Rope Brake Dynamometer Investigation

Humza Ahmed, Pranav Bommireddipalli, Asliraf Haque, Joshua Muwonge, Carina Sinbandhit

Introduction

The objective of this project was to create a dynamometer to test the torque and speed limits of a TT motor, a small brushless DC motor, not meant for heavy duty purposes but rather for a light workload [1]. While numerous dynamometers exist, ranging from rudimentary pulleys to large workstations used for automobiles, this dynamometer needed to measure the very little speed and torque the motor created, and possibly find its load limit. This dynamometer was limited to materials including the motor itself, a toy wheel, strings, rubber bands and parts from a Tetrix kit.

The two candidates for the type of dynamometer used were the Rope-Brake and the Prony-Brake Dynamometer. The Prony-Brake Dynamometer uses a torque arm that is connected to the brake that puts pressure on the moving motor's flywheel. The arm is also connected to some weights which will put pressure on the rotating flywheel. The weights act as the main measurement [2]. The Rope-Brake Dynamometer uses instead a rope attached to a spring balance with the rope providing the pressure and friction. The weight and the tension in the spring balance acts as the measurement [3]. This report will be investigating the Rope-Brake Dynamometer: the method used to construct the dynamometer, to measure the speed and torque, to analyse the data collected from the experimental trials, and to contemplate on improvements that can be implemented.

Keywords: *Rope-Brake Dynamometer, Displacement, Torque, Force Applied, RPM Speed, Curve of Best Fit, Correlation Coefficient, Line of Best Fit, Stall Torque, Zero Load Torque, Hooke's Law, Friction Coefficient*

Labelled Images

Situated below is the final result of the dynamometer:

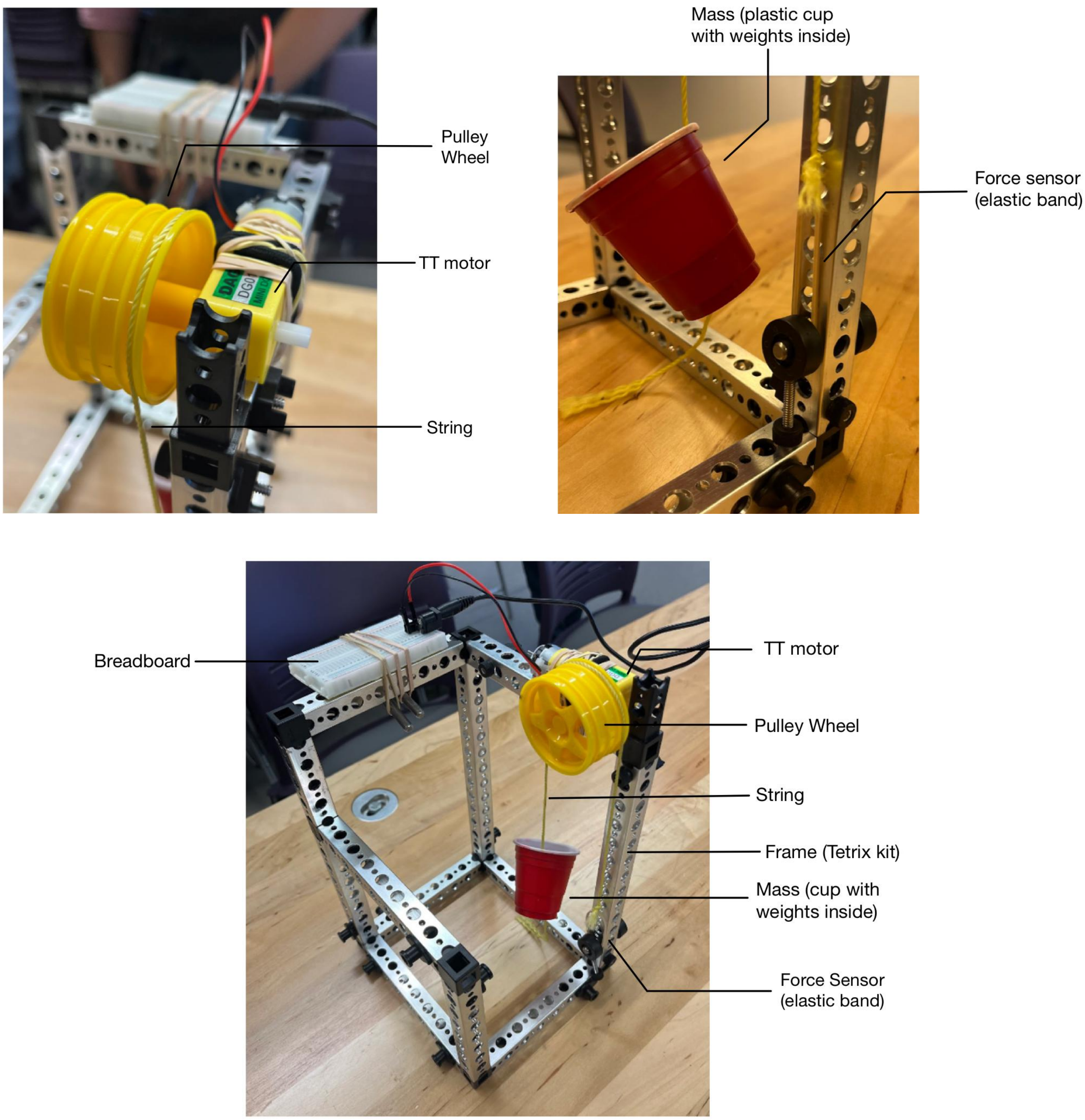

Figure 1 The Final Dynamometer Built

Design Choices

Dynamometer Type:

A Rope-Brake Dynamometer was concluded to be the most practical solution to the problem. As shown in Figure 1, the Rope-Brake Dynamometer used no more than seven main components. In theory a Rope-Brake Dynamometer only requires a motor, pulley, rope, variable mass, and a force sensor to measure torque [3]. This meant that a Rope-Brake Dynamometer could be constructed relatively quickly and with few resources. The available building materials were a breadboard, a TT Motor, a power source, a “Tetrix Prime building kit” and random everyday materials (e.g., coins, hair ties, etc.). As such a Rope-Brake Dynamometer was a reasonable structure to construct given the limited supplies.

Dynamometer Construction:

To create the dynamometer, the motor and the attached breadboard were required to be suspended in the air with the pulley and other components attached to the suspended motor.

Setup:

When making the setup, it proved unnecessary to create an especially sturdy frame. As can be inferred from Figure 1, the main forces acting on the frame are the weight from the motor, breadboard, and other components. All the components are relatively lightweight so creating a simple frame that could be assembled and altered quickly was prioritised over maximising structural integrity. Thus, a lightweight, slightly loose frame constructed from Tetrix beams and connectors was created.

The motor and breadboard were attached to the frame, through tying with multiple rubber bands. The force applied to the motor by the mass load was not too significant so the bands were more than sufficient at keeping the motor and breadboard in place. This simplistic solution also allowed for easy testing of different motor orientations for the dynamometer.

Components:

Most of the components needed for the dynamometer, such as the pulley wheel, string, and motor were easy to implement. However, both the mass load and force sensor required creative solutions.

The cup with small masses added to it was an effective way to create a variable mass load. The cup was tied to the string, as shown in Figure 1, and remained attached for every trial. Screws of known mass were then placed into the cup to increase the mass as needed. This created a time efficient way to change the mass in between trials and quickly collect data as there was no need to untie anything.

Ideally, a spring would have been used to measure the applied force. However, that resource was not available. As such an elastic band was used instead as they also experience a displacement from equilibrium position when experiencing a force which can be used to determine said force. This did mean, however, further investigation had to be done into the relationship between force and displacement for elastic bands (as seen in Figure 2).

Data and Analysis

Table 1 Experimental Trials Conducted to Find Elastic Band Force and Displacement Relationship

Trial Number	Number of Screws	Initial Length of Elastic Band (cm)	Length of Elastic Band (cm)	Elastic Band Displacement (cm)	Elastic Band Displacement (m)	Total Mass Hanged (g)	Force Applied (N)
1	0	3.7	4.2	0.5	0.005	3	0.0294
2	2	3.7	4.7	1	0.01	7.4	0.07252
3	4	3.7	4.9	1.2	0.012	11.8	0.11564
4	6	3.7	5.1	1.4	0.014	16.2	0.15876
5	8	3.7	5.15	1.45	0.0145	20.6	0.20188
6	10	3.7	5.15	1.45	0.0145	25	0.245
7	15	3.7	5.4	1.7	0.0170	36	0.3528
8	18	3.7	5.4	1.7	0.017	42.6	0.41748
9	23	3.7	5.5	1.8	0.018	53.6	0.52528

Table 1:

Referring to Table 1, the data compiled by conducting trials measures the displacement for the accumulative mass of screws inside of the 3-g cup. The initial length of the elastic band was first measured (in centimetres, cm) without any mass, then screws were gradually added subsequent to each trial, acquiring the final stretched length of the elastic band for each quantity of screws. With those values, the displacement (in metres, m) of the elastic band was determined as well as force applied (in Newtons, N) by the cup. This Force Applied vs. Elastic Band Displacement graph was hence formulated (shown in Figure 2) using the values from Table 1, to find an equation relating the displacement and force of the band.

Table 2 Experimental Trials Conducted to Determine Relationship of Force on Motor and Motor Rotation

Trial Number	Number of Screws (cup)	Equilibrium Length of Elastic Band (cm)	Rotations per 15 seconds	Elastic Band Length with Rotation (cm)
1	0	3.7	58	4.8
2	3	3.7	54	5.1
3	8	3.7	52	5.4
4	13	3.7	48	5.4
5	18	3.7	46	5.9
6	23	3.7	44	6.1
7	28	3.7	41	6.7

Table 3 To Calculate the Torque and RPM, using the Equation from Figure 1 and the Data from Table 2

Trial Number	d_x (m)	Force of Band (N)	Force Applied (N)	Force Friction (N)	Torque (Nm)	RPM
1	0.011	0.098273	0.02943	0.068842534	0.001755485	232
2	0.014	0.188614	0.094176	0.094438373	0.002408179	216
3	0.017	0.362007	0.202086	0.159921372	0.004077995	208
4	0.017	0.362007	0.309996	0.052011372	0.00132629	192
5	0.022	1.073055	0.417906	0.655148547	0.016706288	184
6	0.024	1.657233	0.525816	1.131416924	0.028851132	176
7	0.03	6.104763	0.633726	5.471037074	0.139511445	164

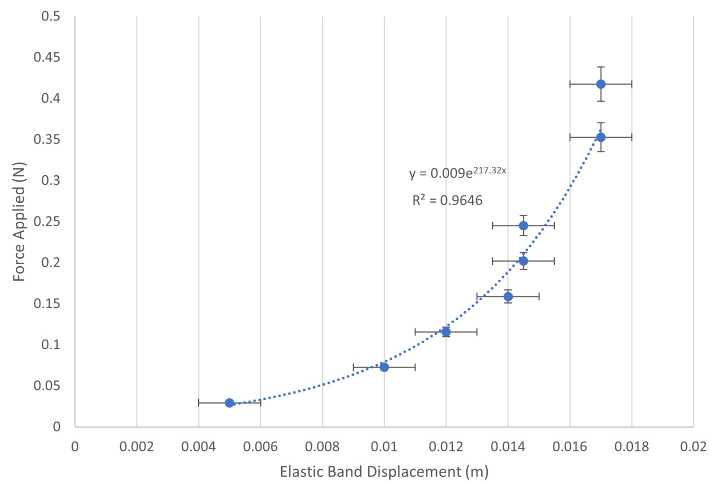

Figure 2 Force Applied vs. Elastic Band Displacement Graph

<u>Figure 2:</u>

Figure 2 depicts the relationship between the force applied by the elastic band and its displacement as an exponential function - a curve of best fit. This graph has a strong-positive correlation coefficient of 0.9646 which proves that the independent variable correspondingly affects the dependent variable: as the length of the elastic band increases, its force applied also increases.

Examining the curve's increasing rate of change, the rapid growth represents the occurrence where the elastic band is easily stretched from the additional mass (4:20 - 4:28) [4]. The graph begins to become steeper when the displacement of the elastic is approximately 0.018-m (4:28 - 4:33) [4].

The equation derived from this graph, $y = 0.009e^{219.32x}$, is applied to compute the force of the elastic band in Table 3. Those values were then used in calculating the Torque vs Speed graph shown in Figure 4.

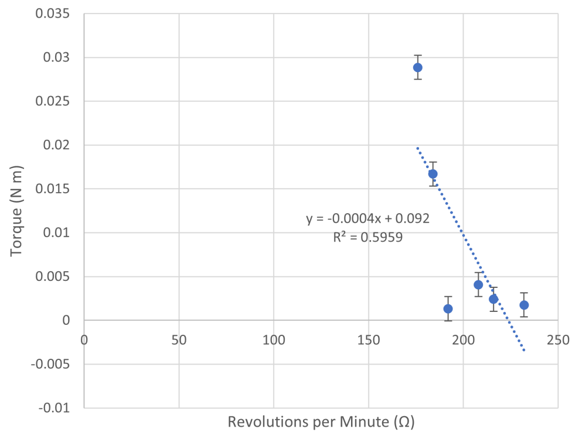

Figure 3 Torque vs. Revolutions per Minute Graph

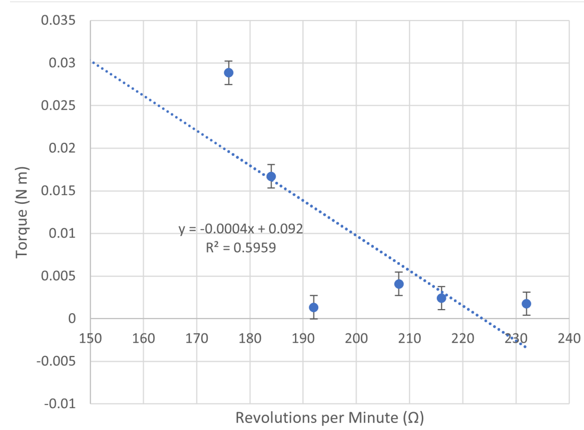

Figure 4 Condensed Version of the Torque vs. Revolution per Minute Graph

<u>Figure 3:</u>

The line of best fit shown in Figure 4 illustrates the relationship of torque and speed: as the speed increases, the torque decreases in a linear fashion. The Figure 3 graph can be extrapolated to find the maximum torque of 0.092 N m when the speed approaches 0 - known as stall torque [5]. Then as the speed of the DC motor increases, the torque decreases until it reaches 0 and the speed of the motor reaches its maximum - known as zero load torque [5].

Torque can be calculated using the equation: $\tau = (W_B - F_B) \times R$ [6, eq. (8-14)],

where, τ = Torque is measured in Newton metres, $N\,m$

W_B= Weight is measured in Newtons, N

F_B= Force of the elastic band is measured in Newtons, N

R = Radius is measured in metres, m

Improvements

A major strength of this design was that minimal assumptions were made in the calculation stage in order to obtain results that were more accurate. For example, when calculating the force vs displacement equation for our elastic band, instead of simply using a line of best fit on Figure 2 and using the slope of the line as k, our design took into consideration that a rubber band does not necessarily have a linear force vs displacement curve (as suggested by Hooke's law). Due to this, an exponential function was created to provide the elastic force of the spring at any given input value of added mass.

Despite our initial design's strong coefficient correlation and the promising results that it provided, there were still a few possible limitations produced by the nature of our design and therefore improvements that were made to improve the accuracy of our dynamometer. Firstly, since we elected to use a rope-break model for our dynamo, such results were dependent on the friction coefficient on both the rope and the wheel that were employed. For example, when we ran our dynamometer with a rubber tire casing surrounding our wheel, stall torque was achieved at a mere 20-g, limiting the amount of measurements we could make. Running the pulley without a rubber tire allowed us to have a much higher load limit, which meant more data could be collected.

Another limitation to our results was our methodology for collecting data on the speed of the motor, which was using a slow motion camera to calculate the number of rotations in 5-seconds and then multiplying the result by 12 to get the total number of rotations per minute. However, while conducting trials we realised that due to our increments of the mass being only 5-g between trials, despite there being a clear reduction in the rpm of the motor, it wasn't significant enough to create a difference when measured in the frame of five seconds since parts of a rotation were rounded down to whole numbers. As a result, we decided to up our time of measurement to 15-seconds and then multiplied the answer by 4, which produced much more accurate results. Regardless, this is still not quite as accurate as if we had recorded for the whole 60-second duration to find the exact RPM of the motor which is a possible improvement for the future if we do not have major time constraints.

In retrospect, a better design choice would have been to use a more accurate force sensor such as an electric scale (i.e., electronic suitcase scale), as the use of an elastic band may have led to errors in our data. The measurements taken from the elastic band may not have been completely accurate as a ruler was used to measure its displacement, meaning the design was subject to observational error. Moreover, the exact spring characteristics of the elastic band were unknown, which could have led to instrumental errors.

References

[1] A. J B. Milne. (2022). ME 100 Design Project 1 [PowerPoint slides]. Available: https://learn.uwaterloo.ca/d2l/le/content/827757/viewContent/4587131/View.

[2] "Mechanical Dynamometers." Mech Bix. bixhttps://www.mechbix.com/p/mechanical-dynamometers.html (accessed Sept. 29, 2022).

[3] "Rope brake dynamometer: Definition, Principle, Diagram, Parts, Working." Mech Content. https://mechcontent.com/rope-brake-dynamometer/ (accessed Sept. 29, 2022).

[4] GCSE Physics Ninja. *Physics GCSE Revision - Force vs Extension graphs*. (Nov. 18, 2016). Accessed: Sept. 29, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=eWgKh9fVGHs.

[5] D. Collins. "The Torque Equation and the Relationship with DC Motors." Motion Control Tips. https://www.motioncontroltips.com/torque-equation/ (accessed Sept. 28, 2022).

[6] R. Hawkes et al., "Rotational Kinematics and Dynamics," in *Physics for Scientists and Engineers: An Interactive Approach 2E*, J. Cochrane, Ed., 2nd ed. Toronto, CA: Nelson Edu., 2013, ch. 8, sec. 1, pp. 270-272.