteries provided in the project parts kit.
   - What happens when you drive your motor with a negative voltage? Equivalently, what happens when you drive your motor backwards? Think about how this reversal affects the design of your motor placement.

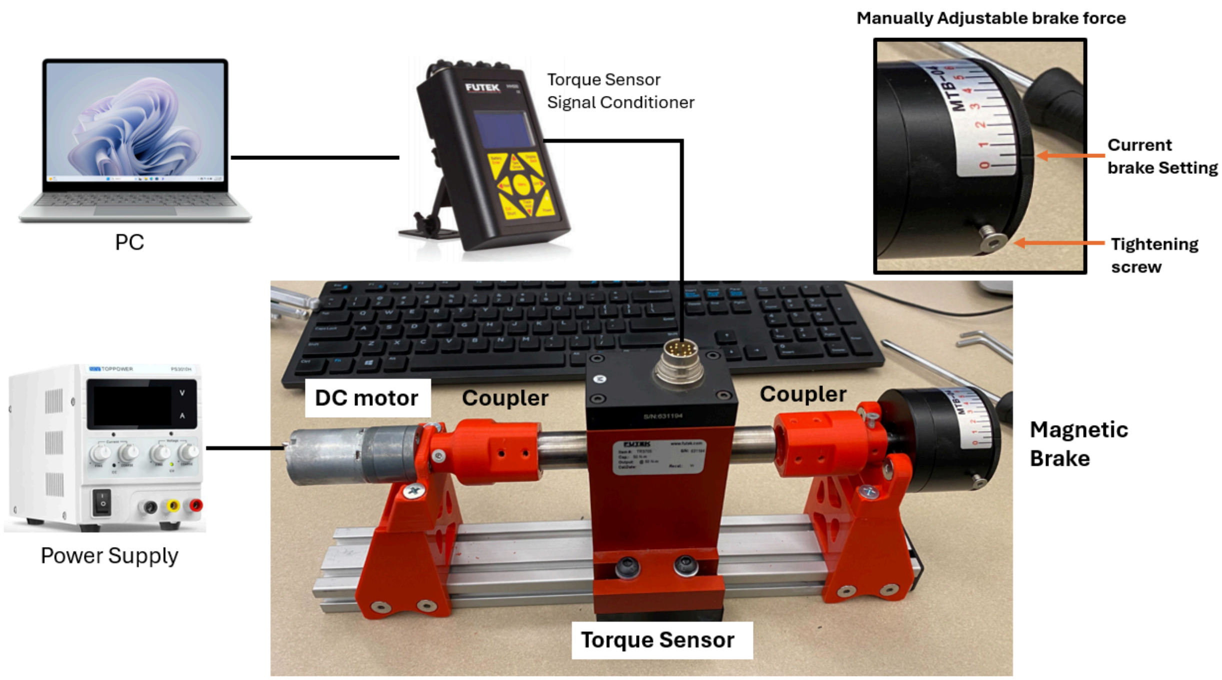
Station B: Load testing

Purpose

The goal is to measure how much the motor slows down when put under a load. The data set will be a simultaneous measurement of torque and motor speed at selected voltages while we vary the shaft torque from zero to the full load (stall). The torque-speed data set, once plotted, essentially represents the motor response behavior, namely as a set of characteristic curves like the ones included in the pre-lab document.

Setup

We will use the Futek IHH500 torque sensor (In-Lab Figure 2) to connect the torque station to the computer. The software SENSIT is used to read data from the torque sensor. The motor is attached to a test rig and connected to the torque sensor using a coupler. In the software, a window will pop up allowing to simultaneously read multiple sets of data such as torque, speed, power, and angle. To apply the load, we use a magnetic brake that is attached on the opposing end of the torque sensor. The brake force on the magnetic brake is manually adjusted to simulate different kinds of loads. All data sets on the screen are stored and saved on the computer.



In-Lab Figure 2: Torque sensor, magnetic brake, and entire set up for the torque sensing and motor couplings.

Procedures

Use the lab worksheet at the end of the document to tabulate results.

a) Make sure that the Futek IHH500 torque sensor is attached to three different points: the power outlet, the computer, and the torque sensor. Additionally, check if the Futek is on, and if it is not, turn it on.

b) Disconnect the motor from the power supply. Turn on the power supply and change the settings to **9.0V**.

c) Turn off the power supply, reattach the motor, and turn on the power supply.

d) Double-click the **SENSIT 2.3** Shortcut on the desktop

Figure 4: SENSIT 2.3 Shortcut

e) This should open the **SENSIT Test and Measurement** window. Verify that the device is enabled and then click "Load".

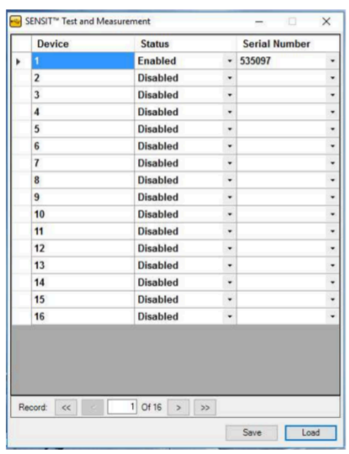


Figure 5: SENSIT Test and Measurement Window

f) After the software loads, Figure 6 should be visible. Click on the **Live Graphing Mode** tab and into the **Live Graph Setup** subtab. Click the "1. Settings" button

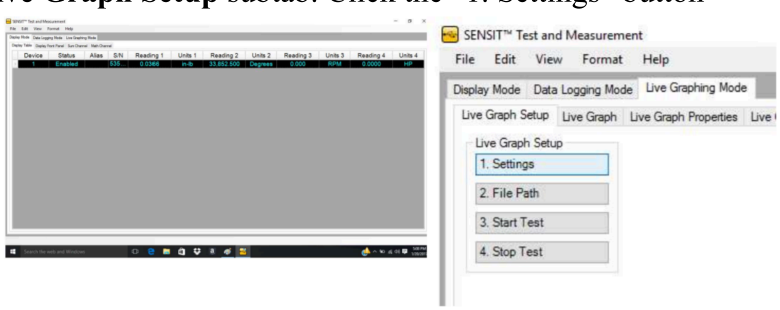


Figure 6: Live Graphing Mode Tab

g) An input window should open (Figure 7). For “Test Duration”, change the hours from **0** to **2**. For the “Test Interval”, change the seconds to **1**. The “Refresh Rate” should be set to **1** and “Samples to Display” should be set to **100**. Make sure the X-Axis Values is checked as “Sample Number”. Microsoft Excel Options is “Disable Auto Chart”. Graph Values the “Peak Values” and “Valley Values” are unchecked. Check the “Enable Rotation Values”. Click **Apply** then **OK**.

If you do NOT check Apply, the settings will NOT be saved.

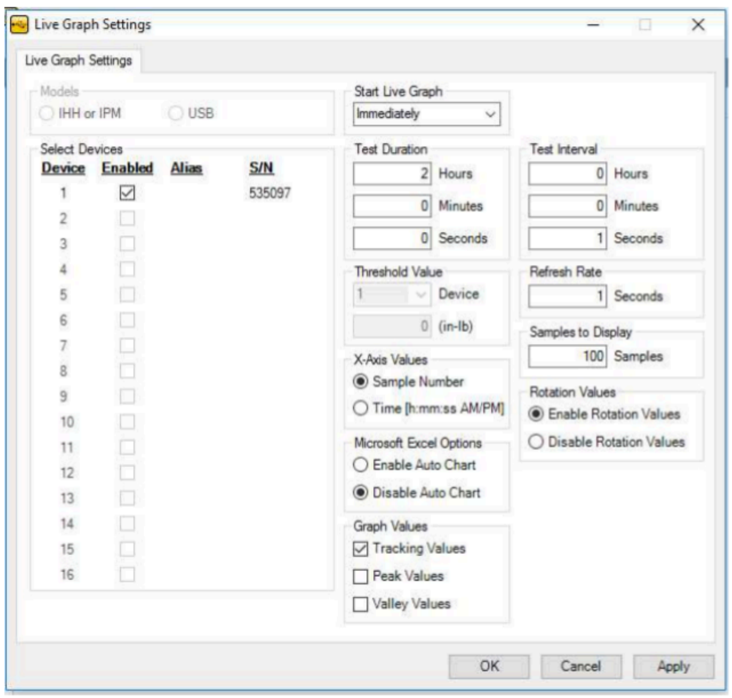


Figure 7: Live Graph Settings

h) Click on “2. File Path”. Make a folder with your team number. Make sure the file is saved as an **Excel 2007-2010 Workbook**. Click “Ok”.
If you do NOT save as a 2007-2010, the file will NOT save correctly.

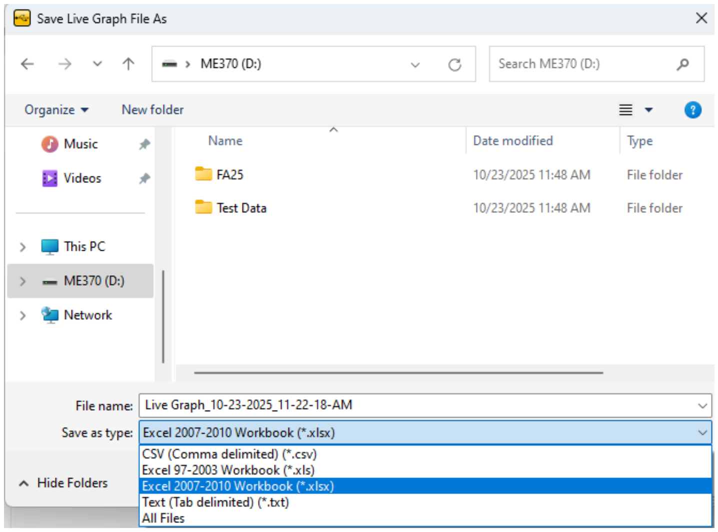


Figure 8. File Path

i) If you are not able to read any 'angle' or 'RPM' values, be sure to hit 'Display → 'Reset' on the torque sensor. The FUTEK sensor screen should appear as it does in Figure 9. Click on "3. Start Test". The screen should flicker a few times before the **Live Graph** should appear (Figure 10).

Figure 9. FUTEK Sensor Display

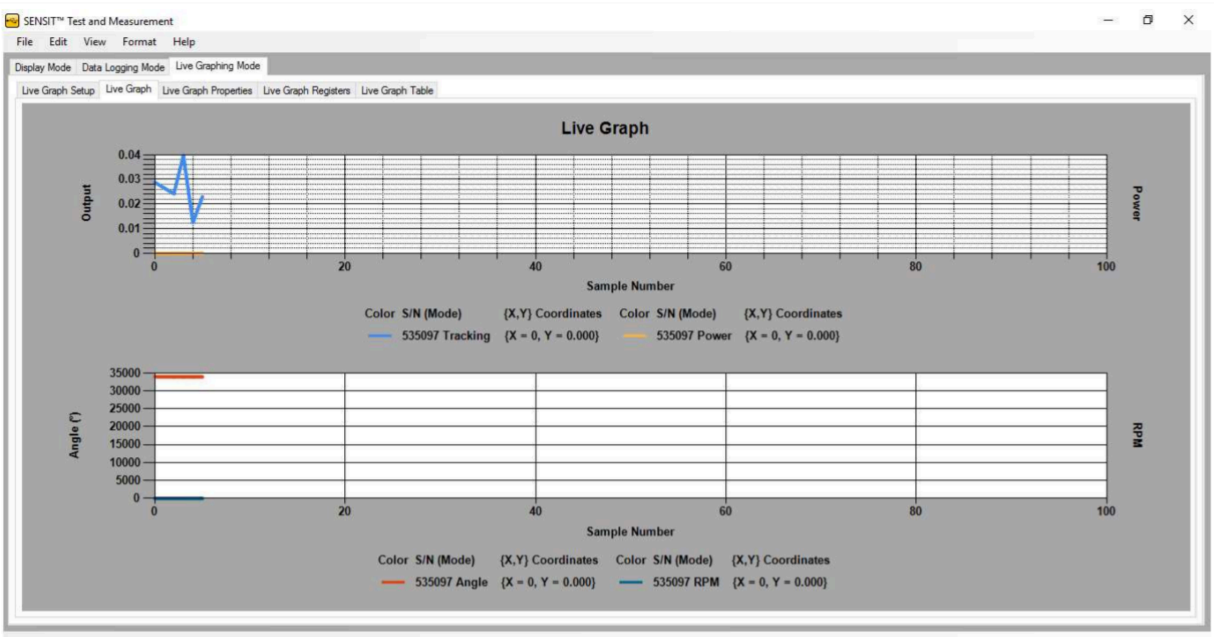


Figure 10. Live Graph

j) Start with 9.0 Volts at no load. From the computer screen choose the sample interval for speed and torque (tracking value) readings and write down the sample points.

Important note on interpreting the computer plots, and sample intervals:

a. Since the plotted curves will fluctuate when any change is made, you need to allow enough time for each parameter (i.e., speed, torque) to settle before reading. After the lab is over, take the average of these data from the generated Excel file, which will indicate the value of the measured parameter.

k) Repeat step j three more times, but with amount of brake forces (**settings: 0, 3, 6, 9)** by manually adjusting the brake force setting. To adjust brake force, simply loosen the adjustment screw using an Allen key wrench, set the brake dial to desired setting, and tighten the adjustment screw again.

   a. Make sure you are saving files as an **Excel 2007-2010 Workbook.**
   b. **Press 'Reset'** every time a new test is run to **reset the angular position.**

l) **Do NOT stall the motor.** When you are done with the measurement, refer to this link (https://www.pololu.com/product/3204) to obtain data for stall torque.

   a. You will need to extrapolate to get the 9V stall torque.

m) After all 4 brake forces have been collected, return to **the Live Graph Setup** and click "4. Stop Test." After a moment, Figure 10 should appear.

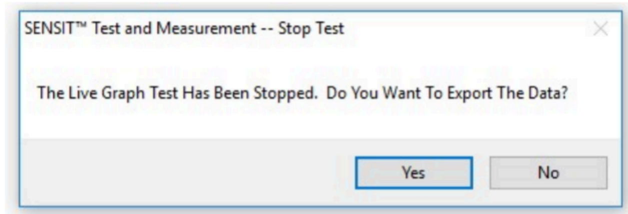
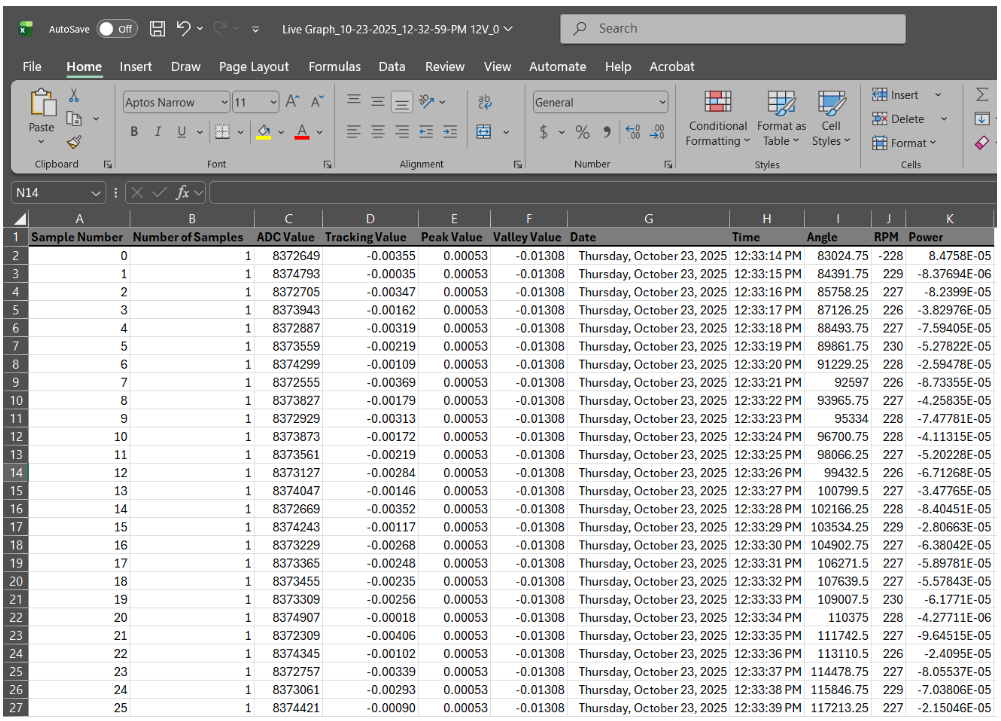


Figure 10: Stop Test

n) **Wait 5 seconds.** Then, click "Yes". Afterwards, the Excel file window should appear (Figure 11). If the Excel file window does NOT appear, then you previously did not set the correct Excel file type.



	Sample Number	Number of Samples	ADC Value	Tracking Value	Peak Value	Valley Value	Date	Time	Angle	RPM	Power
2	0	1	8372649	-0.00355	0.00053	-0.01308	Thursday, October 23, 2025	12:33:14 PM	83024.75	-228	8.4758E-05
3	1	1	8374793	-0.00035	0.00053	-0.01308	Thursday, October 23, 2025	12:33:15 PM	84391.75	229	-8.37694E-06
4	2	1	8372705	-0.00347	0.00053	-0.01308	Thursday, October 23, 2025	12:33:16 PM	85758.25	227	-8.2399E-05
5	3	1	8373943	-0.00162	0.00053	-0.01308	Thursday, October 23, 2025	12:33:17 PM	87126.25	226	-3.82976E-05
6	4	1	8372887	-0.00319	0.00053	-0.01308	Thursday, October 23, 2025	12:33:18 PM	88493.75	227	-7.59405E-05
7	5	1	8373559	-0.00219	0.00053	-0.01308	Thursday, October 23, 2025	12:33:19 PM	89861.75	230	-5.27822E-05
8	6	1	8374299	-0.00109	0.00053	-0.01308	Thursday, October 23, 2025	12:33:20 PM	91229.25	228	-2.59478E-05
9	7	1	8372555	-0.00369	0.00053	-0.01308	Thursday, October 23, 2025	12:33:21 PM	92597	226	-8.73355E-05
10	8	1	8373827	-0.00179	0.00053	-0.01308	Thursday, October 23, 2025	12:33:22 PM	93965.75	227	-4.25835E-05
11	9	1	8372929	-0.00313	0.00053	-0.01308	Thursday, October 23, 2025	12:33:23 PM	95334	228	-7.47781E-05
12	10	1	8373873	-0.00172	0.00053	-0.01308	Thursday, October 23, 2025	12:33:24 PM	96700.75	228	-4.11315E-05
13	11	1	8373561	-0.00219	0.00053	-0.01308	Thursday, October 23, 2025	12:33:25 PM	98066.25	227	-5.20228E-05
14	12	1	8373127	-0.00284	0.00053	-0.01308	Thursday, October 23, 2025	12:33:26 PM	99432.5	226	-6.71268E-05
15	13	1	8374047	-0.00146	0.00053	-0.01308	Thursday, October 23, 2025	12:33:27 PM	100799.5	227	-3.47765E-05
16	14	1	8372669	-0.00352	0.00053	-0.01308	Thursday, October 23, 2025	12:33:28 PM	102166.25	228	-8.40451E-05
17	15	1	8374243	-0.00117	0.00053	-0.01308	Thursday, October 23, 2025	12:33:29 PM	103534.25	229	-2.80663E-05
18	16	1	8373229	-0.00268	0.00053	-0.01308	Thursday, October 23, 2025	12:33:30 PM	104902.75	227	-6.38042E-05
19	17	1	8373365	-0.00248	0.00053	-0.01308	Thursday, October 23, 2025	12:33:31 PM	106271.5	227	-5.89781E-05
20	18	1	8373455	-0.00235	0.00053	-0.01308	Thursday, October 23, 2025	12:33:32 PM	107639.5	227	-5.57843E-05
21	19	1	8373309	-0.00256	0.00053	-0.01308	Thursday, October 23, 2025	12:33:33 PM	109007.5	230	-6.1771E-05
22	20	1	8374907	-0.00018	0.00053	-0.01308	Thursday, October 23, 2025	12:33:34 PM	110375	228	-4.27711E-06
23	21	1	8372309	-0.00406	0.00053	-0.01308	Thursday, October 23, 2025	12:33:35 PM	111742.5	227	-9.64515E-05
24	22	1	8374345	-0.00102	0.00053	-0.01308	Thursday, October 23, 2025	12:33:36 PM	113110.5	226	-2.4095E-05
25	23	1	8372757	-0.00339	0.00053	-0.01308	Thursday, October 23, 2025	12:33:37 PM	114478.75	227	-8.05537E-05
26	24	1	8373061	-0.00293	0.00053	-0.01308	Thursday, October 23, 2025	12:33:38 PM	115846.75	229	-7.03806E-05
27	25	1	8374421	-0.00090	0.00053	-0.01308	Thursday, October 23, 2025	12:33:39 PM	117213.25	227	-2.15046E-05

Figure 11. Excel File ('Tracking Value' is torque)

o) Repeat Steps a) through n), but at **12 volts** instead of **9 volts**.

p) After lab, plot your tabulated results and plot lines to interpolate the characteristic curve for each voltage. You will use these results in the post-lab assignment. Note that the "Tracking Value" column contains the torque values (in *Nm*).

Station C: Drill gear train

Purpose: We will open a cordless drill and inspect the transmission of motion from the motor to the tip of the drill. We will count the number of teeth in each of the gears in order to calculate the gear ratio of the entire mechanism.

In-lab Figure 12: Cordless drill used in the disassembly part of the lab.

Guidelines

Watch the YouTube video linked below. During lab, disassemble the drill following the steps below, sketch a diagram of the gear train, count the number of teeth from each gear, and calculate the gear ratio.

YouTube Video Link: https://www.youtube.com/watch?v=dacXjjZQmP0

Disassembly: 1:30 ~ 3:40

Assembly: 7:17 ~ 10:50

Suggestions before starting disassembly

- Keep the table clear of unnecessary objects.
- Put all the screws on a tray or cup so you do not lose them.
- Use a cell phone to take pictures of the inner mechanism before and after removing any of the gears. This is helpful both for reassembling it and for understanding the transmission.
- Do not force any component into position when reassembling. That means it is out of place!

Procedures:

To disassemble the cordless drill:

1) Use the provided screwdrivers to remove all the screws on the lateral side of the drill.
2) After removing the pin of the handle, open the orange plastic casing.
3) Separate the battery pack from the rest of the components.

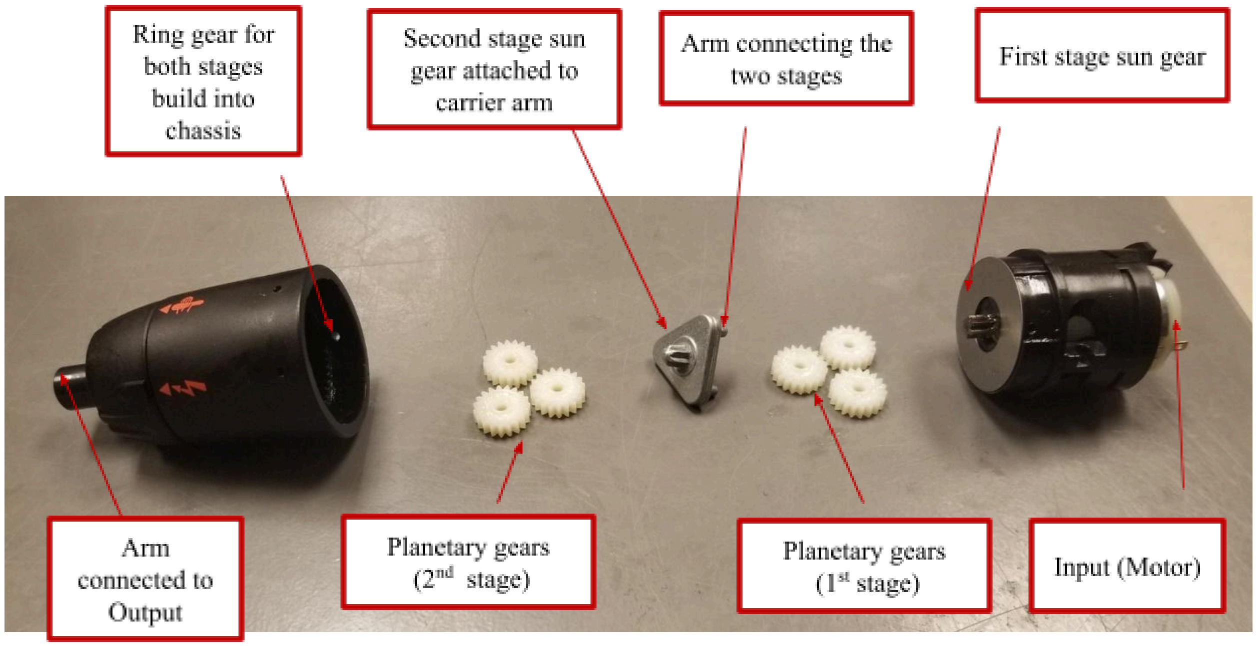
In-lab Figure 13: Disassembled drill.

4) In order to open the front part of the drill where the gear train is located, remove the U-shaped clip.
5) Then **very carefully** pull the two sections apart. Otherwise, some of the gears may fall before you can see where they were positioned.

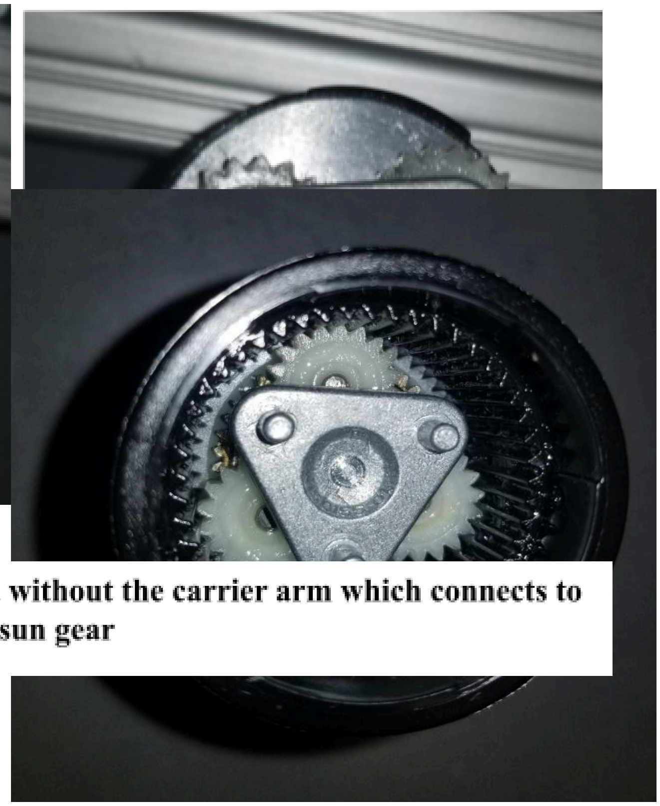
In-lab Figure 14: Disassembled U-shaped clip.

6) Take pictures and schematically draw how the gears are assembled. Then, carefully remove each gear and count the number of teeth on each. For each gear, make sure you have a clear idea on whether it can rotate or is kept fixed, whether it is driving or being driven.
7) Don't forget to count the number of teeth on the outer ring gear as well.
8) After checking if you have the necessary information for the **Questions** below, reassemble the drill.

In-lab Figures 15-18 detail the entire gear train. You should be able to reconstruct the entire gear train from these pictures. However, it is easier to do this if you deconstruct the drill yourself and see which gears are moving and how they connect together.

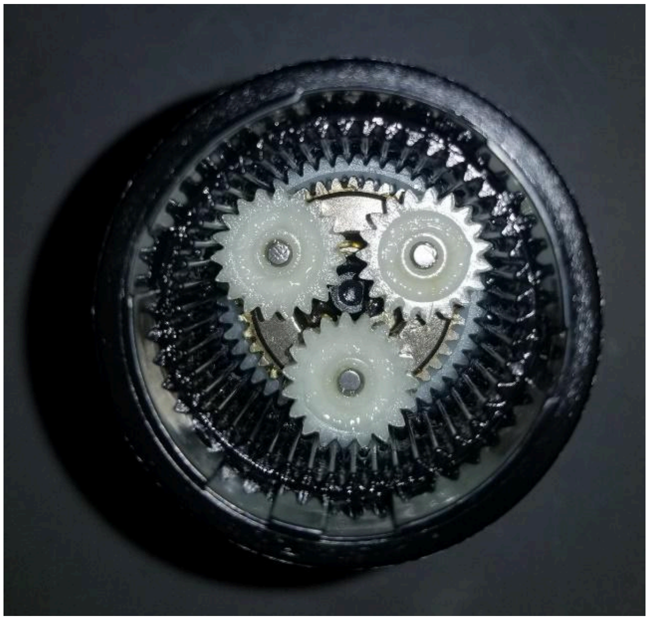


In-lab Figure 15: The drill's gear train.

In-lab Figure 16: First stage gears with and without the carrier arm which connects to stage 2 sun gear

In-lab Figure 17: Second stage gears with and without the sun gear and carrier arm which connects to stage 1 planets



In-lab Figure 18: Second stage without the planet gears, showing the carrier arm connected to the drill output (metal) and the fixed ring gear built into the chassis (black gear).)
<u>The ring gear is fixed and extends back to cover both stages</u>

Table 1. Station A: No-Load Testing

Test #	Voltage [V]	Current [A]	Speed [rpm]	Speed [rad/s]	Input Power [W]
1	2				
2					
3					
4	4				
5					
6					
7	6				
8					
9					
10	8				
11					
12					
13	10				
14					
15					
16	12				
17					
18					

Table 2 & 3. Station B: Load Testing

- Average the data saved on the Excel files and calculate the torques and speeds for each load for 9 V and 12 V

Table 2. Load Testing, Voltage = 9 V

Torque	Speed [rpm]	Speed [rad/s]	Output Power [W]
$T_1 = 0$			
$T_2 =$			
$T_3 =$			
$T_4 =$			
$T_{stall} =$			

Table 3. Load Testing, Voltage = 12 V

Torque	Speed [rpm]	Speed [rad/s]	Output Power [W]
$T_1 = 0$			
$T_2 =$			
$T_3 =$			
$T_4 =$			
$T_{stall} =$			

Post Lab

In a short report, summarize your results and include the following calculations, plotting and analysis. Submit your report as a pdf on Gradescope. This is a **group assignment.**

No Load Station (10 pts):

- (5 pts) Plot input power-speed curve for each input voltage (Watts vs $\frac{rad}{sec}$)
- (5 pts) In a few sentences, explain the relationship between input power and speed.

Load Station (30 pts):

- (10 pts) Plot torque vs. speed for all four brake settings and both voltages in one graph. Average each value so that you have one data point for each voltage and brake setting. Include a best fit curve for each voltage, and state the equation of the curve.
- (10 pts) Plot output power vs. speed for both voltages in one graph. Average each value so you have one data point for each voltage and brake setting. Include a best fit curve for each voltage, and state the equation of the curve.
- (10 pts) In a few sentences, explain the resulting trends at both low and high speeds.

Drill Disassembly (20 pts):

1. (4 pts) Sketch the entire gear train inside the drill from motor to output.
2. (4 pts) Measure and report on the number of teeth on the (a) sun, (b) planets, and (c) ring gears on each of the stages.
3. (4 pts) Write an equation for the total gear ratio from the motor to the output of the drill in terms of the number of teeth for each gear kept as a variable N.
4. (4 pts) Calculate the resulting gear ratio of the entire gear train using the measured number of teeth.
5. (4 pt) Why are planetary gear systems an ideal solution for drill transmission?

Tips for analyzing the provided Excel files

- The motor torque values are stored in the 'Tracking Value' column. The units are Nm.
- For the output mechanical power, do not use the power values tabulated in the 'Power' column. Calculate it yourself by multiplying torque and angular velocity.
- You should be able to distinguish the data points for the 5 different motor torques (0, 3, 6, 9, and stall) by observing the sample number at which each of the brake forces are applied.
- For the torque-speed and power-speed graphs, take the average of the values for each brake force and voltage. So, you would have only 5 data points for each voltage. The graphs would get messy otherwise.
- Be consistent with units. Make sure to convert torque, RPM and power units to N-m, rad/sec and Watts respectively while processing the data.