A Brief, Informal Introduction to Motor Testing

(And other interesting motor things...)

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1 Before we Begin

This notebook is a basic guide to dynamometer motor testing, the physics of a dynamometer, and how one works. It was written for people who may or may not know about motors and don't know too much about motor testing. I'm going to try to outline the important parts of a dynamometer, why you might need a dynamometer, and how to interpret the data that comes out of a dynamometer based on what I learned working on one in the lab. I'm essentially going to consider the motor as a "black box" component of the system initially and may go into more detail later. I will, like a good little scientist, explain my assumptions on the motor's controller before launching into the dynamometer.

I'm also by no means an expert on dynamometers, essentially this is a document on the basics of what I've learned, so if I leave anything out of course let me know — adim@mit.edu

2 Basics of a Dyno

Before we launch straight into the basics of the dynamometer, I promised some assumptions about motors and motor control.

2.1 Prerequisite Assumptions

In this guide we will assume that you have access to two theoretical motors (see Figure 1).

2.1.1 The Motor Under Test

Motor 1, which is the "motor under test" which has a control system that can perform perfect current control. The motor under test is the motor which we are trying to measure the performance parameters on (the torque speed curve, the Kt, etc). We want to be able to perform current control on the motor
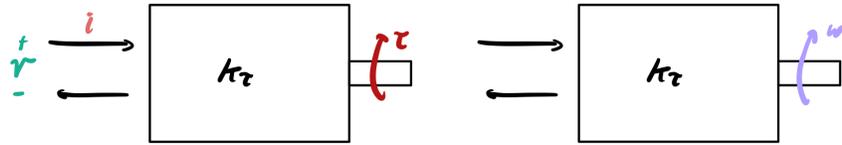
Figure 1: A torque control motor, and a speed control motor. The speed control motor must be more powerful than the torque control motor.

as a typical DC motor produces an output torque directly proportional to the current in its phase windings by a constant called the motor constant K_t.

$$\tau = K_t * i$$

We will assume this current controller is perfect for example if we command 5A the torque producing current in the motor will be equal to 5A and the controller will have the correct control bandwidth. The distinction "torque producing current" is important for brushless DC motors. For more information on motor control we recommend Sang-Hoon Kim's fantastic motor control textbook.

2.1.2 Driving Motor

Motor 2, which is the "driving motor" which has a control system that can perform perfect velocity control. The driving motor is the motor that sets the speed of the dynamometer and provides the required "resistance" or "simulated load" felt at the shaft of the motor under test. We want to perform velocity control on this motor so we can set the speed at which the motor under test should produce its torque, this way we can measure power and build up a torque-speed curve for the motor.

We will assume this velocity controller is perfect which means any commanded velocity will be the velocity of both the driving motor and the motor under test and the velocity controller has a bandwidth that is 5x less than that of the current controller (see the motor control textbook).

Motor 2 must either be the same size or more powerful than Motor 1. That means it should be able to achieve both the same or higher torque at the same or higher speed.

2.1.3 Control System Design

We will, finally, also assume the controller gains have been specc'ed such that resonance in the shaft of the dynamometer and between the motors is not

possible and will not cause the system to go unstable. Most design do not have to worry about this by default as the torsional stiffness of metal-shaft-dynamometers is fairly high (see Figure 2).
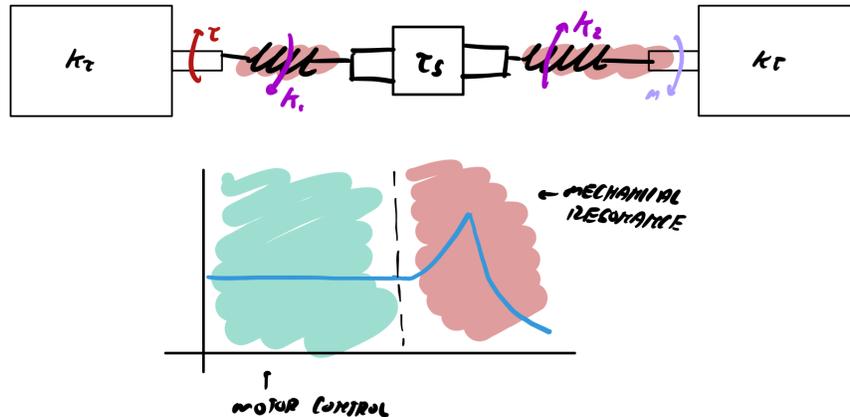
Figure 2: As always we should consider the mechanical stiffness and dynamics of the system when determining control authority and bandwidth.

2.1.4 Some Resources for Motors

- Electric Motor Control Sang-Hoon Kim — Electric Motor Control Textbook DOI

- Motors & Motor Control Chaper — Professor Harry Asada, MIT 2.12 Introduction to Robotics

2.2 What can a Dyno tell us?

A dyno is used to characterize motor performance and this can be useful for many reasons. It allows us to understand a motor's operating limits to be able to select the correct size motors for certain applications, it also allows us to understand if the control methods we are using are taking full advantage of a certain motor allowing it to perform at its maximum capabilities. It can be a great debugging platform in addition to analyzing motor performance.

2.2.1 Focusing on Motor Performance

The dynamometer allows us to primarily measure the following for a motor.

- The motor's Torque/Speed curve at a given voltage (or at different voltages as you vary the voltage).

- The motor's power map, essentially what electrical power is required at each torque and speed.

- The motor's efficiency map.

- The motor torque constant K_t.

The max speed of the motor is the K_v value times the voltage you run the system at. Essentially for any motor you can keep increasing the voltage and gaining higher possible max speeds at no cost until the motor driver or the motor itself explode, it's free performance. The hard limit is the magnetic saturation of the iron in the core of the motor which provides the torque limit, again this is a hard limit.

2.2.2 The Torque Speed Curve & Power

A basic motor torque speed curve looks like the following (as seen in Figure 3).
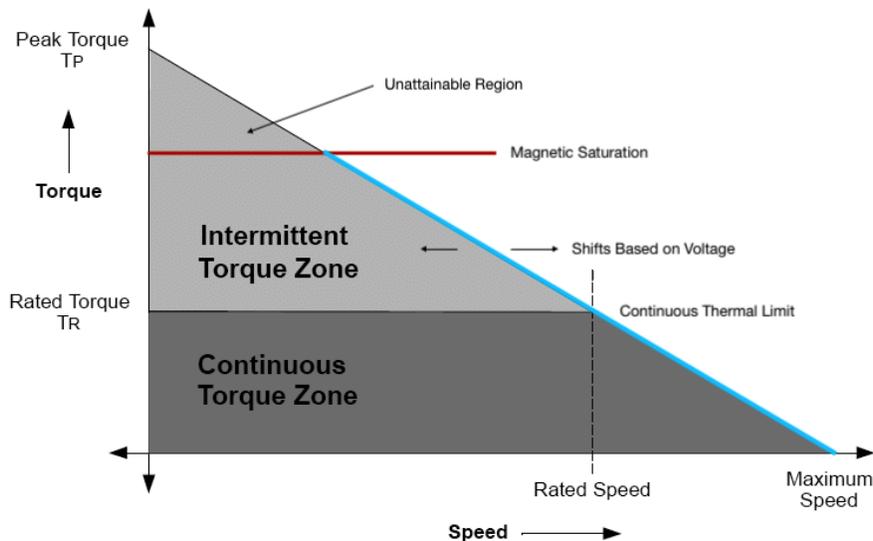
Figure 3: The basic torque-speed curve of a motor from Srujana Eaga edited for educational purposes.

The red line is a hard limit on motor performance, that's the magnetic saturation, the blue line is a limit that comes from the inherent electrical dynamics of the motor, it comes from $L\frac{di}{dt} + Ri = V - K_b\omega$. And it shifts along the x axis based on the voltage applied. The continuous torque zone comes from the continuous thermal limit from the motor and motor controller (how much power can we continuously pump through the system before it gets so hot it explodes). And in the intermittent zone we can pump this amount through the motor for a certain amount of time t_f before the motor fails, once again this is thermal.

4

2.2.3   A Real Torque Speed Curve w/ Power

The following was data we actually collected using a dynamometer in our lab. These are for the U10 motor modules.
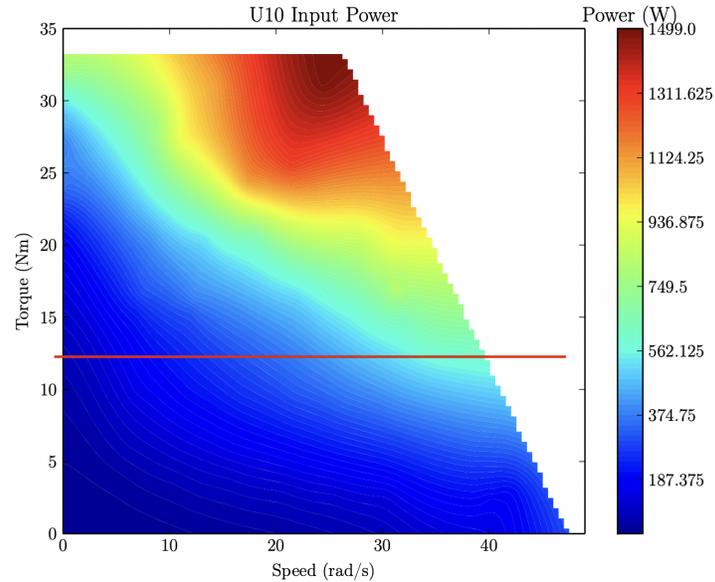
Figure 4: The torque/speed/power map for the U10 from Elijah Stanger-Jones' masters thesis.

The power in this case comes from multiplying the current going into the power terminals of the motor driver and the voltage going into the same terminals. The red line on the diagram in Figure 4 indicates where we think the continuous limit of this motor might be. The power measurement locations are shown in Figure 5.

Efficiency μ_m in this case is defined as the mechanical power P_m over the electrical power P_e. Mechanical power is measured at the output face of the motor module.

$$P_m = \tau * \omega$$

$$P_e = i * v$$

$$\mu_m = P_m/P_e$$

2.2.4   Focus of this Notebook

There's a lot more things dynos can tell us but this is more meant to be an intro to dynamometers. We may add a few appendices that show some data we

5
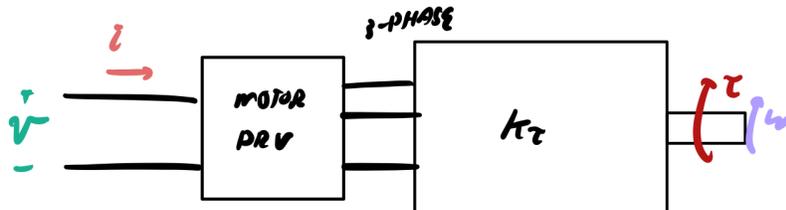
Figure 5: Where we define mechanical and electrical power in motor testing.

collected and what that says about our controllers and control gains and etc, but for now we want to move on to the actual dynamometer.

3 Introduction to the Dyno

Now it's time to talk about the dyno itself! We are going to go through the hardware as well as some of the data collection techniques. In the last sections and appendices I will touch on interpolation as well as data interpretation.

3.1 Components of a Dyno

A dyno consists of a few components which we detail in Figure 7. There's the two motors, a motor under velocity control, a motor under torque control (which is the motor under test), a torque sensor connecting the shafts of these two motors, a current sensor on the input of the motor controller for the torque motor, and a voltage sensor in the same location as the current sensor.

3.1.1 The Motors

We explained the two motors in the previous section, but essentially M1 and M2 are the motor under test and the driving motor respectively and MC are the motor controllers for each of these motors. The motor under test is the motor that is under torque/current control and the driving motor is controlled with a speed controller.

The last point we want to make for the motors is the direction of their reference frames. The motor shaft pointing away from the front of the motors is the direction of the motor's z axis. If we do the right hand rule around the shaft of the motor with our thumb pointing away from the motor's face, we will define the direction our fingers curl as the positive direction of torque and speed. Note that the positive direction for the two motors is opposite in a dyno because the shafts are facing each other. One motor will always be doing positive work
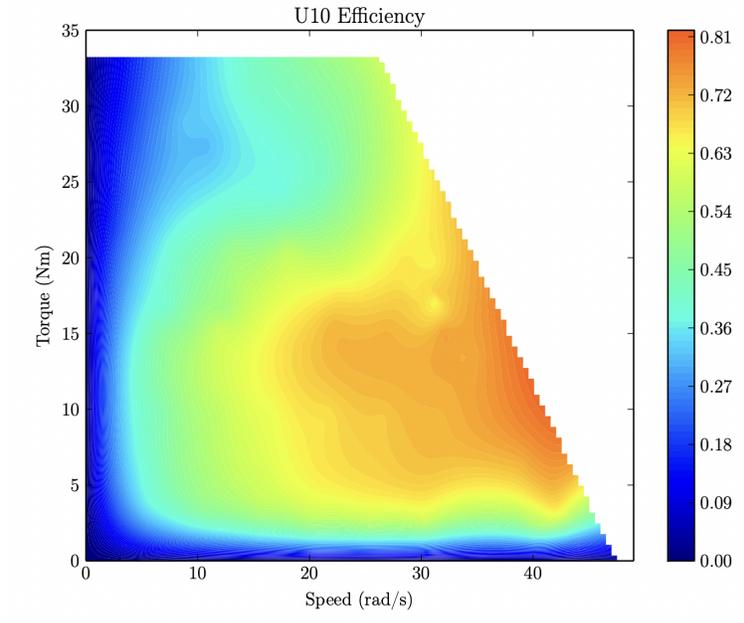
Figure 6: The torque/speed/efficiency map for the U10 from Elijah Stanger-Jones' masters thesis.

(torque and speed in the same direction) and one motor will be doing negative work (torque and speed in opposite direction). In the positive work region, the motor is using power, in negative work, the motor is generating power.

3.1.2 The Current & Voltage Sensor

The current and voltage sensor are placed on the input of the motor controller for the motor-under-test. These measure the current and voltage individually used by the motor we are testing and allow us to calculate the electrical power the motor is using. It's important to measure them independently and not simply measure power because the current reading will allow us to calculate the motor torque constant. We measure these parameters at the input to the motor controller because this allows us to characterize the motor and motor controller together.

These components should of course be appropriately sized to at least 10V or so higher than the expected voltage we will run the motor at and higher than the current we expect the motor to draw.

3.1.3 Regenerative Braking Protection Unit

The Regen Protection goes between the DC power supply and the motor controllers. This is to protect the power supply in case braking sends current into the power supply that it cannot sink. These circuits are also called Shunt Regulators and we've linked an example. Essentially if too much power is being sent back into the power supply, the regulator trips and dissipates the power through the resistors.

These aren't necessary for all dynos but on systems where we expect to test the electrical braking capabilities of a motor or "regen" this is a must.
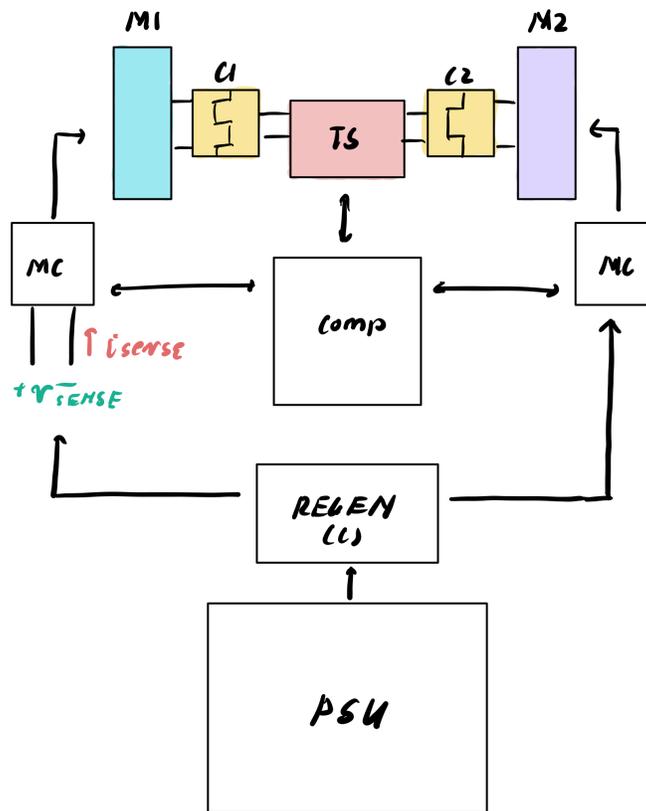
Figure 7: A high level 'map' of the components of a Dyno. Note an encoder to measure the speed of the shaft is also required somewhere in the system.

3.1.4 The Power Supply

The power supply for a dyno is generally a normal lab DC power supply but one that can run at the voltages and supply the currents required. Sizing the

power supply is somewhat tricky sometimes and we will explain that now and refer to Figure 8.

Essentially we can think about power flow in a dynamometer as three nodes — the two motors and the power supply. In the normal operation of the dynamometer, the torque motor produces a torque that is commanded which means unloaded it would keep increasing in speed until it reached the fastest possible speed the motor could go. The job of the speed control motor then is to apply a counter-torque to slow the speed motor down to the desired speed we want to collect data at. The motor under test is the motor we want to measure the parameters of, so we want to collect data when the torque is in the positive direction with respect to the face of the motor (right hand rule) and the angular velocity is also positive — we will discuss the control strategy for this later but we want the motor spinning in the same direction that it's producing torque. If this is happening, the motors and power supply follow the following power-flow-diagram.
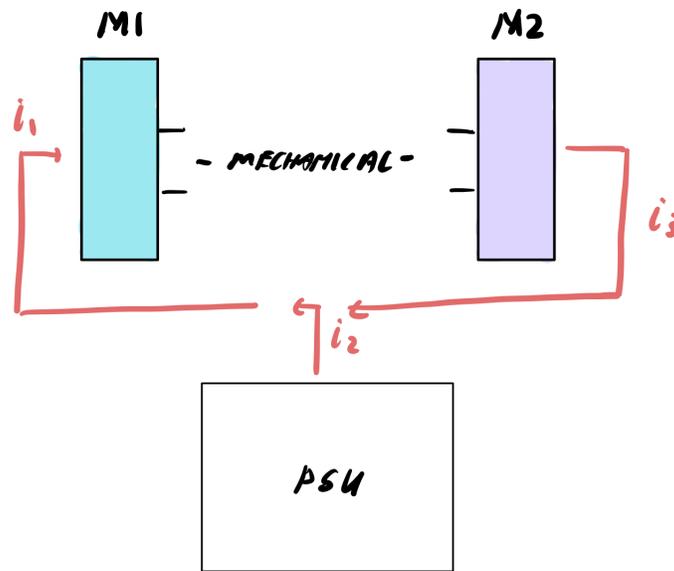
Figure 8: Power flow during normal dynamometer operation.

Essentially, the motor-under-test produces a positive torque and a positive velocity. It is doing positive work and therefor using electrical power to create mechanical power so current goes into the motor. Motor 2 is producing a torque to counter the torque produced by Motor 1 to slow it down, but its velocity is opposite the direction that it's producing torque. It is in braking mode, also known as regen. It is doing negative work meaning in this case it is converting

mechanical power to electrical power therefor current is leaving Motor 2 and going into the circuit. Theoretically, if the motors were 100% efficient, looking at Figure 8 and knowing Kirchoff's Current Law, you might imagine a power supply wouldn't be needed at steady-state and you'd be correct. The PSU supplies "extra power" that's lost due to heat and mechanical losses. The power it supplies is equal to the power lost between both motors.

Therefor, the size of the PSU is specified by knowing the size and efficiencies of your motor. Many dynos just use large power supplies in the range of 100V 50A just to be safe. Doing an analysis like this on your power supply will also tell you, based on what you are doing on the dynamometer, if you need a regen protection circuit or not as described in section 3.1.3! There are many events that could cause a negative current going into the power supply and this can damage many lab power supplies. Another option is a large bi-directional power supply which allows for sinking regen current but these tend to be expensive.

3.1.5   Misalignment Couplers & the Torque Sensor

The last components of the dynamometer are C1 and C2 the misalignment couplers and TS which is the torque sensor. Since we are connecting three shafts together (the two shafts of the motors and the shaft of the torque sensor), depending on the mechanical mounting of this system the three shafts will not be exactly aligned. So to avoid any issues that arise from shaft misalignment (residual stress and torques in the shaft that could case errors in data and also wear on the machine) we use misalignment couplers.

The torque sensor in a dynamometer goes between the two shafts and measures the torque between them. Futek has a line of cool rotary torque sensors which allow the shaft to spin but also measures the torque in the shaft. Some of these sensors also have encoders that allow you to measure the angular velocity of the shaft at the torque sensor itself. It is a good idea to measure the velocity of the shaft with an encoder that is not contained inside the motor you are testing unless you really trust the encoder on the motor.

3.1.6   The Computer System

The dynamometer computer must be able to send commands to the motors, read from the sensors, and log the data in a useful format such as a *.csv file.

3.2   Control & Datalogging

Now we want to talk briefly about the control and datalogging in a dynamometer to get the data we want. We'll also touch on what tests/trajectories to run to get the data we need to fit the torque speed curve, and we will go over how to do this in section 3.3.

3.2.1 Making the Motors Spin in the Correct Direction

The first thing we need to talk about is something that confused me for a while when thinking about dynos. A dyno works by having the two motors "fight" each other this allows us to simulate a "load" on the motor under test to allow it to produce a torque at a defined speed. The logical jump many people make from this is that the commands of the motors should be in opposite directions for them to fight each other and if they're in the same direction the system would just spin off to infinity.
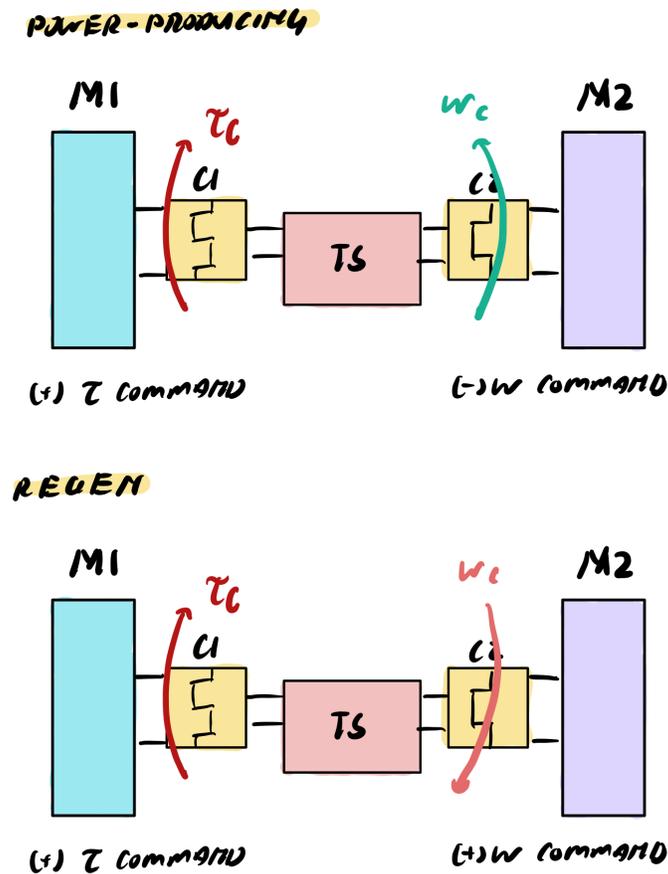
Figure 9: Power testing vs. Regen testing in the dyno system.

This would be true if we were doing torque control on both motors but we aren't. The motor that's supposed to provide the simulated load or "counter-torque" has a PID speed controller wrapped around it. Which means if we command a velocity in the same direction as the other motor is commanding a

torque, it won't speed up to infinity. The controller will automatically produce the correct negative counter torque to allow Motor 1 to produce a positive torque at the positive angular velocity we want. This is a NEGATIVE velocity from the perspective of Motor 2 but a POSITIVE velocity from the perspective of Motor 1.

If we were to command a positive velocity on Motor 2, Motor 1 would see a negative angular velocity but still produce a positive torque. It would be in the "regen" region which is not representative of the power the motor can produce if we drive it with electricity rather the electricity it can produce if we drive it mechanically.

One isn't more favorable than the other, if you're testing the motor's electrical braking or "impact absorption" capabilities you might want the second setup. But it's important to know what you're testing for so that you can drive the motors in the correct direction to get the right data.

3.2.2 Tests to Run on a Dyno

There are many tests we can run on a dynamometer platform, but we will focus on the tests we ran to get efficiency data, torque-speed data, and power data for a set of motors in our lab. Some of the tests are done with just one motor, and some are done with two.

- **Free-Speed Test** — the first test we tend to run is a free-speed test where we command a torque high enough that sends Motor 1 to its fastest speed. We do this while Motor 2 is both electrically and mechanically disconnected and the output shaft of the motor unconstrained. Our goal here is to find what is the fastest speed our motor can travel at the given driving voltage when we give it all we've got. This is called the free-speed of the motor. This gives us the x-intercept on the torque-speed graph.

- **Stall Tests** — Stall tests are when we replace Motor 2 in the diagram with a wall that does not allow the motor shaft to spin. Essentially we mechanically lock the motor shaft from spinning and measure the max torque the motor can produce at zero-speed. The maximum value here gives us the magnetic saturation line on the torque-speed graph, this is how we know when to stop increasing the torque command for the Torque/Speed sweeps.

- **Torque/Speed Sweeps** — now we go back to the two motor setup and we command a torque and sweep commanded speed. For example, we tell Motor 1 to produce 5Nm of torque, and then we command -5rad/s, -10rads/s, -15rads/s, etc. to Motor 2 until we start seeing a significant drop in the torque being produced by Motor 1. Essentially we should see the torque sensor read 5Nm all the way until we're reaching the power limit of the motor where the motor physically can no longer produce the requested torque at the requested speed. We'll see the speed stay at the commanded speed and the torque read by the sensor drop to a much lower

value (maybe 1Nm or 0Nm). That's how we know when to stop increasing speed (see Figure 10).
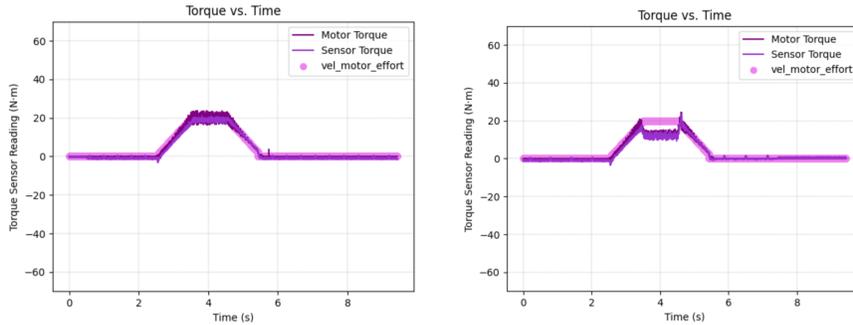
Figure 10: On the left is a normal torque-speed sweep. On the right is what the torque sensor reads when we've reached the power limit.

3.2.3 Control Strategy for the Dyno

The last thing on control before we move onto data and datalogging, is how to actually send these commands to the motor. We found that a "ramping" strategy works quite well. Essentially we start the torque and speed command at zero and perform a linear ramp of the command over the course of 2 seconds (for our system) up to the desired torque and speed. We hold that torque and speed for another 2 seconds (again you can choose these time values) and we then ramp back down to zero over the course of another 2 seconds. This avoids hard starting the motor or large initial current spikes or "jerks" in the controller that could cause many issues in the mechanical system of the motors, could hurt the torque sensor, and could send the controller unstable. An example of this trapezoidal profile is also shown in Figure 10. All of these are controlled from the computer that controls the datalogging and interfaces with the motor controllers.

3.2.4 Datalogging for the Dyno

A dynamometer that doesn't log data is, frankly, very useless. We want to be able to see the trapezoidal curves we are commanding as we command them so we know when we've reached the limits of the motor and so we know the controllers are tracking correctly. We will also parse this data later to create the motor's torque-speed curve. The minimum parameters we need to log are contained in the following list.

- The **torque** read by the torque sensor.

- The **speed** read by the encoder (wherever you decided to place it).

- The **voltage** at the terminals of Motor 1's motor controller.

- The **current** going into the terminals of Motor 1's motor controller.

Other things that are useful might be to pre-multiply voltage/current and torque/speed to get the electrical and mechanical powers and log those. Sometimes it's useful to log the commanded torque and velocity to see how close you're getting to the target at any given point. All electrical measurements should be made from the perspective of Motor 1.

It's recommended to test all your sensors to ensure you know they're working correctly. Speed sensors can be tested with a high-speed-camera, torque sensors can be tested with a torque wrench.

The speed at which you log data is also somewhat important depending on what you're trying to do. If you're using a dynamometer to discover issues in your motor controllers and to debug the motor controllers, a high logging rate (3kHz) would be beneficial to capture transients in what the motor is doing. For general testing of the motor just to determine a torque speed curve, lower logging rates are probably ok (500Hz). The minimum logging rate is probably around 100Hz to get any useful data using the trapezoidal control strategy. I think the strategy is to get it logging as fast as you possible can. The more data you have the better.

3.3 Interpreting Results

If you've made it to this point you probably have a whole lot of CSV files. Figure 11 shows how our lab dynamometer data looked like after many runs.

Figure 11: Many csv files! Lot's of data, yay!

We want to parse these log files and start building up the torque-speed curve for our motor. Each csv file contains one trapezoidal profile for the velocity, torque, current, and voltage of one run for the system. Which means we need to first take the data in each csv and average across the steady-state it achieved

14

to get the average torque, current, voltage, and velocity for the run, and the combine data from the runs to plot the torque speed curve.
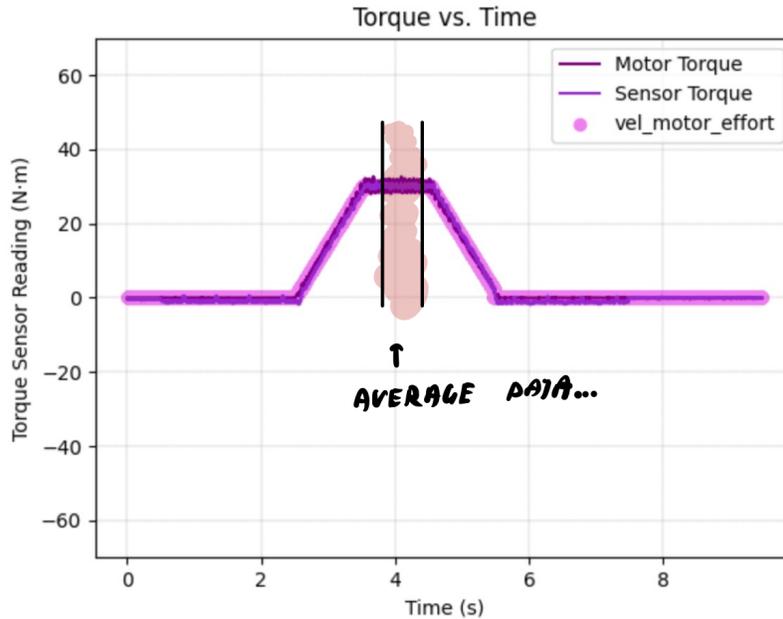
Figure 12: We want to average all the data in steady state for each csv. This is just for torque but we do this for current, voltage, and velocity as well.

Each csv file or run becomes a single datapoint on the torque-speed curve. For example the 5Nm at 10rads/s run will give us values like 4.9567 average Nm at 11.287232 rads/s average, at a voltage of 59.234 volts, and average current of 1.9845 amps. We plot these averages to form the torque speed curve. Here's a demo on how to do that now.

3.3.1 Plotting the Torque-Speed Curve

Most of the following process can be automated but briefly we will conceptually explain how to build up a torque-speed curve. See Figure 13 for a pictorial depiction.

We start with the free-speed test we did. This gives us the maximum speed the motor can travel while producing no torque at the given voltage we are running at. We plot this point on the x axis or speed axis as the intercept.

We then can take the stall data we collected and find the saturation torque by finding the maximum torque the motor could produce while the rotor was locked (the speed was zero). We draw this line as the saturation line on the torque speed curve.
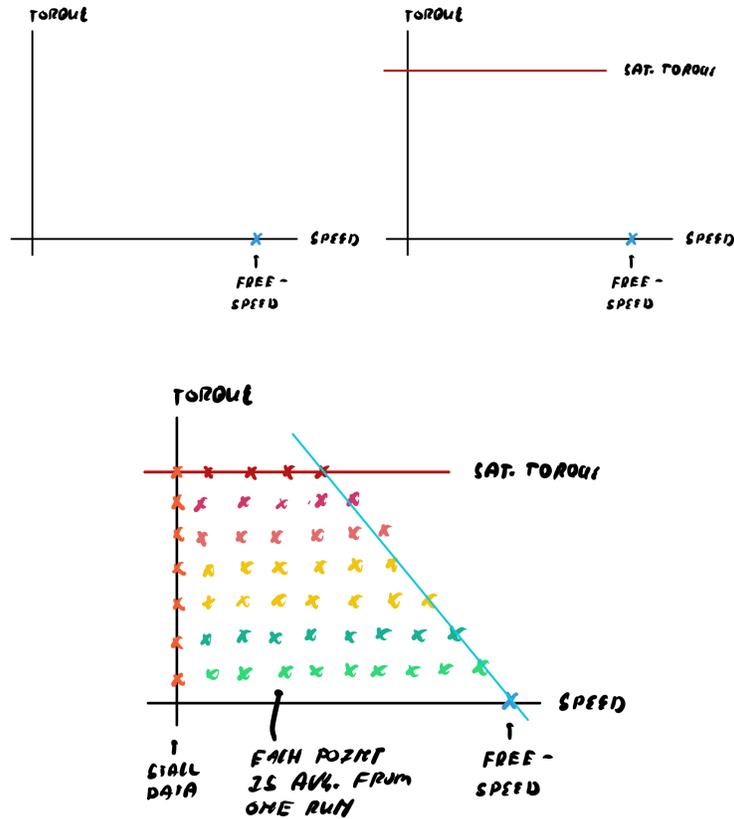
Figure 13: Steps to build up the T/S curve. Each point is the averages from a single run.

Then we take the averages we gained from all the csv files from all the runs we performed and start plotting the average torque and speed we found on the graph. We'll see the points fill in the area under the saturation line and the edge will form a negative slope diagonal line between the saturation torque and the free speed point on the x axis. Note that the data points will not be as clean as what we show in Figure 13, but with enough runs and using intuition the location of the speed limit line should be able to be found. The point at which the speed line and the saturation line intersect is the peak power of the motor in question and is called the "knee" of the torque-speed curve.

Once again we're not going into this in too much detail but other maps can be created. A heat-map can be generated like the ones shown in figures 4 and 6 for power and efficiency respectively which can be calculated from the log data. We can also create a graph of torque versus current and fit a line of the form $\tau = K_t * i$ below to find the motor's torque constant.

3.3.2 Interpolation

It's impractical to run the torque-speed data for every single velocity and current at a resolution fine enough to build up maps like the ones shown in figures 4 and 6. So often what happens is we collect enough data (like what is crudely shown in figure 13) and use an interpolation scheme to fill in the gaps. For example, to get efficiency and power data in the form of heat-maps, a simple bi-linear interpolation scheme may be used. Other forms of interpolation include a radial basis function.

This would take the toque-speed-power data that was collected on the platform itself and interpolate to find the electrical power required to perform a certain torque/speed at locations under the curve we didn't collect data for. Chances are you would not interpolate efficiency. You would interpolate power and then calculate efficiency from the results of the interpolation.

We won't go too much into interpolation in this notebook, but it's in here more to be presented as an option to consider.

4 Further Uses for Dynamometers

Here I'll list a few other uses for dynamometers to consider besides collecting power data for motors and determining motor torque constant.

- Determining performance of controllers, how well do controllers track speed and torque.

- Sim-to-real. If you are doing trajectory optimization on a robot in simulation, you can use a dynamometer to run a torque/speed trajectory on real hardware before running it on a full robot to see if the motor and the controllers are capable of that level of performance.

- If you can test motors to failure (if you have that kinda money and time), you could add a temperature sensor and find the continuous power limit, you could also find out how long the motor can run at peak power, test to failure, and etc.

When building a dynamometer it's important to have an emergency stop as well as a poly-carbonate shield. The E-stop allows you kill power to the system quickly, and the poly-carbonate shield protects from flying debris should something fail.

5 Appendix—Note on Currents

Please note that in motor testing we can test many types of motors. In the case of PMSMs (or Brushless, Permanent-Magnet motors), the current i we use to measure the torque constant is the i_q phase current calculated through the

clarke and park transforms. And the current i we use to calculate the efficiency, is the DC-bus current going INTO the main terminal of the motor controller.

For each type of motor, and even motor controller, this will change. It's important to understand the type of motor you are using and how to determine the parameters to log to get the appropriate k_t. If you're confused, feel free to email me adim@mit.edu!

6   References

Special thanks to the following resources in addition to the motor resources we listed above.

- MIT Biomimetic Robotics Lab, Elijah B. Stanger-Jones

- MIT 2.74 Bio-Inspired Robotics & Professor Sangbae Kim

- MIT 6.131 Power Electronics Lab & Professor Steven B. Leeb

- MIT Solar Car & MIT Motorsports Teams

- Misc. Google Resources (thank you)!