Engineering 450

North Central College

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Engineering Professor: Dr Harwath

Capstone Project

Subject: Dynamometer

Start: 8/31/2021
End: 12/12/2021

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Executive Summary

The purpose of this project was to build a machine capable of measuring the performance of electric motors and generators. To evaluate performance, the Dynamometer motor is directly coupled to the shaft of the motor/generator being measured. Once coupled, the machine determines how much torque is required to spin the shaft at different RPMs with an electric load attached to the electric terminals of the motor/generator being measured.

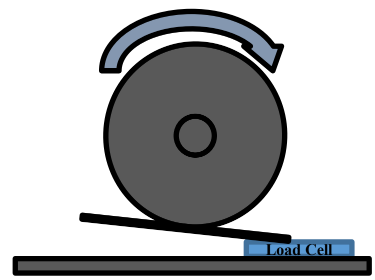


Fig 1: Machine motor body rotating around central shaft

To determine the torque required, the motor of the Dynamometer is mounted in the machine such that the body of the motor is capable of freely rotating about the central axis of the shaft. By measuring the rotational force applied to the central axis shaft while the machine is on, a relationship can be developed between torque, RPM, and load.

To control the Dynamometer, a serial console session can be established with the machine by USB cable. After establishing the connection, the user is prompted with a decision tree to select how the machine operates. In Dynamometer mode, the user can select from a list of speed profiles;

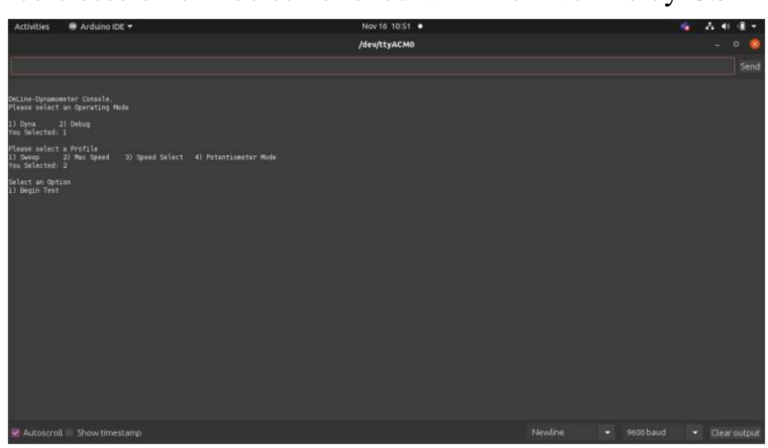


Fig 2: Serial Console Session Established through Arduino IDE

1)Sweep 2)Max Speed 3)Speed Select 4)Potentiometer Mode

The data is recorded in a csv file through a second serial connection monitored and recorded by putty console logger. The output can be exported to a graphing program such as Microsoft Excel.

Problem Statement

The customer requires the ability to evaluate the power output of a motor/generator to determine the feasibility of using different motor sizes/types for a bicycle powered electric generator.

The generator attached to the bicycle in Fig 3 is the component which the customer requires the ability to be evaluated.

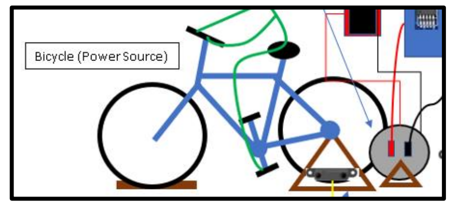


Fig 3: Customer's bicycle powered electric generator

A dynamometer is a device capable of evaluating motor performance under load. The dynamometer needs to be capable of measuring RPM, determine the output Voltage/Current from the generator, determine the torque required to spin the motor, and measure the motor temperature vs power output. Normally, this type of machine (dynamometer) would measure the torque **produced** by the motor being evaluated. In this specific application however, the machine measures the torque **required** to rotate the generator shaft for loaded/unloaded conditions.

Specifications

Dynamometer: This machine is capable of evaluating the performance of electric motors/generators.

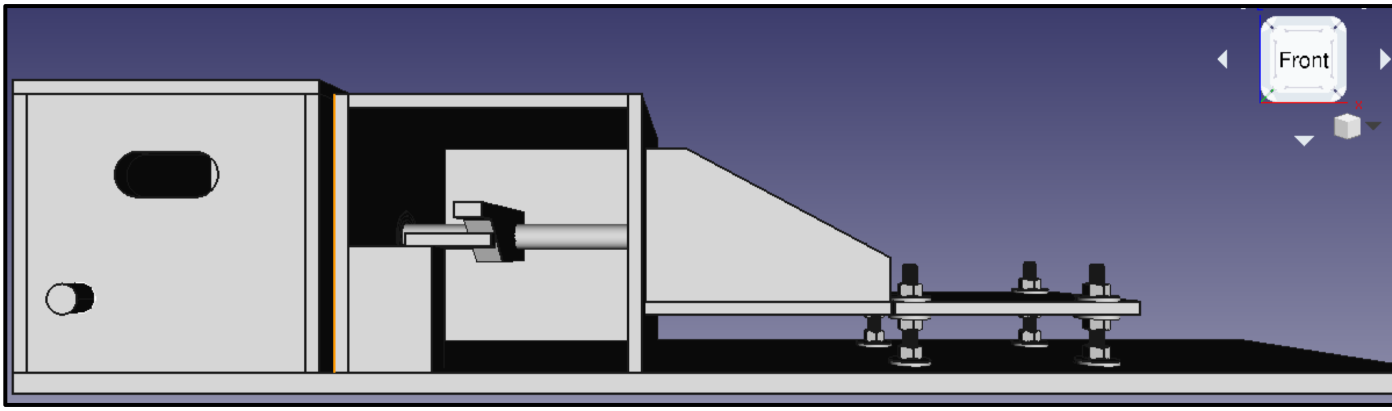


Fig 4: Dynamometer Machine Assembly

COST	$276
MACHINE MOTOR OUTPUT	500W
MAX SPEED	2500 RPM
INPUT VOLTAGE	120/240V AC
ELECTRICAL PLUG	NEMA 5-15P
PEAK CURRENT	20A
NO-LOAD CURRENT	2.2A
MAX TORQUE	2 Nm
MAX ATTACHED MOTOR TORQUE	2 Nm
MAX ATTACHED MOTOR WEIGHT	20lbs
MACHINE WEIGHT	50lbs
MAX ATTACHED MOTOR POWER	480W
MACHINE FLOOR SPACE	240mm Wide x 720mm Long x 250mm Tall
MACHINE INTERFACE	USB-B x 2
SPEED PROFILES	4

Specifications Continued

Dynamometer Motor:

COST	**$78.89**
OUTPUT	500W
RATED SPEED	2500 RPM
RATED VOLTAGE	24V DC
RATED CURRENT	27.4A
NO-LOAD CURRENT	2.2A
RATED TORQUE	1.5Nm
PEAK EFFICIENCY AT 24V	78%
REVERSIBLE	(with polarity swap)
MOTOR WEIGHT	9lbs (4kg)
MAXIMUM LOAD	200lbs (90kg)

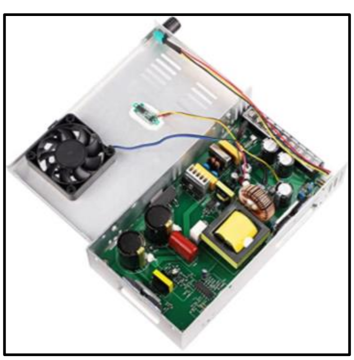
Product Link:

https://www.amazon.com/WPHMOTO-Brushed-Electric-Scooter-Bicycle/dp/B078RKRV5P/ref=sr_1_5?dchild=1&keywords=500w+dc+motor&qid=1631220947&sr=8-5

Specifications Continued

Dynamometer Power Supply:

COST	**$35.99**
OUTPUT POWER	480W
INPUT VOLTAGE	110V-220V
RATED OUTPUT VOLTAGE	0-24V DC
MAX OUTPUT CURRENT	20A
WEIGHT	1.94lbs (0.88kg)

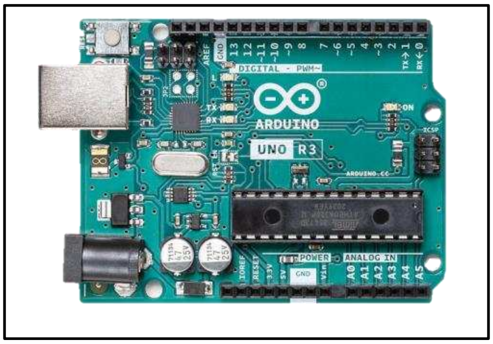


Product Link:

[Amazon.com: Adjustable Voltage DC Power Supply, DROK AC 110V-220V to DC Output 0-24V, LED Digital Display 12V 24V 20A 480W Switching Power Supply Regulated Converter Step Down Transformer Built in Cooling Fan : Electronics]

Specifications Continued

Dynamometer Controller:



COST	**$23.00**
MICROCONTROLLER	ATmega328P
OPERATING VOLTAGE	5V
INPUT VOLTAGE (RECOMMENDED)	7-12V
INPUT VOLTAGE (LIMIT)	6-20V
DIGITAL I/O PINS	14 (of which 6 provide PWM output)
PWM DIGITAL I/O PINS	6
ANALOG INPUT PINS	6
DC CURRENT PER I/O PIN	20 mA
DC CURRENT FOR 3.3V PIN	50 mA
FLASH MEMORY	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
CLOCK SPEED	16 MHz
LED_BUILTIN	13
LENGTH	68.6 mm
WIDTH	53.4 mm
WEIGHT	25 g

Product Link:

https://store-usa.arduino.cc/products/arduino-uno-rev3

Specifications Continued

Dynamometer Controller Continued:

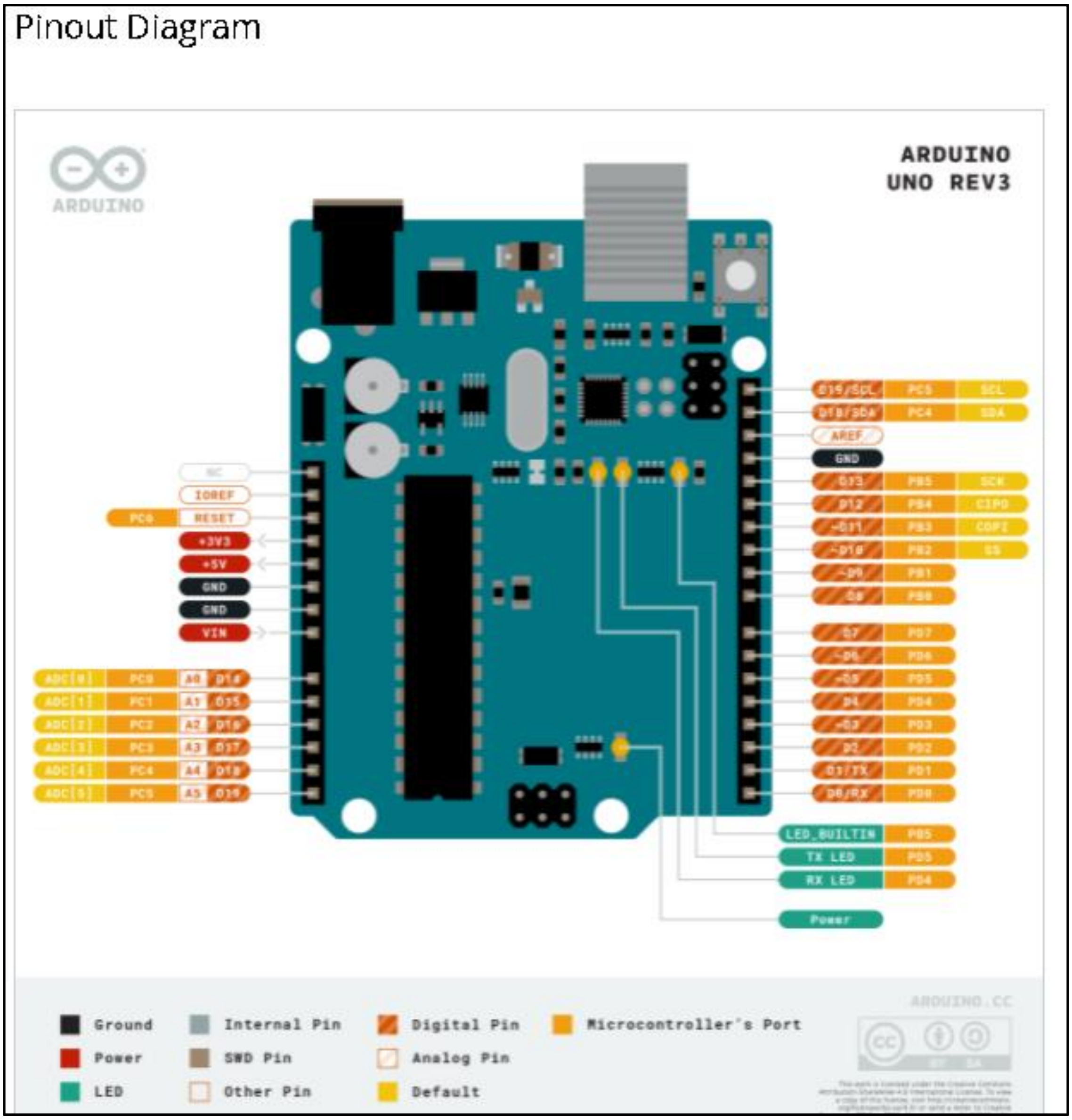
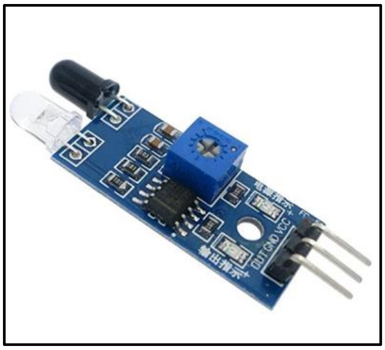


Fig 4: Dynamometer Controller Pin Diagram

Specifications Continued

Photoelectric Tachometer:



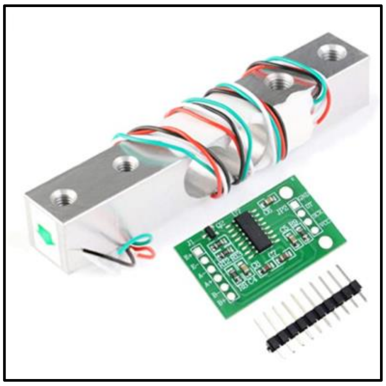
COST	**$0.83 / Module**
BRAND NAME	HiLetgo
COLOR	Blue
VOLTAGE	3.3V / 5V
MINIMUM DISTANCE	2cm
MAXIMUM DISTANCE	30cm
DIGITAL I/O PINS	3
PIN DEFINITION	OUT, GND, VCC
INTERFACE	I2C
SIZE	15mm x 34.5mm
VALUE ADJUST	Potentiometer

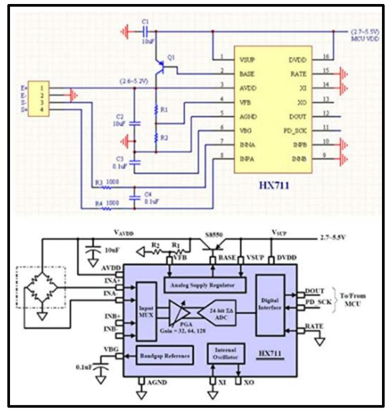
Product Link:

[Amazon.com: HiLetgo 10pcs IR Infrared Obstacle Avoidance Sensor Module for Arduino Smart Car Robot 3-Wire Reflective Photoelectric for Arduino Smart Car Robot : Electronics]

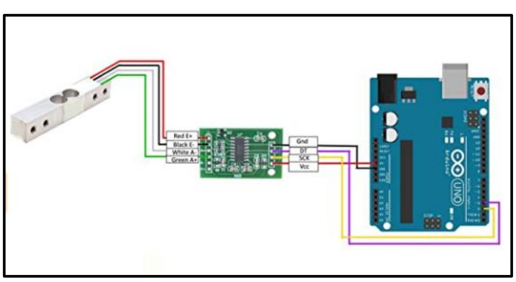
Specifications Continued

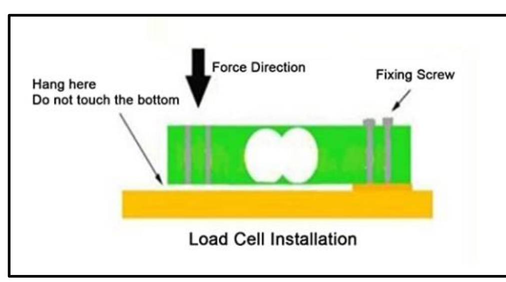
Digital Load Cell with Module





COST	$7.99
BRAND NAME	ALAMSCN
OUTPUT DATA RATE	10Hz or 80Hz
VOLTAGE	5V-10V
MAX LOAD FORCE	1Kg
ACCURACY	0.1g
DIGITAL I/O PINS	4
PIN DEFINITION	GND, DT, SCK, VCC
INTERFACE	I2C



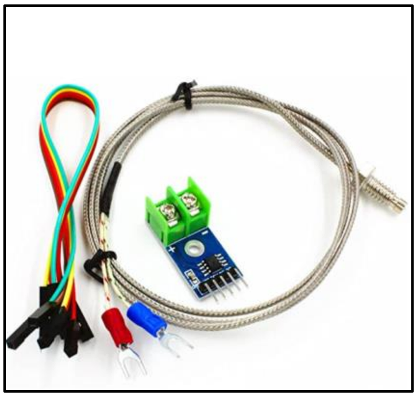
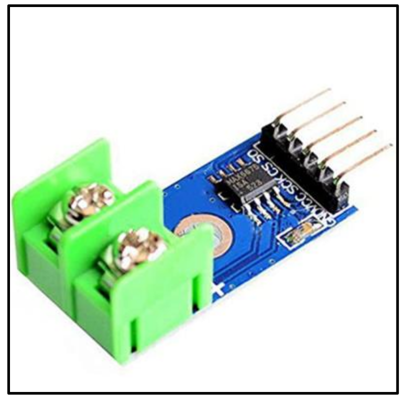


Product Link:

[Amazon.com: ALAMSCN Digital Load Cell Weight Sensor + HX711 Weighing Sensor ADC Module for Arduino DIY Portable Electronic Kitchen Scale Kit (1KG+HX711) : Industrial & Scientific]

Specifications Continued

Thermocouple with Module

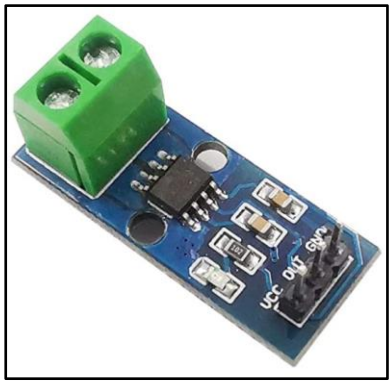
COST	$7.99
BRAND NAME	ALAMSCN
OUTPUT DATA RATE	10Hz or 80Hz
VOLTAGE	3.3V / 5 V
MIN TEMP	0°C
MAX TEMP	1024°C
DIGITAL I/O PINS	5
PIN DEFINITION	GND, VCC, SCK, CS, SO
INTERFACE	SPI
MODULE SIZE	15mm x 28mm

Product Link:

Amazon.com: ALAMSCN Digital Load Cell Weight Sensor + HX711 Weighing Sensor ADC Module for Arduino DIY Portable Electronic Kitchen Scale Kit (1KG+HX711) : Industrial & Scientific

Specifications Continued

Current Sensor Module



COST	**$12.99**
BRAND NAME	ZkeeShop
VOLTAGE	5 V
MIN CURRENT	0
MAX CURRENT	30A
DIGITAL I/O PINS	3
PIN DEFINITION	VCC, Out, GND
INTERFACE	Analog Voltage
MODULE SIZE	15mm x 28mm

Product Link:

[Amazon.com: ZkeeShop 5pcs 5A Current Sensor Module ACS712 Module Compatible for Arduino : Electronics]

Concept

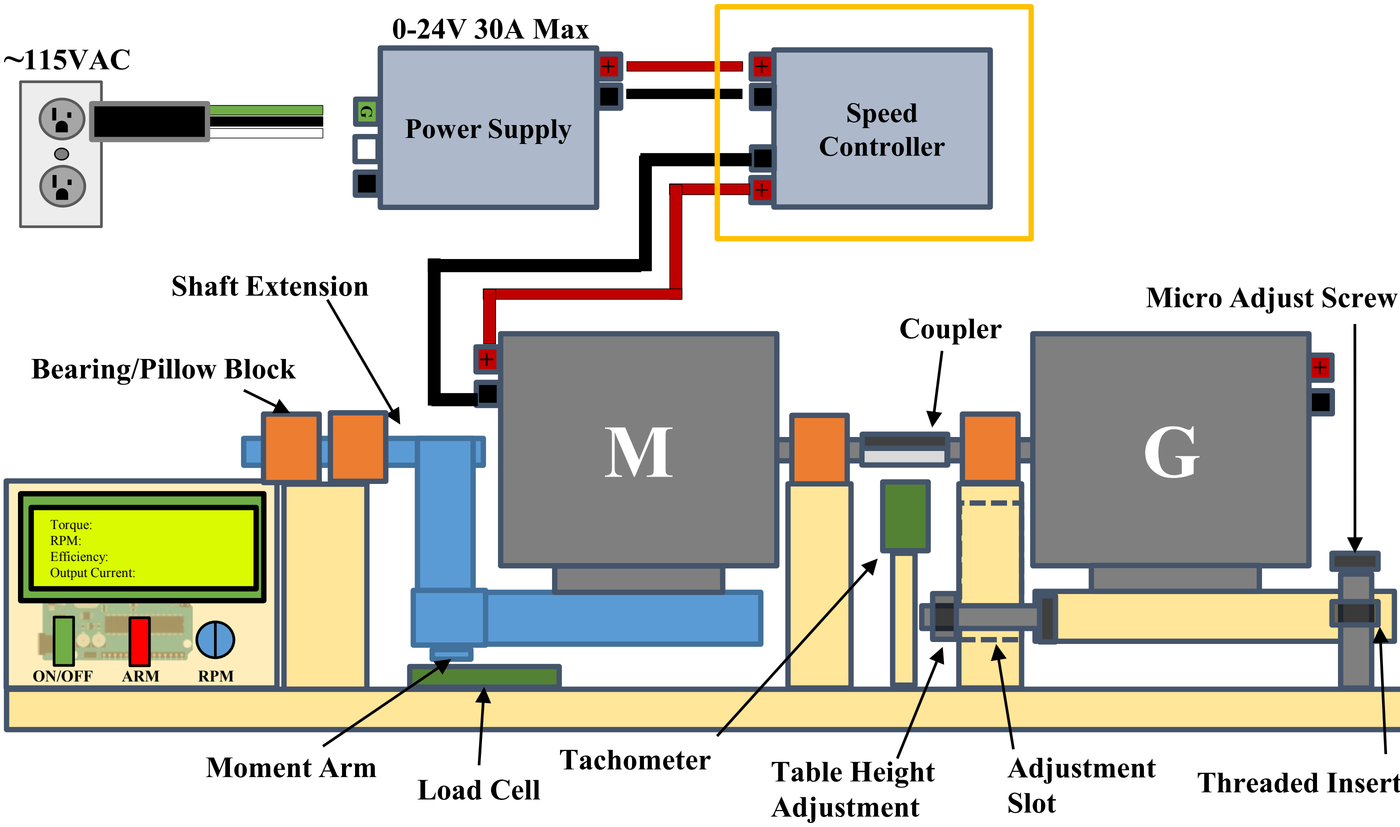


Fig 5: Dynamometer Concept Diagram

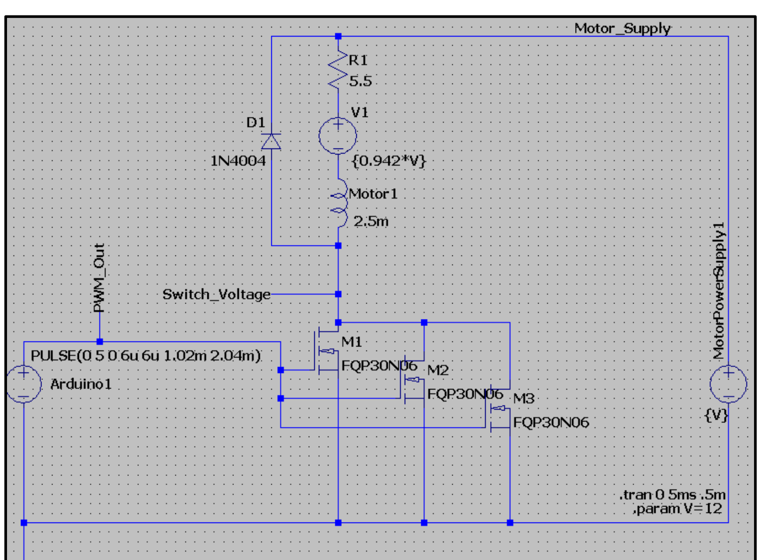


Fig 6: Motor Speed Controller Circuit

Design

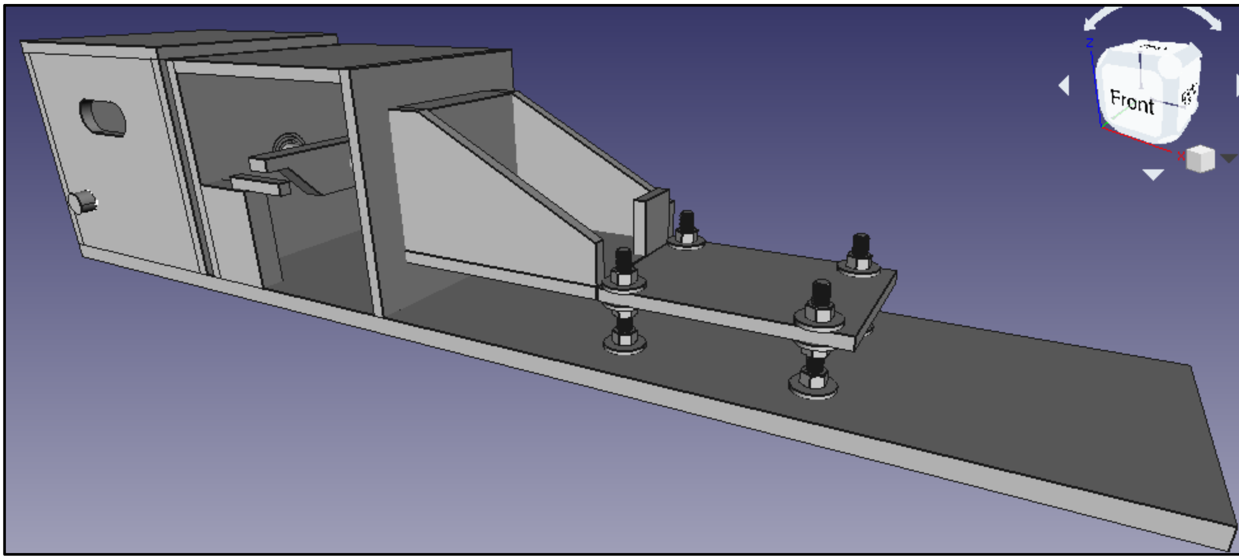


Fig 7: Dynamometer Assembly

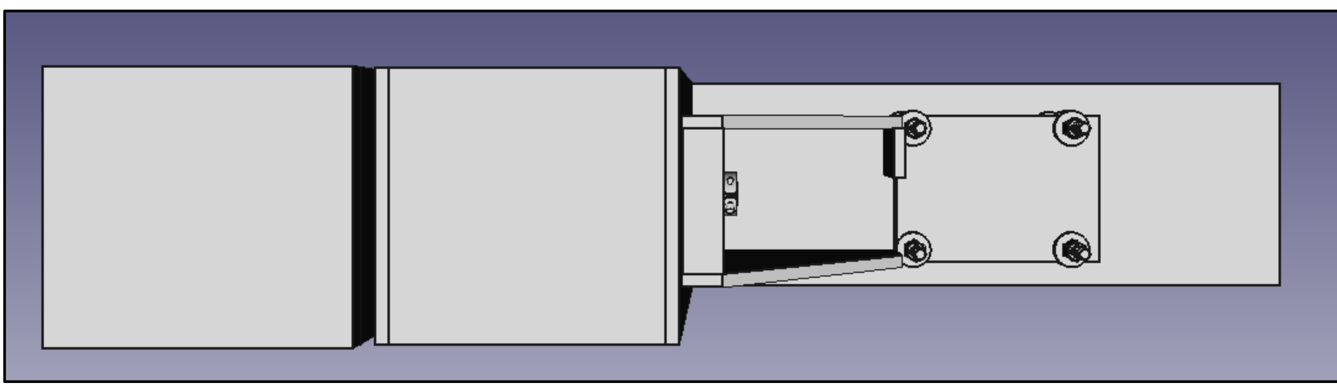


Fig 8: Top View – Dynamometer Assembly

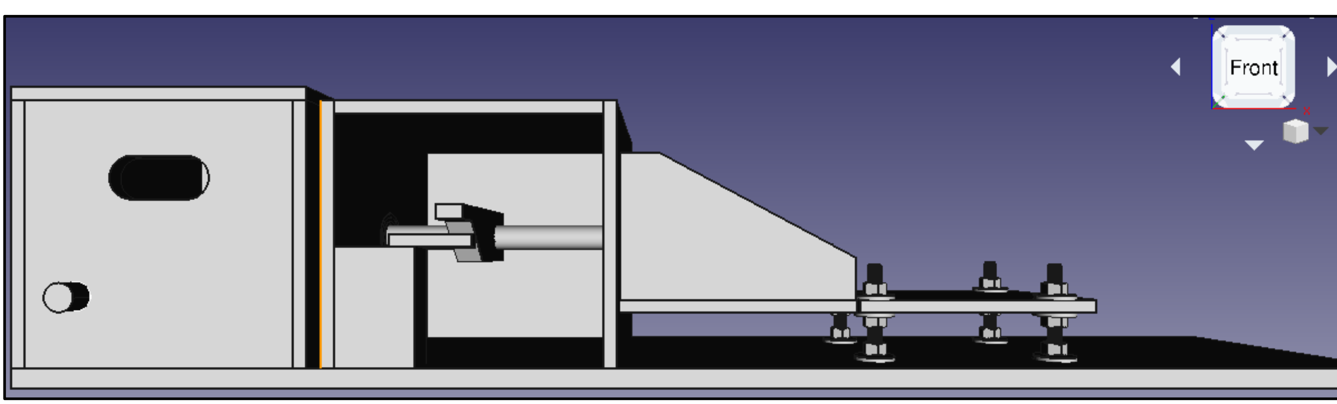
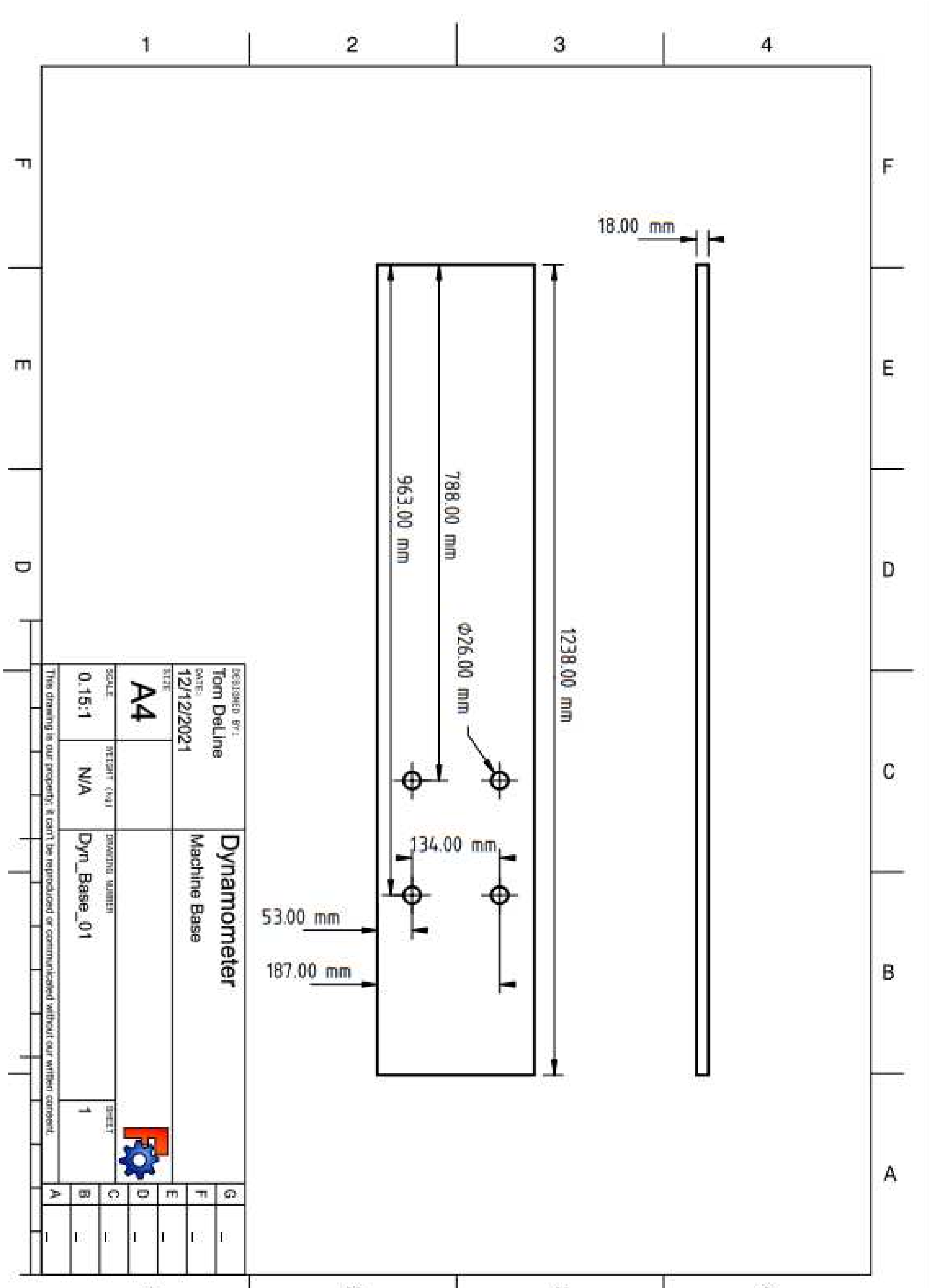
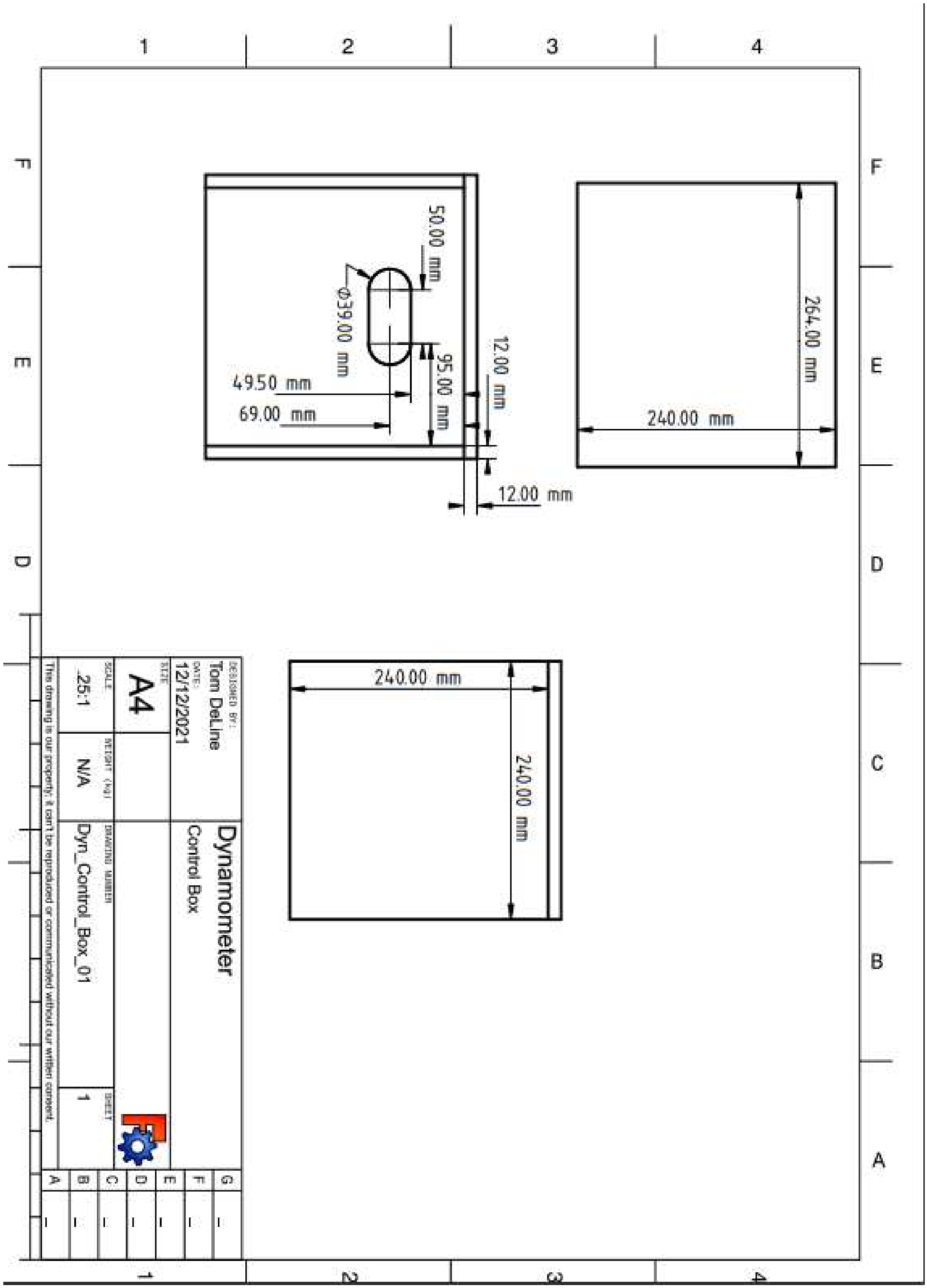
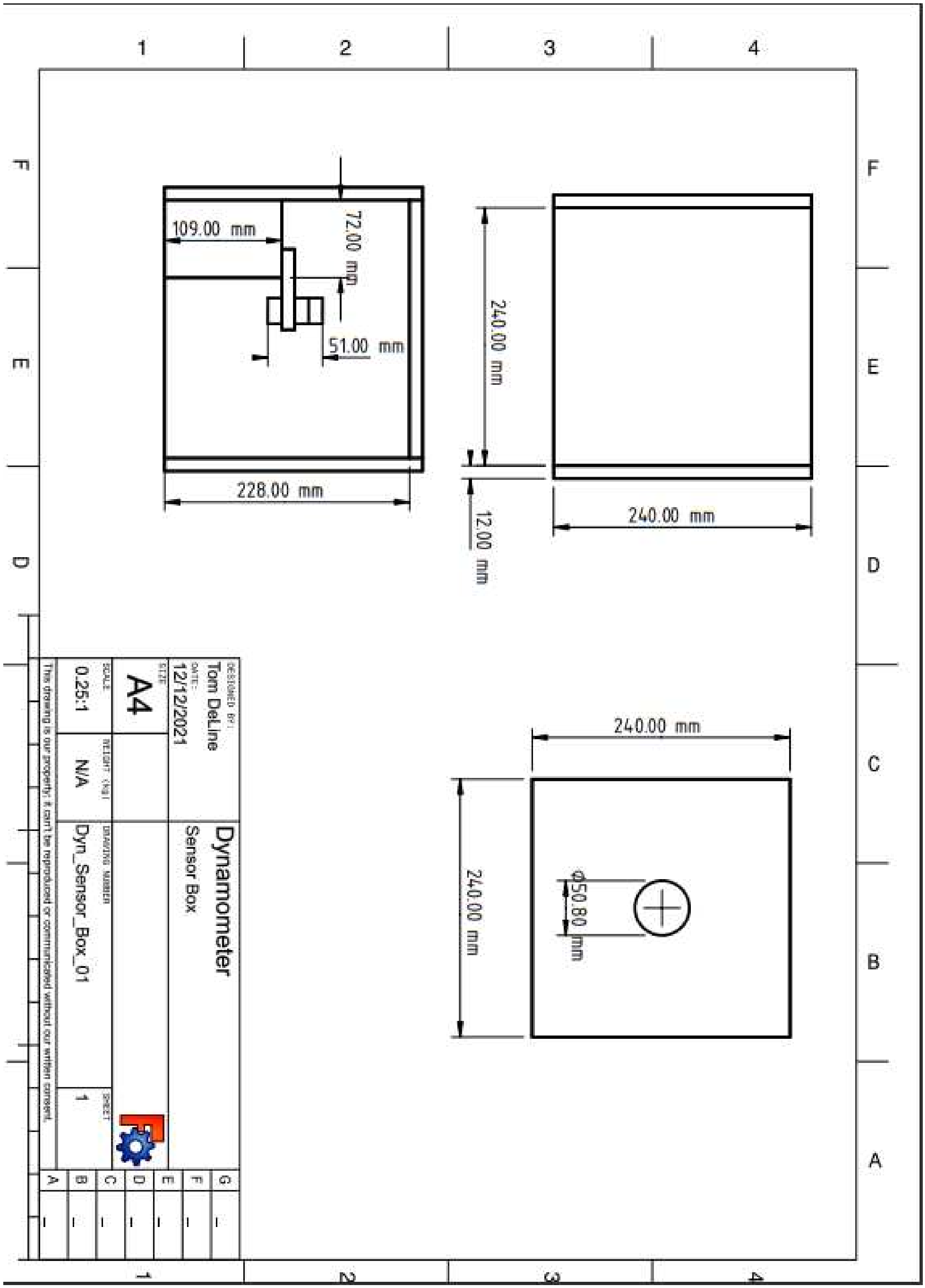
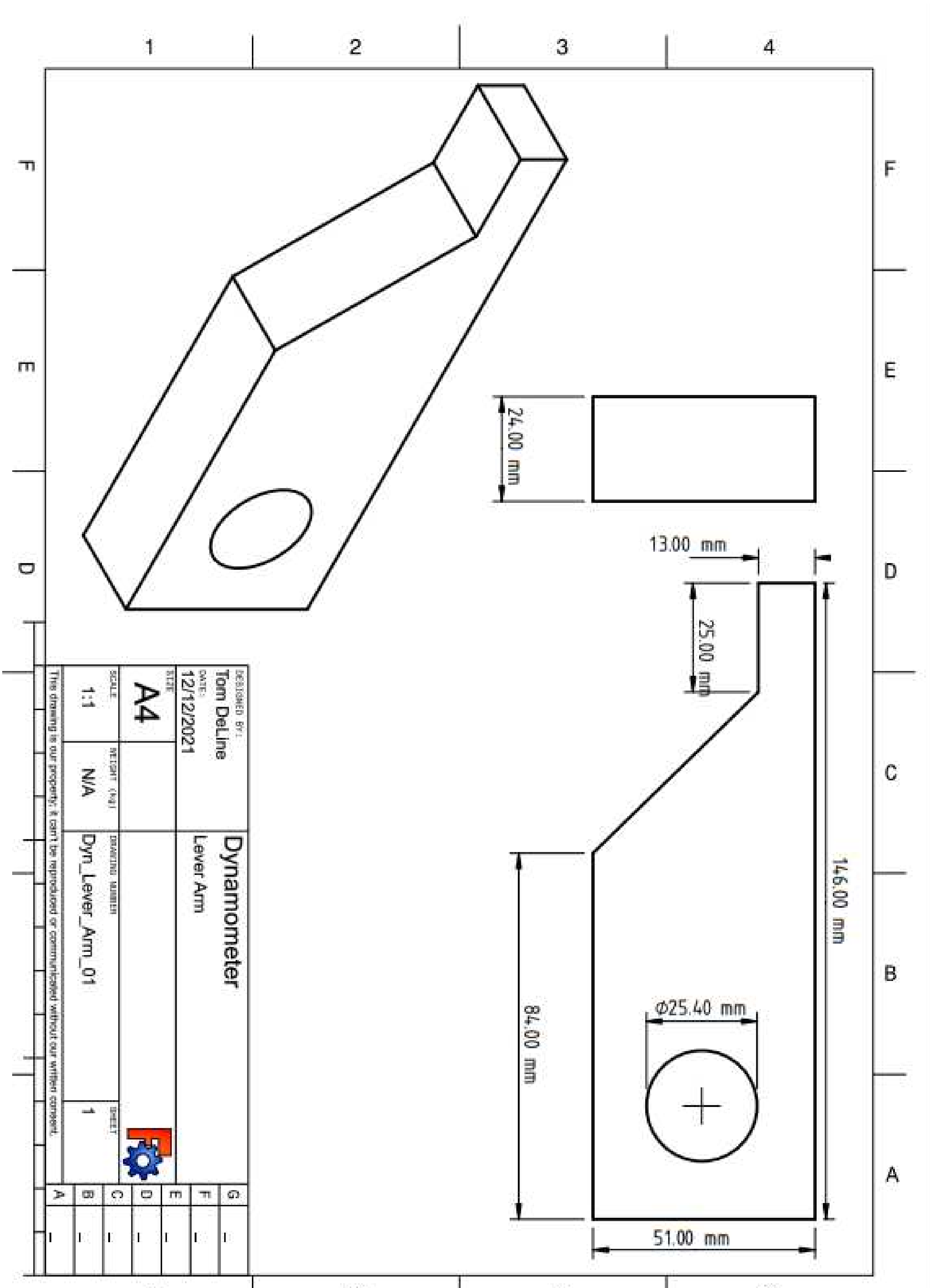


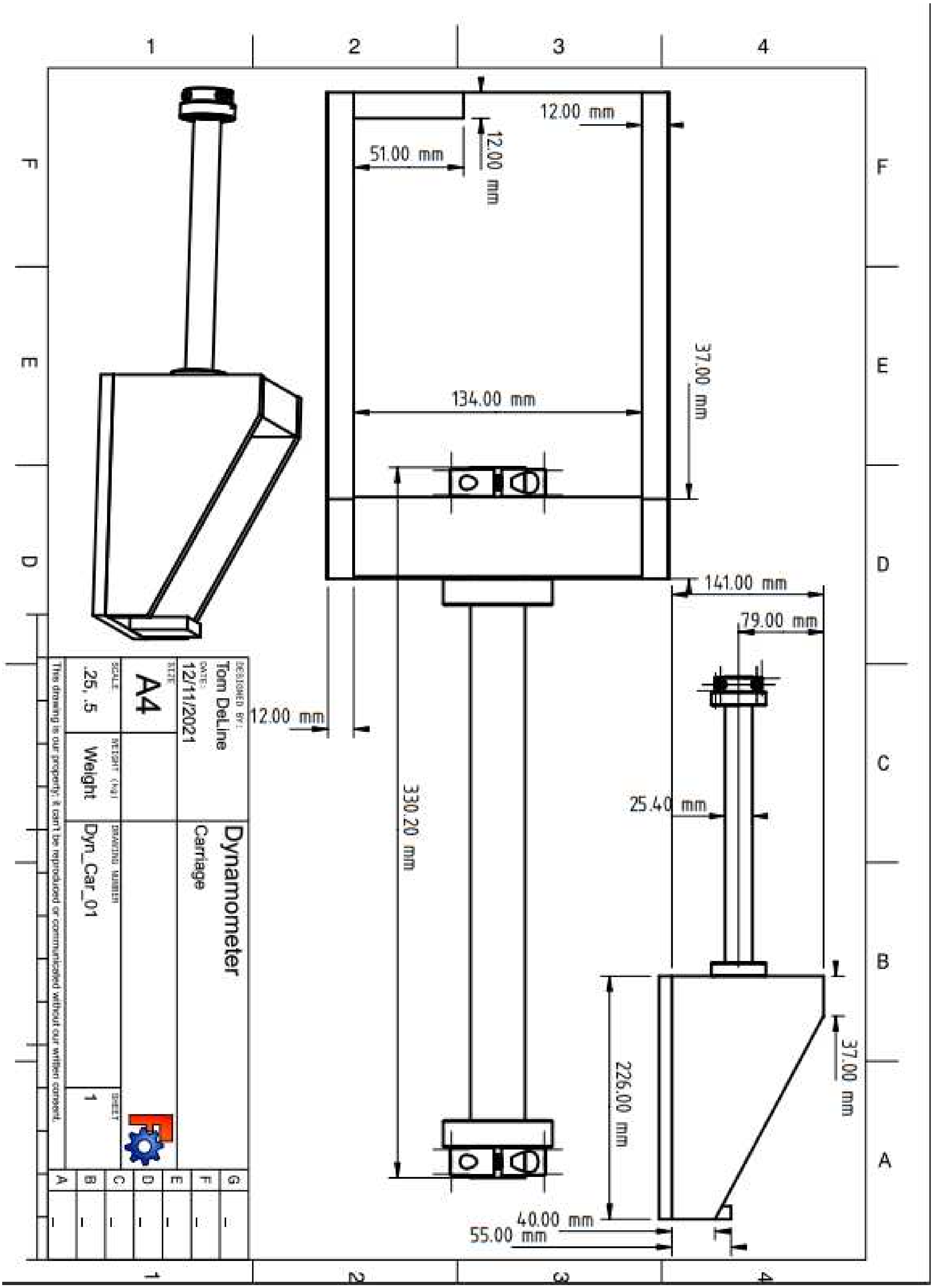
Fig 9: Front View – Dynamometer Assembly

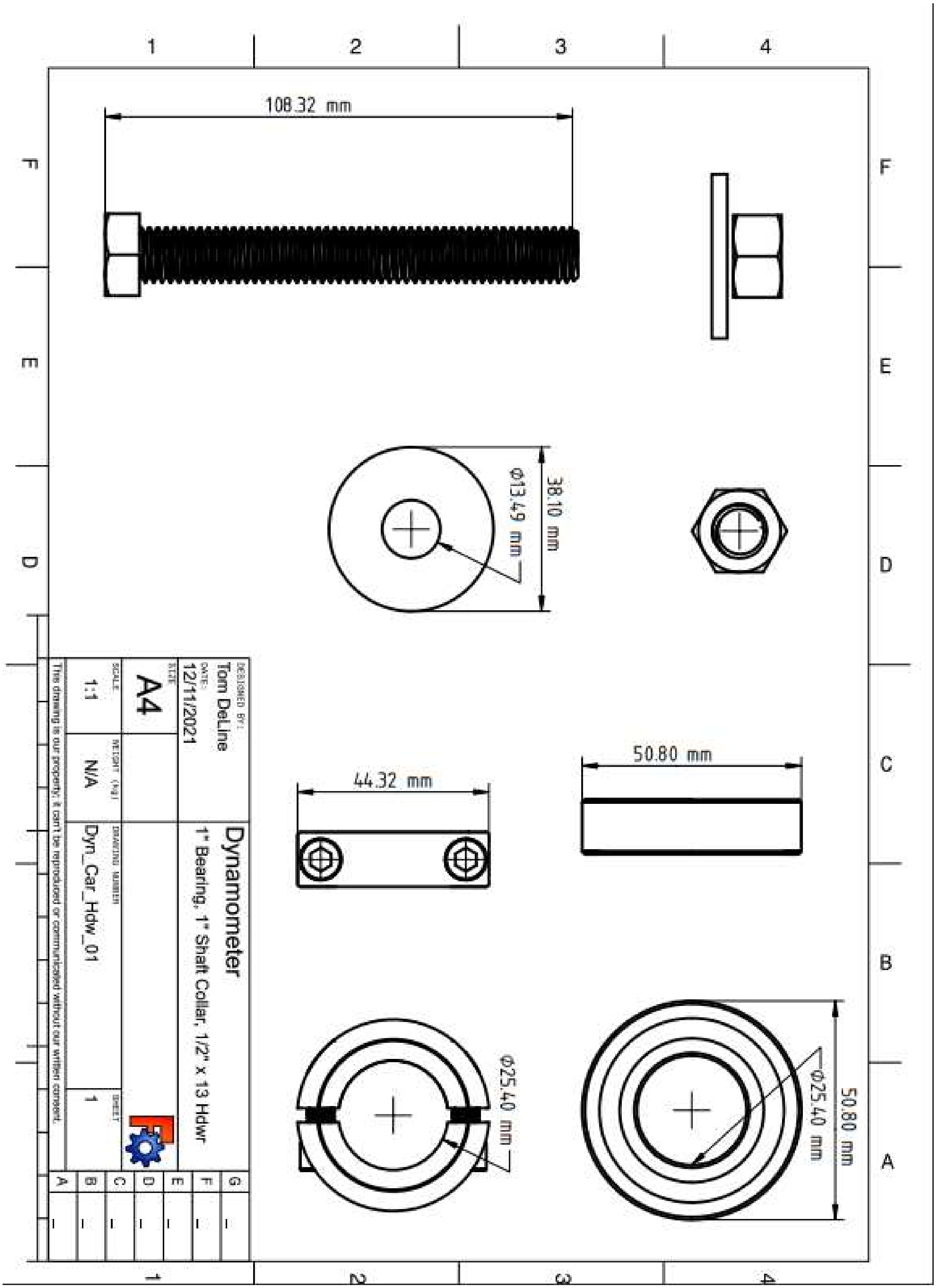

18.00 mm
788.00 mm
963.00 mm
Φ26.00 mm
1238.00 mm
134.00 mm
53.00 mm
187.00 mm
DESIGNED BY:
Tom DeLine
DATE:
12/12/2021
Dynamometer
Machine Base
SIZE
A4
SCALE
0.15:1
WEIGHT (kg)
N/A
DRAWING NUMBER
Dyn_Base_01
SHEET
1
This drawing is our property; it can't be reproduced or communicated without our written consent.


50.00 mm
Φ39.00 mm
49.50 mm
69.00 mm
95.00 mm
12.00 mm
12.00 mm
264.00 mm
240.00 mm
240.00 mm
240.00 mm
DESIGNED BY:
Tom DeLine
DATE:
12/12/2021
SIZE
A4
SCALE
.25:1
WEIGHT (kg)
N/A
DRAWING NUMBER
Dyn_Control_Box_01
SHEET
1
Dynamometer
Control Box
This drawing is our property; it can't be reproduced or communicated without our written consent.

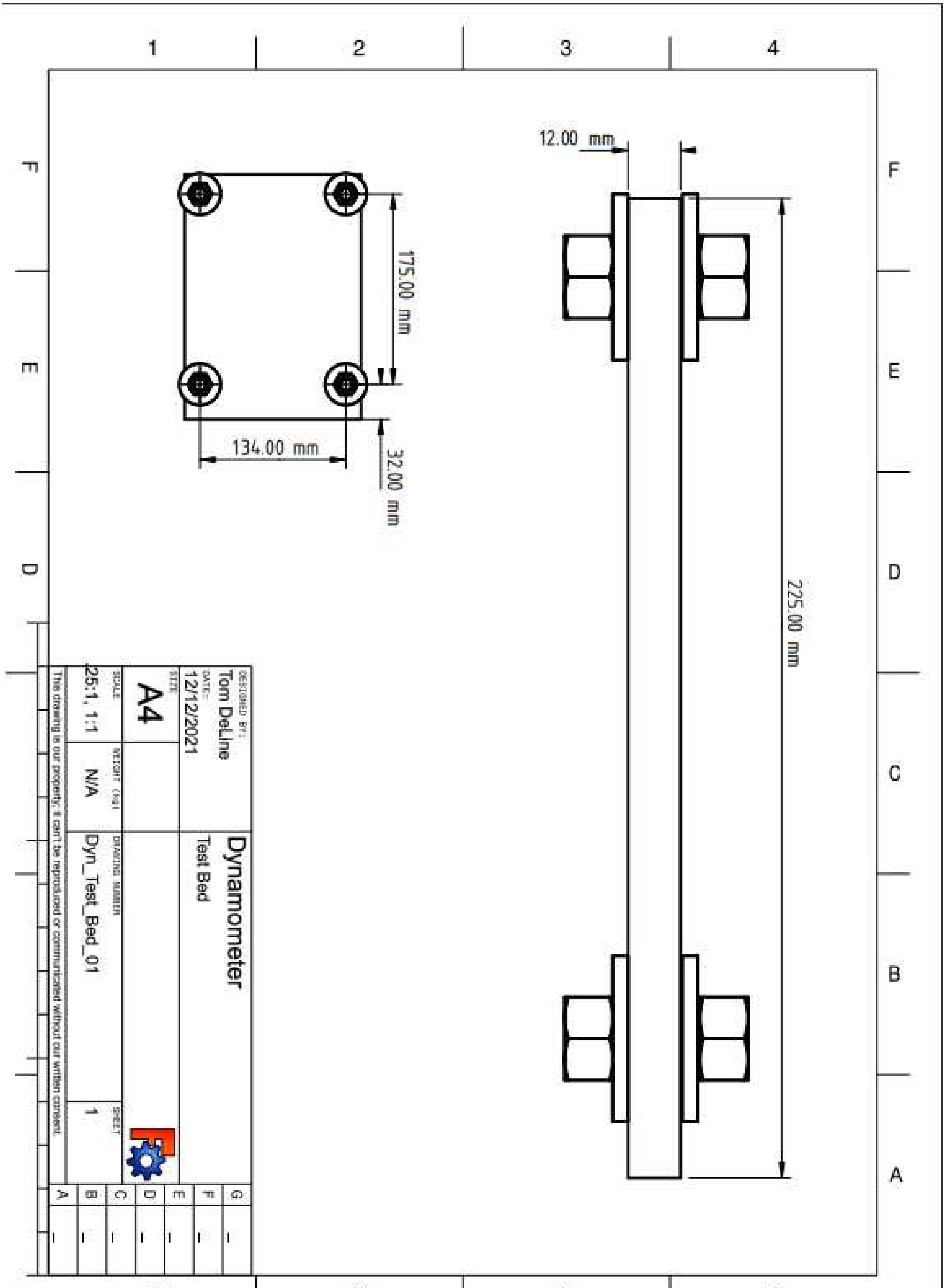

109.00 mm
72.00 mm
51.00 mm
228.00 mm
240.00 mm
12.00 mm
240.00 mm
240.00 mm
240.00 mm
Φ50.80 mm
DESIGNED BY:
Tom DeLine
DATE:
12/12/2021
SIZE
A4
Dynamometer
Sensor Box
SCALE
0.25:1
WEIGHT (kg)
N/A
DRAWING NUMBER
Dyn_Sensor_Box_01
SHEET
1
This drawing is our property; it can't be reproduced or communicated without our written consent.


24.00 mm
13.00 mm
25.00 mm
146.00 mm
84.00 mm
Ø25.40 mm
51.00 mm
DESIGNED BY:
Tom DeLine
DATE:
12/12/2021
SIZE
A4
SCALE
1:1
WEIGHT (kg)
N/A
Dynamometer
Lever Arm
DRAWING NUMBER
Dyn_Lever_Arm_01
SHEET
1
This drawing is our property; it can't be reproduced or communicated without our written consent.

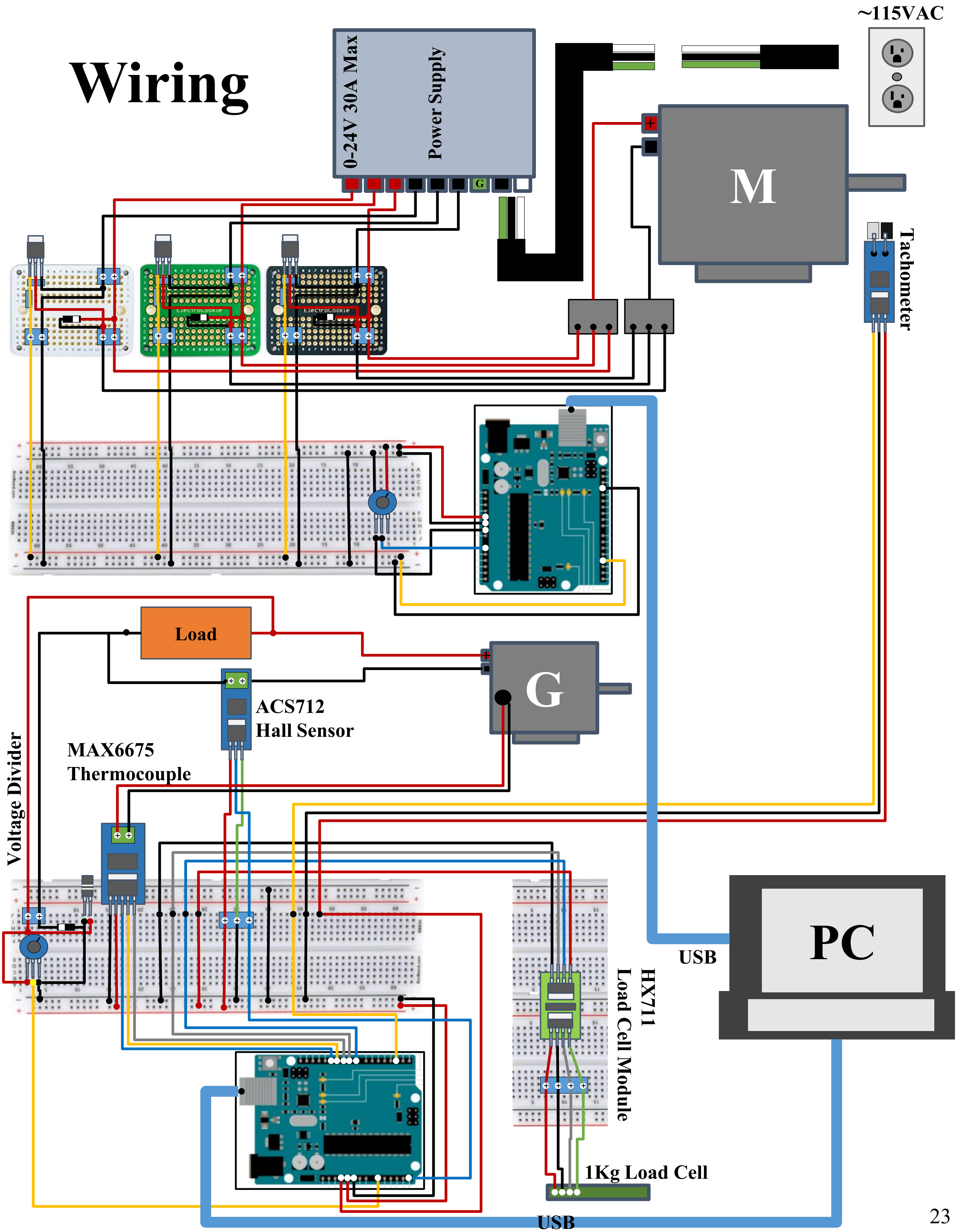

12.00 mm
51.00 mm
12.00 mm
37.00 mm
134.00 mm
141.00 mm
79.00 mm
12.00 mm
330.20 mm
25.40 mm
226.00 mm
37.00 mm
40.00 mm
55.00 mm
DESIGNED BY:
Tom DeLine
DATE:
12/11/2021
SIZE
A4
SCALE
.25, .5
WEIGHT (kg)
Weight
DRAWING NUMBER
Dyn_Car_01
SHEET
1
Dynamometer
Carriage
The drawing is our property; it can't be reproduced or communicated without our written consent.



108.32 mm
Ø13.49 mm
38.10 mm
44.32 mm
50.80 mm
Ø25.40 mm
50.80 mm
Ø25.40 mm
DESIGNED BY:
Tom DeLine
DATE:
12/11/2021
SIZE
A4
SCALE
1:1
WEIGHT (kg)
N/A
DRAWING NUMBER
Dyn_Car_Hdw_01
SHEET
1
Dynamometer
1" Bearing, 1" Shaft Collar, 1/2" x 13 Hdwr
This drawing is our property; it can't be reproduced or communicated without our written consent.


12.00 mm
175.00 mm
134.00 mm
32.00 mm
225.00 mm
Tom DeLine
12/12/2021
A4
25:1, 1:1
N/A
Dynamometer
Test Bed
Dyn_Test_Bed_01
1
This drawing is our property; it can't be reproduced or communicated without our written consent.

Wiring



~115VAC
0-24V 30A Max
Power Supply
G
M
Tachometer
Load
ACS712
Hall Sensor
G
MAX6675
Thermocouple
Voltage Divider
HX711
Load Cell Module
1Kg Load Cell
PC
USB
USB

Design Analysis

Characterizing the Arduino Uno PWM Signal is necessary for simulating the Arduino Uno Micro-controller in LTSpice. By defining the Turn-on/Turn-off times and the Period of the signal, LTSpice can emulate the function of the Arduino PWM signal. Based on measured values, the Arduino-Uno PWM output frequency is 490.19Hz This switching frequency is well within the audible range of human ears and will likely be heard through the motor at nearly every RPM.

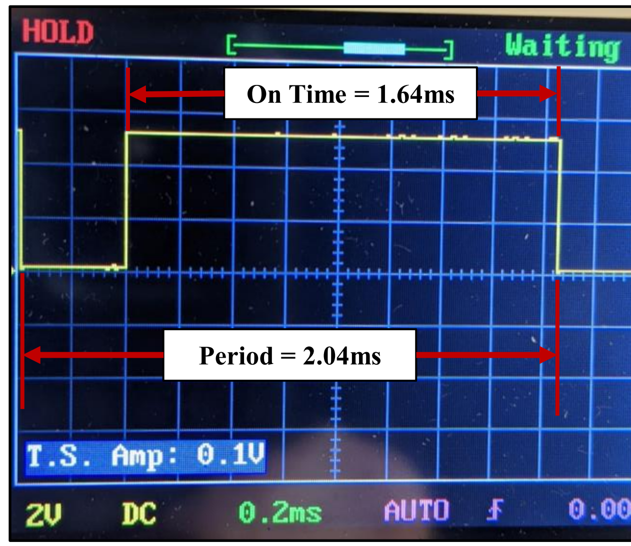


Fig 10: Arduino Uno PWM Period = 2.04ms
Sampled Duty Cycle = 1.64/2.04 = 80%

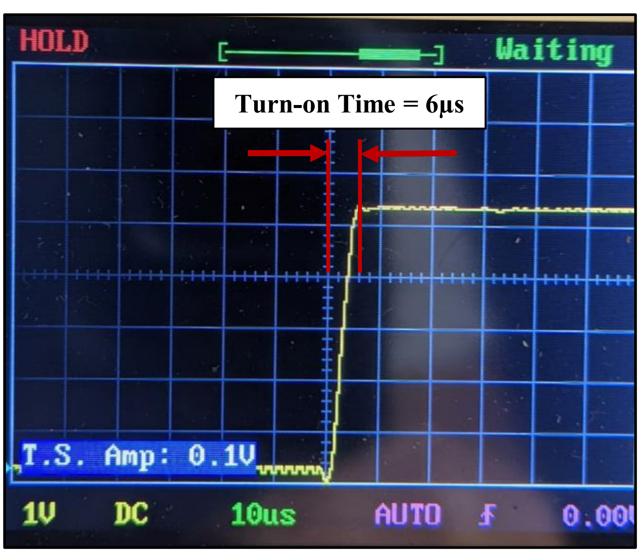


Fig 11: Arduino Uno PWM Turn-on Time

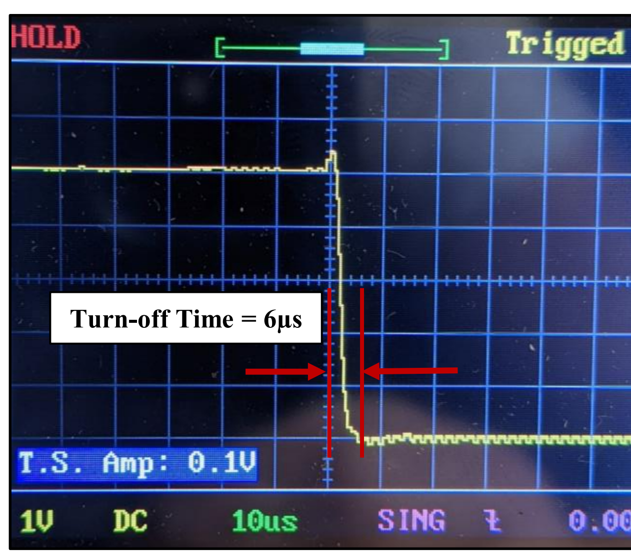


Fig 12: Arduino Uno PWM Turn-off Time

Simulation of the control circuit was performed in Ltspice XVII. A small-scale prototype system was built and tested on a small 12V DC hobby motor utilizing a single MOSFET for switching operations.

The small-scale circuit validated the current through the MOSFET in the simulation.

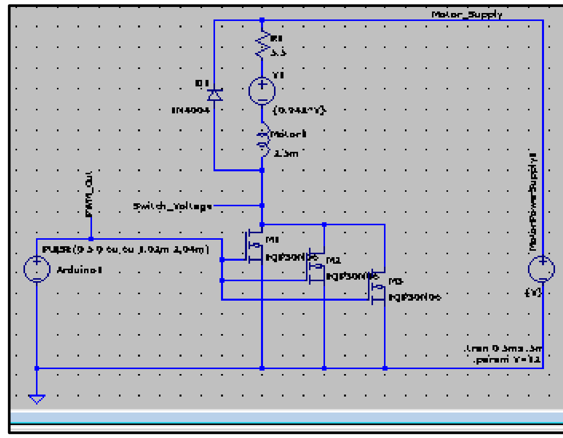


Fig 13: Dynamometer Speed Controller Diagram

Further simulation of a slightly modified circuit to include 3 MOSFETs was then performed to confirm the idea of utilizing 3 MOSFETs in parallel to evenly split the power dissipation into 3 MOSFET heatsinks.

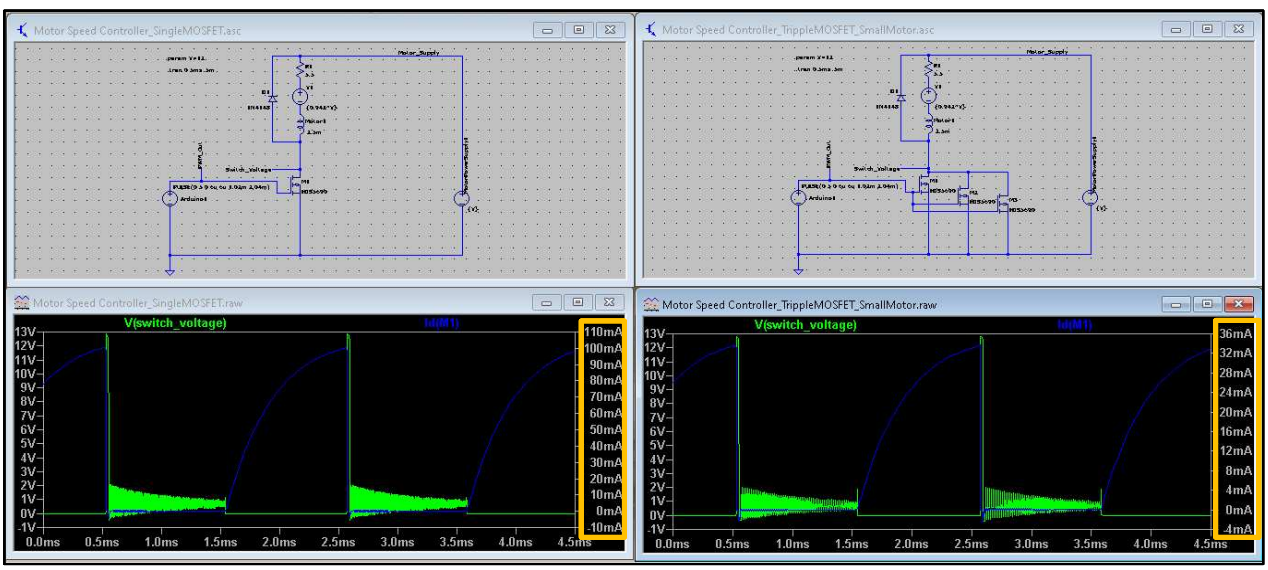


Fig 14: Motor Speed Controller Circuit Simulation Single MOSFET [LEFT]

Motor Speed Controller Circuit Simulation Triple MOSFET [RIGHT]

Power dissipated by the MOSFET is the power lost from R_{DS} while switching states. Simulations showed 123.22mW for average power dissipation through a single MOSFET version of the motor speed controller. The FQP30N06 has the following Thermal Resistance Properties;

1) Junction to Case = $1.90\frac{℃}{W}$
2) Junction to Ambient = $62.50\frac{℃}{W}$

Therefore,

$$62.50\frac{℃}{W}\ x\ 0.12322\frac{W}{1} = 7.70125℃ \text{ and } 1.90\frac{℃}{W}\ x\ 0.12322\frac{W}{1} = 0.24℃$$

Total temperature rise of the MOSFET is then calculated

$$7.70125℃ + 0.24℃ = 7.94125℃ + 25℃ = 32.94125℃$$

which further yields the case temperature in ambient conditions under no load.

To understand the maximum power dissipation of the MOSFET under the maximum motor voltage 'V' and current 'I' condition

$$R_{DS\ ON}\ x\ I_{MAX} = V_{MOSFET}$$

$$0.4(\Omega)\ x\ 27.4(A) = 1.096(V) x\ 27.4(A) = 30.0304\ W \text{ Power Dissipation}$$

since V x I = P.

A simple calculation of the case temperature rise with heatsink can be concluded from;

$$T_J = P(R_{JC} + R_{CH} + R_{HA}) + T_A$$

1) T_j = Temperature of the semiconductor junction, T_A is ambient temp
2) R_{JC} = Thermal resistance between junction and case = $1.90\ \frac{℃}{W}$
3) R_{CH} = Thermal resistance between case and heatsink = $0.25\ \frac{℃}{W}$ with thermal paste
4) R_{HA} = Thermal resistance between heat sink and ambient = $2.70\ \frac{℃}{W}$ for chosen heat sink

In order to provide a safety factor for the MOSFETs, the calculated power dissipation requirement will be doubled to $60W$.

Therefore;

$$T_J = 60W\left(1.90\frac{°C}{W} + 0.25\frac{°C}{W} + 2.7\frac{°C}{W}\right) + 25°C = 316°C$$

which is well above the 175°C maximum case temperature for the FQP30N06.

Splitting the thermal load between three MOSFETs should reduce the maximum calculated temperature of the case by approximately one third keeping T_{Max} near 100°C per case.

In order to determine the size of the required load cell for the Dynamometer, it is necessary to calculate the Torque produced by the motor under max load conditions. Since the machine motor is 500W and rated at 2500RPM, the Torque (τ) of the motor can be found after converting Revolutions Per Minute (RPM) to Radians Per Second.

$$2500\frac{revolutions}{minute}\ x\ 2\pi\frac{radians}{revolution}\ x\ \frac{1}{60}\frac{minute}{seconds} = 261.79\frac{radians}{second}$$

Since Power = Torque x Speed,

$$\tau_{Max} = \frac{P_{Max}}{\omega_{Max}} = \frac{500W}{261.79\frac{radians}{second}} = 1.9 Newton \cdot meters\ (Nm) = 0.194kgm$$

Therefore, at 1m from the center axis of rotation, the motor would apply 0.194kg force through a lever arm of 1m. To prevent the machine from being 1m wide, the lever arm can be shortened by;

Torque $(\tau) = Force(N) x\ radius(m) \rightarrow 1.9Nm = F\ x\ 0.25m \rightarrow F = 7.7N = 0.78kg$

With $F = 0.78kg$ the load cell then should be capable of reading values from 0-1kg.

To determine the load for the generator output, the maximum power output can be calculated $24(V)x\ 14(A) = 336(W)$, but because of internal loses and friction, the manufacturer of the generator motor claim 250(W) power output. Since the generator motor will output steady voltage at a given ω, increasing the load will increase the current consumption at given voltage. The first proposed generator load was lights/heat lamps. If a heat lamp were used as a load and assuming a linear relationship $\frac{120(V)}{2.1(A)} = \frac{24(V)}{x(A)} \rightarrow x = 0.420(A)$ at 24(V), which uses 10.08(W). In order to draw 250(W) out of the generator, the machine would need roughly 25 x 250(W) heat lamps operating at 24(V). A more feasible load solution then is a power resistor. Power resistors are high current load resistors that dissipate heat through an aluminum heatsink case. In order to draw the maximum power from the generator, the load should be impedance matched. The generator motor characteristics are $24V = 14(A)\ x\ R\ \rightarrow\ R =\ 1.71\Omega$. To meet the customer's load requirements, 2 x 100W (2 Ω) power resistors can be wired in series with the generator output.

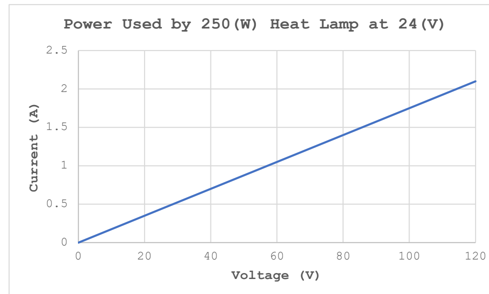


Fig 15: Linear VI graph of Heat Lamp

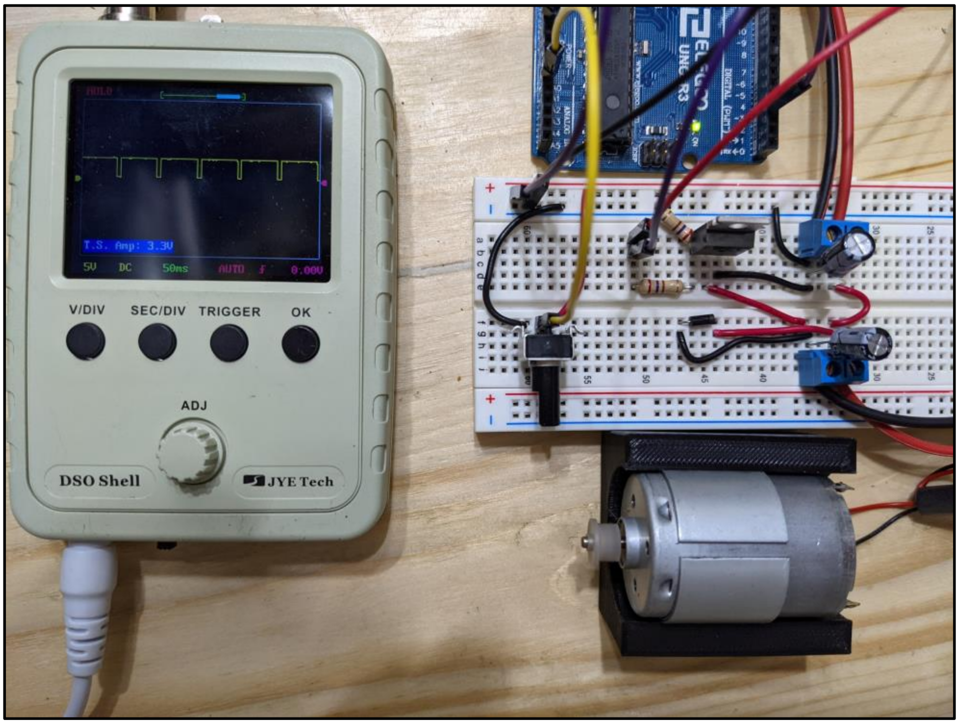


Fig 16: Dynamometer Motor Speed Controller

A small-scale prototype was developed to test the implementation of the designed circuit and the functionality of the motor speed controller code. Once verified, the circuit was built at full scale using the calculations found in the Design Analysis section of this report. As seen in Fig 16, the MOSFET gate is pulsed with a PWM signal to adjust the output voltage applied to the Dynamometer motor and thus vary its speed.

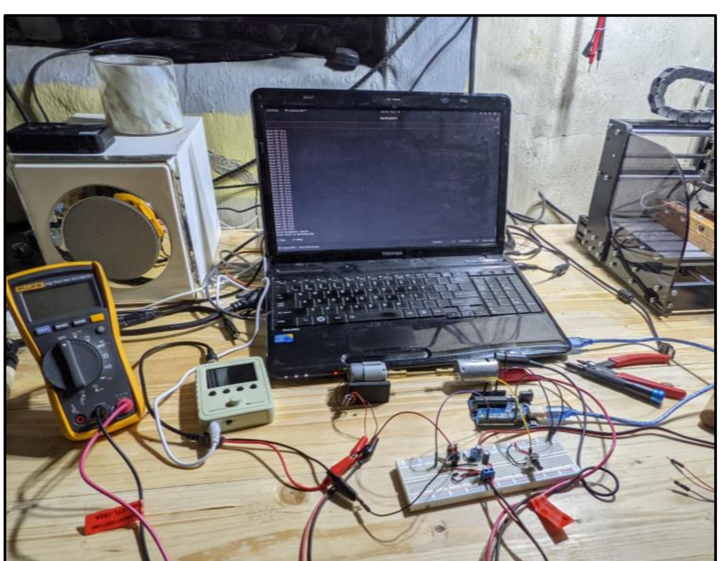


Fig 17: Dynamometer Motor Speed Controller Test Setup

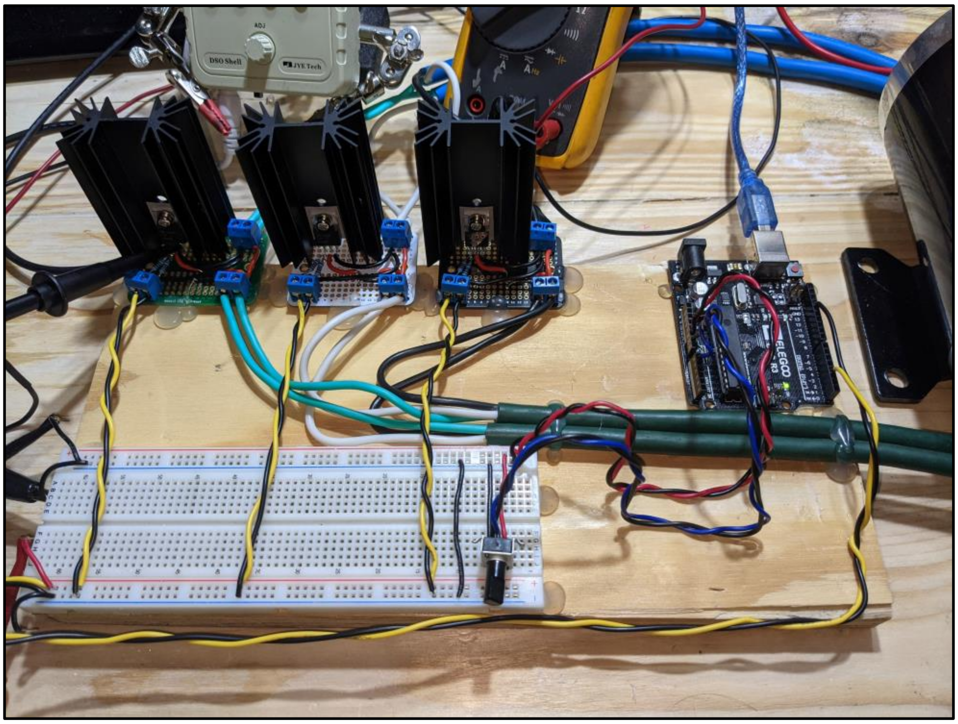


Fig 18: Dynamometer Motor Speed Controller Circuit Example

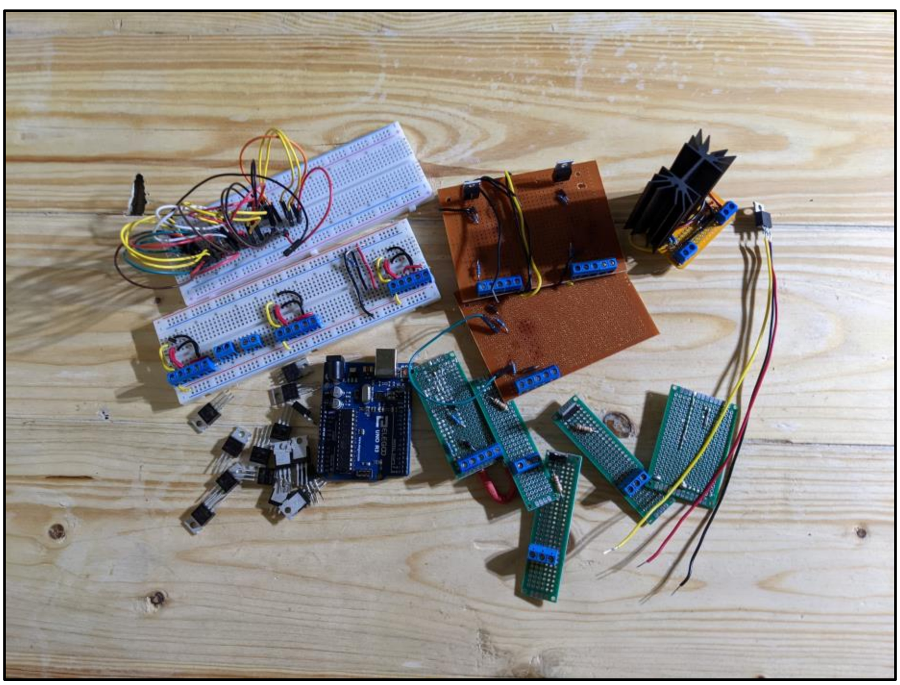


Fig 19: Failed attempts

Producing the full-scale Dynamometer motor speed controller took several attempts. A total of 15 MOSFET switches, 1 x Arduino Uno microcontroller, and multiple solder boards were converted to electronics waste as failed design attempts.

Bill of Materials

Bill of Materials					
Item #	**Item Description**	**Vendor**	**Cost**	**Quantity**	**Total**
1	500W DC Motor	Amazon	$78.89	1	$78.89
2	480W DC Power Supply	Amazon	$35.99	1	$35.99
4	Infrared Sensor Module Reflective Photoelectric Light (10-Pack)	Amazon	$8.29	1	$8.29
5	Load cell 1kg	Amazon	$7.99	1	$7.99
6	Load cell 5kg	Amazon	$7.99	1	$7.99
7	588-FA-T220-64E TO-220 Heat Sink 3°C/W	Mouser	$2.82	5	$14.10
8	Thermocouple Module	Amazon	$6.99	1	$6.99
				Total	$160.24

Bill of Materials					
Item #	**Item Description**	Vendor	Cost	Quantity	Total
9	Uxcell 12mm - 12mm Shaft Coupler	Amazon	$13.49	1	$13.49
10	30PCS Alligator Clips	Amazon	$9.89	1	$9.89
11	Comidox 100W 2R Ohm Power Resistors (Set of 5)	Amazon	$8.99	1	$8.99

Budget

Budget					
Item #	Item Description	Vendor	Cost	Quantity	Total
1	500W DC Motor	Amazon	$78.89	1	$78.89
2	480W DC Power Supply	Amazon	$35.99	1	$35.99
4	Infrared Sensor Module Reflective Photoelectric Light (10-Pack)	Amazon	$8.29	1	$8.29
5	Load cell 1kg	Amazon	$7.99	1	$7.99
6	Load cell 5kg	Amazon	$7.99	1	$7.99
7	588-FA-T220-64E TO-220 Heat Sink 3°C/W	Mouser	$2.82	5	$14.10
8	Thermocouple Module	Amazon	$6.99	1	$6.99
9	LCD Display	Amazon	$8.59	1	$8.59
10	Arduino-Uno	Arduino	$23.00	1	$23.00
11	MOSFETs (10 - Pack)	Amazon	$8.99	1	$8.99
12	Diodes	Mouser	$0.20	10	$1.98
13	100Ω Resistors	Mouser	$0.14	10	$1.43
14	1000Ω Resistors	Mouser	$0.56	10	$5.62
15	Bearings (10-Pack)	Amazon	$30.50	1	$30.50
16	Steel Rod	McMaster-Carr	$11.83	1	$11.83
17	Plywood 1/2" 4x8 CDX	Menards	$24.35	1	$24.35
				Total	$276.53

Schedule

Dynamometer

School North Central College

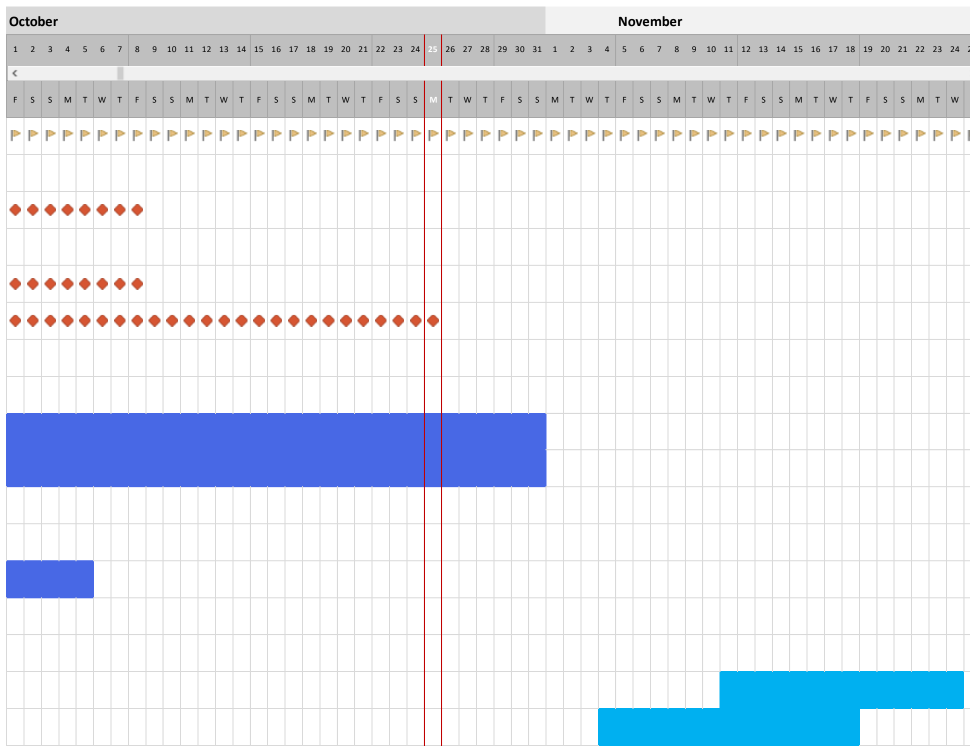
Project lead Tom DeLine

Project Start Date: 8/25/2021

Scrolling Increment: 37

Legend: On track | Low risk | Med risk | High risk | Unassigned

Milestone description	Category	Progress	Start	Days
Report	Milestone	75%	8/25/2021	100
Preliminary Report	Goal	100%	8/25/2021	7
Specifications	Goal	100%	8/25/2021	45
Concept	Goal	100%	8/22/2021	30
Simulations	Goal	100%	9/10/2021	29
Calculations	Goal	100%	8/31/2021	56
Small Scale Prototype				
Build Breadboard	Goal	100%	9/21/2021	3
Measure Values	Med Risk	50%	9/23/2021	39
Record Data	Med Risk	50%	9/23/2021	39
Full Scale Prototype				
Control Box	On Track	50%	9/22/2021	4
Bearing Walls	Med Risk	5%	9/22/2021	14
Motor Plates	Med Risk	0%	9/22/2021	6
Machine Base	On Track	0%	9/22/2021	3
Name Plate	Low Risk	10%	11/11/2021	14
Measure Values	Low Risk	0%	11/4/2021	15



Results/Data

The first documented measurements with the Dynamometer were of RPM. To make this measurement, a piece of black electrical tape was wrapped around the output shaft of the machine motor. A white chalk marker was then used to draw a single white line along the shaft as depicted in Figure 20. An IR distance module was used to track the amount of time it takes for the white line to make 1 revolution.

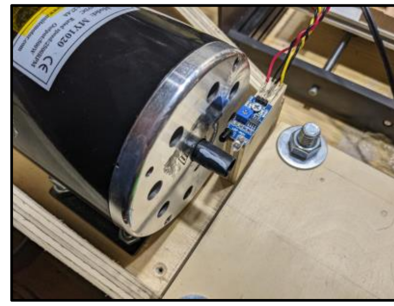


Fig 20: Motor shaft with tape and white line

The pulseIn(pinToMonitor, Rising/Falling Edge) function built into the Arduino IDE is used for monitoring the pulse length as received from the IR module each time the white line reflects the IR light. To calibrate the tachometer, the motor was set to run at 12.0(V). The oscilloscope in Figure 21 measures the amount of time elapsed between pulses.

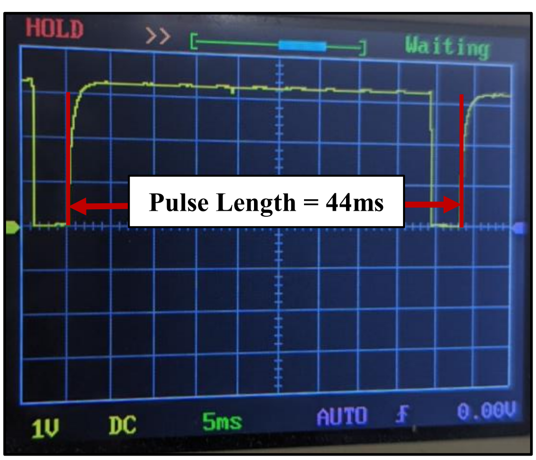


Fig 21: Tachometer Pulse goes LOW each time the rotor makes 1 rotation

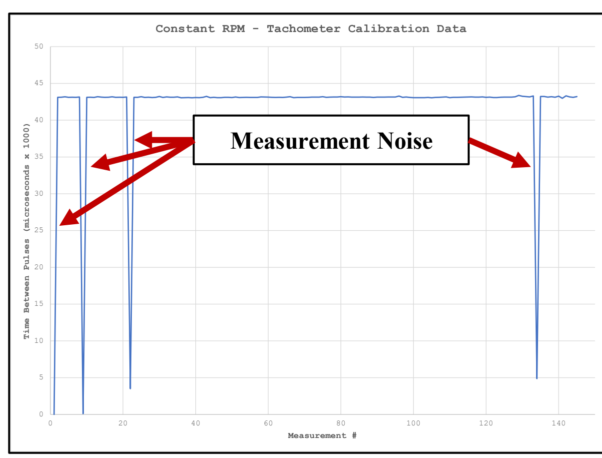


Fig 22: One-hundred forty - sequential measurements of pulse length using Arduino IDE pulseIn( ) function. Motor held at constant 12V

Since the oscilloscope pulse length matches the length of the pulse measured by the Arduino, a simple calculation of RPM can be concluded from:

$$\frac{Revolutions}{minute} = \frac{1}{\frac{microseconds}{revolution}} x\ 1000 \frac{\mu s}{s}\ x\ 60 \frac{seconds}{minute}$$

Where time is initially recorded in microseconds but can be converted to minutes through basic unit analysis. As seen in Figure 23, the measurements include some amount of undesired noise. To reduce the amount of noise reported by the system, the code compares the rate of change of the pulse length with a constant value. If the rate of change is larger than the constant, the data is not reported by the controller and the noise is omitted since the motor can't physically accelerate or decelerate at the rate reported by the tachometer module. Figure 23 shows the amount of noise being reported by the system is high enough to significantly alter the RPM output.

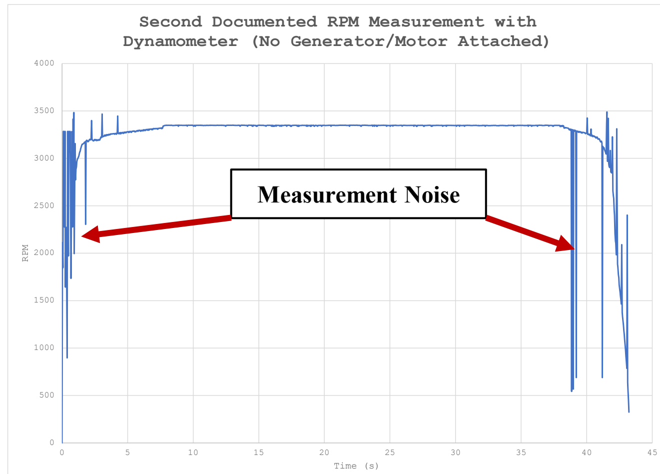


Fig 23: Measurement noise being reported in RPM by controller

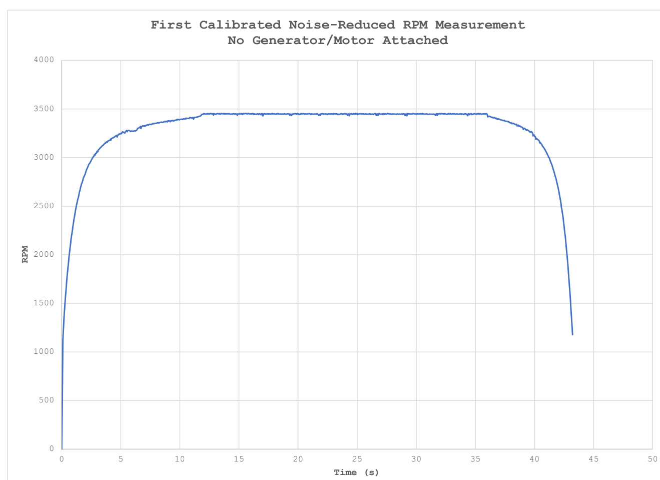


Fig 24: Calibrated Motor Tachometer

Figure 24 however shows the correct RPM being reported by the tachometer after filtering the noise digitally through signal rate of change analysis.

After the tachometer was successfully calibrated, the Dynamometer temperature sensor was installed and calibrated by submerging the thermocouple end in boiling water followed by subjecting it to the surface of an ice-cube. If the water measures 100°C when boiling and approximately 0°C on the surface of the ice-cube, the sensor is reporting accurately enough for the Dynamometer to compare generator temperature rise vs power output. Once the thermocouple was calibrated, baseline measurements of the machine's motor temperature and MOSFET heatsink temperature after running at maximum RPM for 10 minutes were recorded.

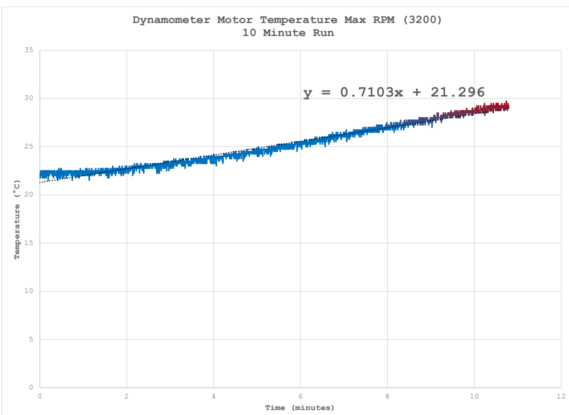


Fig 25: Motor Temperature Rise after 10 minutes

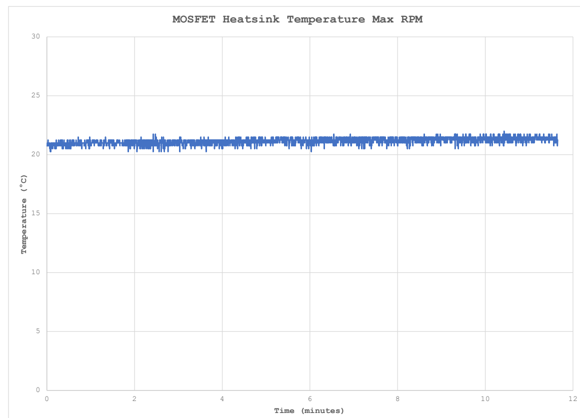


Fig 26: MOSFET Heatsink Temperature Rise after 10 minutes

The machine motor temperature increased at approximately 0.75°C per minute for 10 minutes while operating at maximum RPM with no load attached. The temperature of the MOSFET heatsink, as measured next to the M3 mounting screw of the MOSFET, maintained a relatively stable temperature of 21°C while operating at maximum RPM with no load attached.

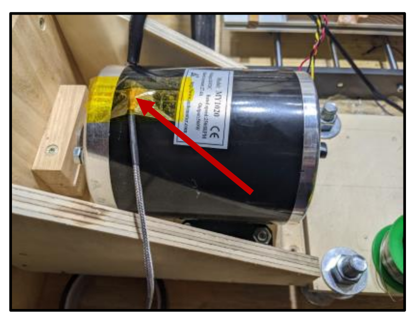


Fig 27: Thermocouple sampling location on motor from heat rise graph

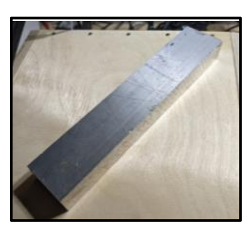


Fig 28: Aluminum Block

Calibration of the Dynamometer load cell began by measuring the mass of an aluminum block with a kitchen scale to be 396.58(g).

The aluminum block was then placed on the load cell while executing the load cell calibration sketch included with the HX711 library which can be referenced in the appendix. In the sketch, a load cell calibration factor is tuned through an active console session until the output of the load cell matches the output of the kitchen scale.

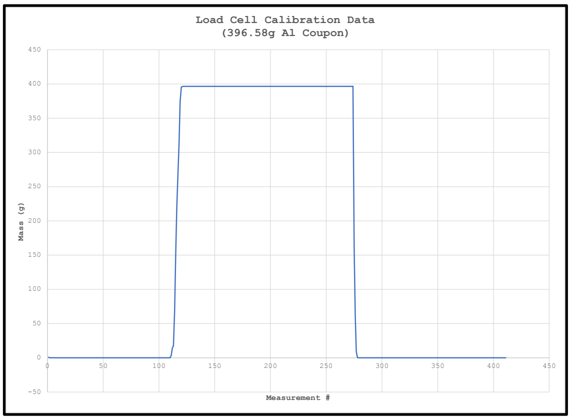


Fig 29: Load Cell Calibration Data

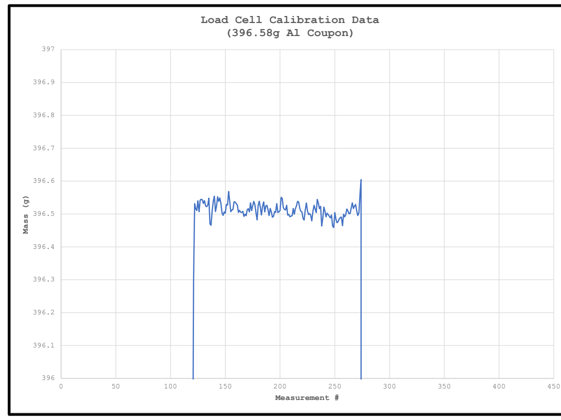


Fig 30: Magnified region of Load Cell Calibration Data

Figure 29 shows the aluminum block being placed on the scale and then removed. Figure 30 shows a magnified region around 396.5(g). A histogram analysis of the load cell measurement data shows the average measured mass of the Aluminum block to be 396.51(g)

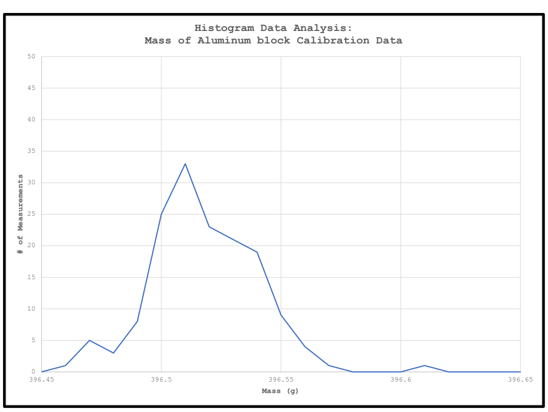


Fig 31: Frequency of data reported by load cell

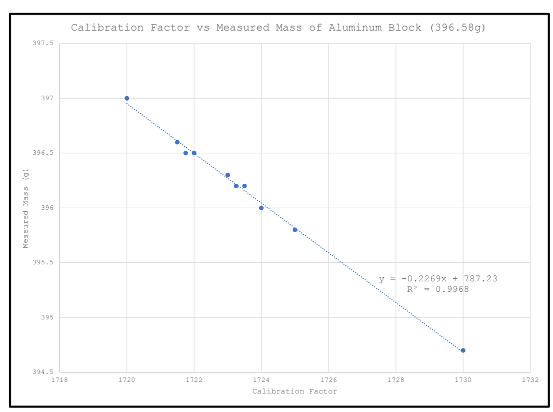


Fig 32: Load Cell Calibration Data showing $y(396.58) = -0.2269x + 787.23 \rightarrow x = 1721.68$

Fig:___ shows the method used for finding the exact value of the calibration factor required for the aluminum block to measure 396.58(g) and was determined to be 1721.68 based on the data collected.

With the sensor suite fully functional, a spring can be added to the Dynamometer lever arm to keep it in constant contact with the load cell. Since the load cell now has the added force pressing down on it from the spring, the code executes a tare( ) function before recording any measurements in order to zero the scale. The spring location was chosen to have minimal force pulling down on the load cell so that it’s rated values were not exceeded. The current spring location and spring size correlates to 300(g) pulling down on the load cell. This value may have to be decreased if the load cell becomes saturated, or the load cell size could be increased to the 5kg max version.

Fig 33: Load Cell Spring Location

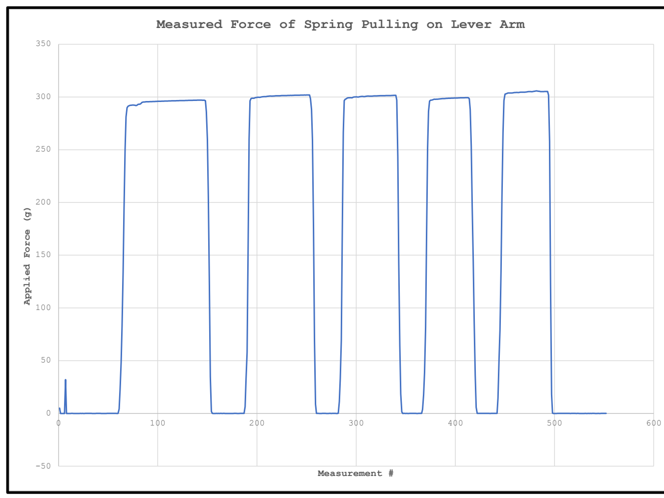


Fig 34: Five measurements of the spring force pulling down on the load cell

After inspecting the location of the spring and determining its location to be sufficient for testing purposes, the Dynamometer can now deploy all three of its sensors nearly simultaneously to produce an output as shown in Figure 35 with comma delimited data points.

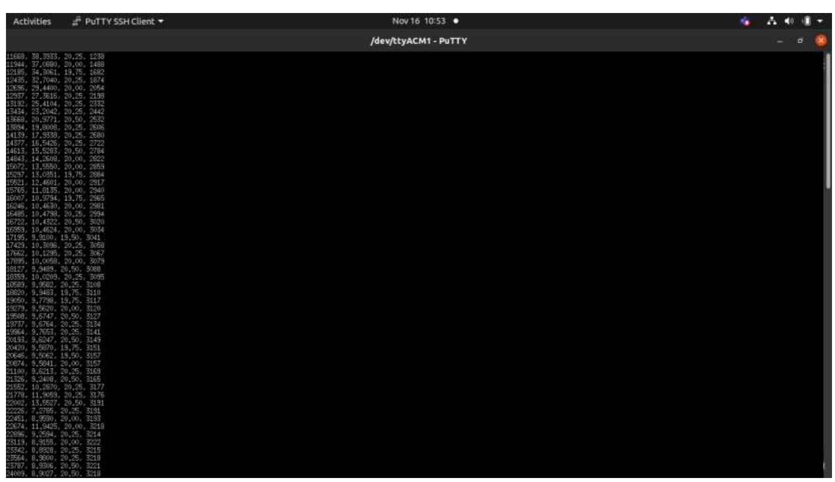


Fig 35: Time (ms), Force (g), Temperature (°C), ω (RPM)

The first ever recorded, baseline measurement of the Dynamometer operating in Max Speed mode can be analyzed and interpreted from the three graphs, Temperature vs Time, Force vs Time, and RPM vs Time, respectively.

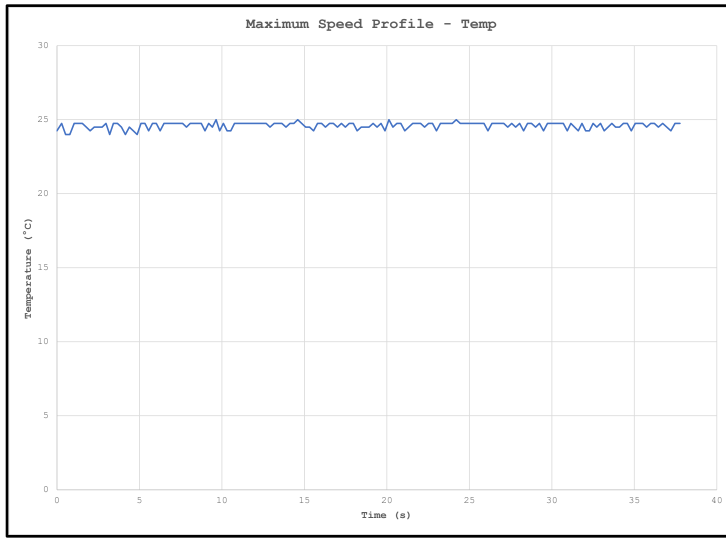


Fig 36: Machine Motor Temperature vs Time

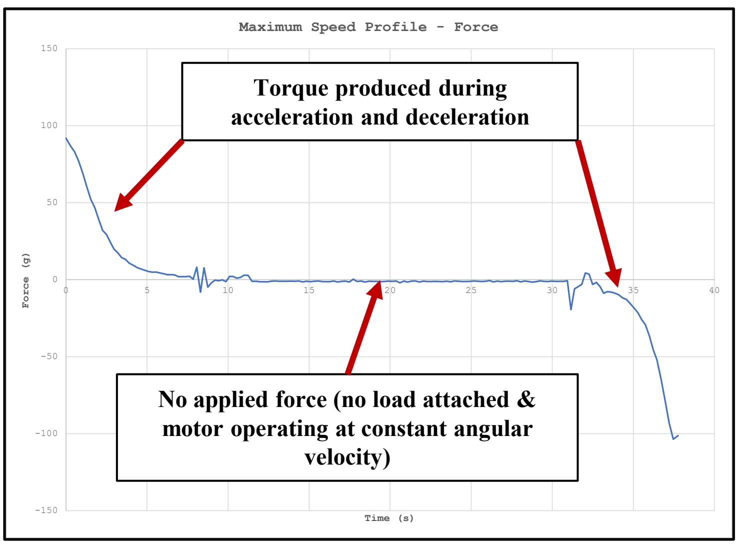


Fig 37: Force vs Time

All the data for the three graphs was obtained in a single run of the Max Speed mode without a second motor/generator attached.

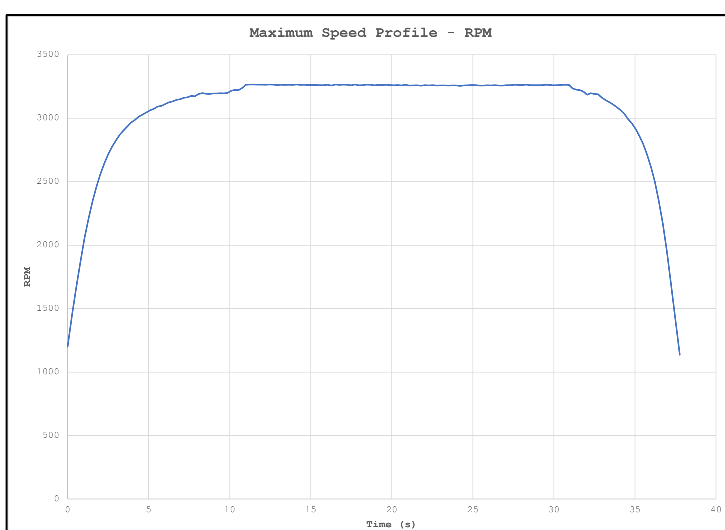


Fig 38: RPM vs Time

Generator Performance

The Generator was coupled to the Dynamometer using a 12mm x 8mm shaft coupler. Test 7 is the first test with Dynamometer coupled to the generator and the results can be seen in seen in Fig below. The peak Power Output during this test was 150W at 17.76V with RL = 2.1 Ω. The efficiency of the motor during this output was 68%, but the highest efficiency calculated during this test was 72% with RL = 4.1Ω.

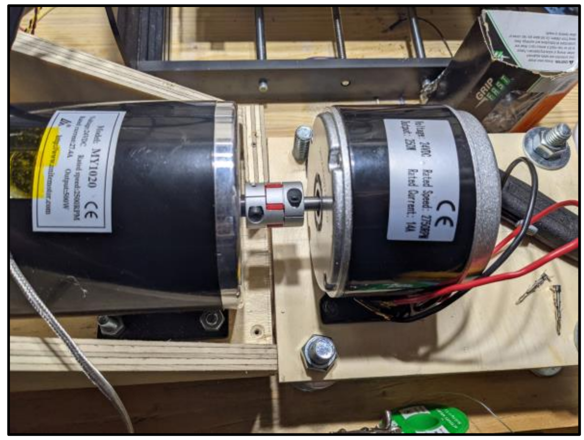


Fig 39: Motor shaft with tape and white line

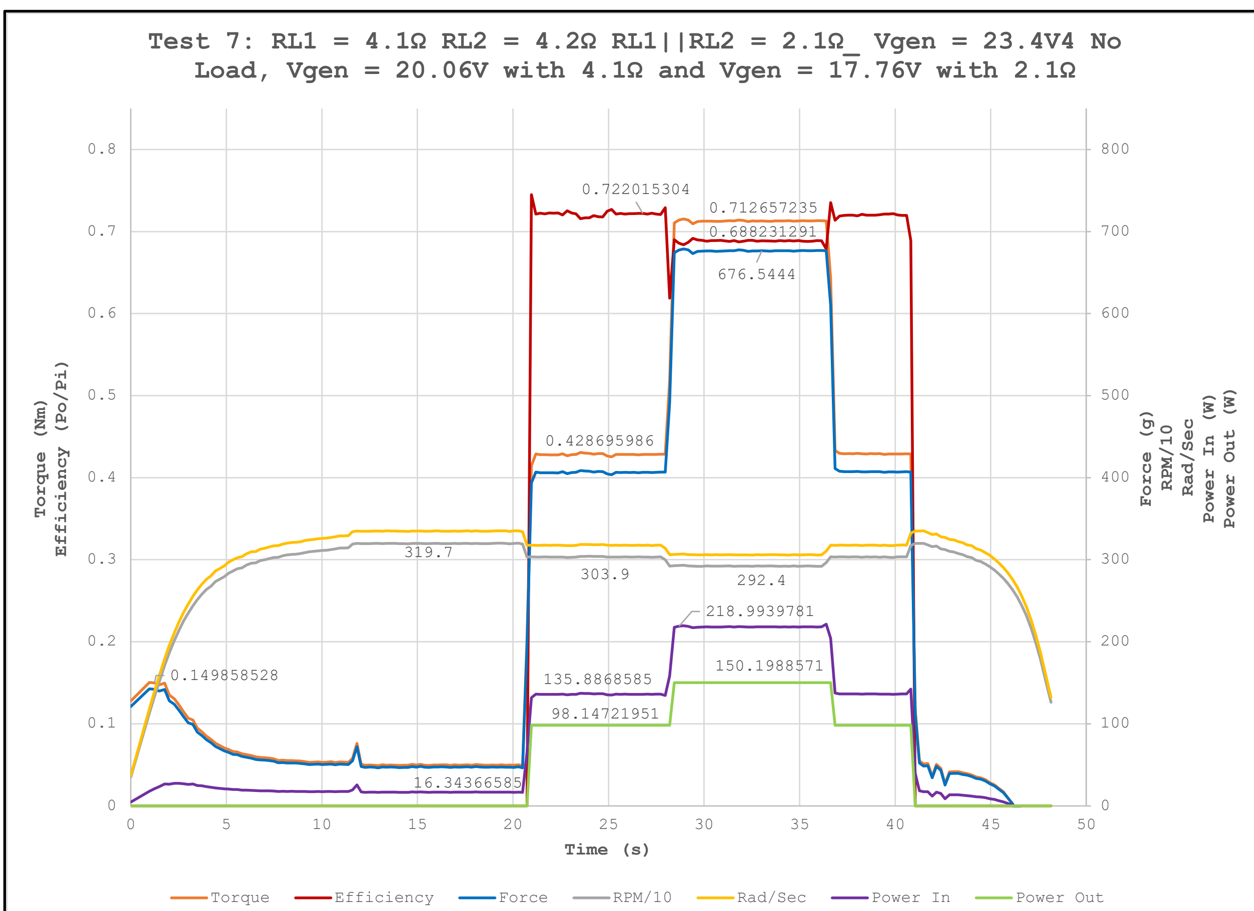


Fig 40: Test 7

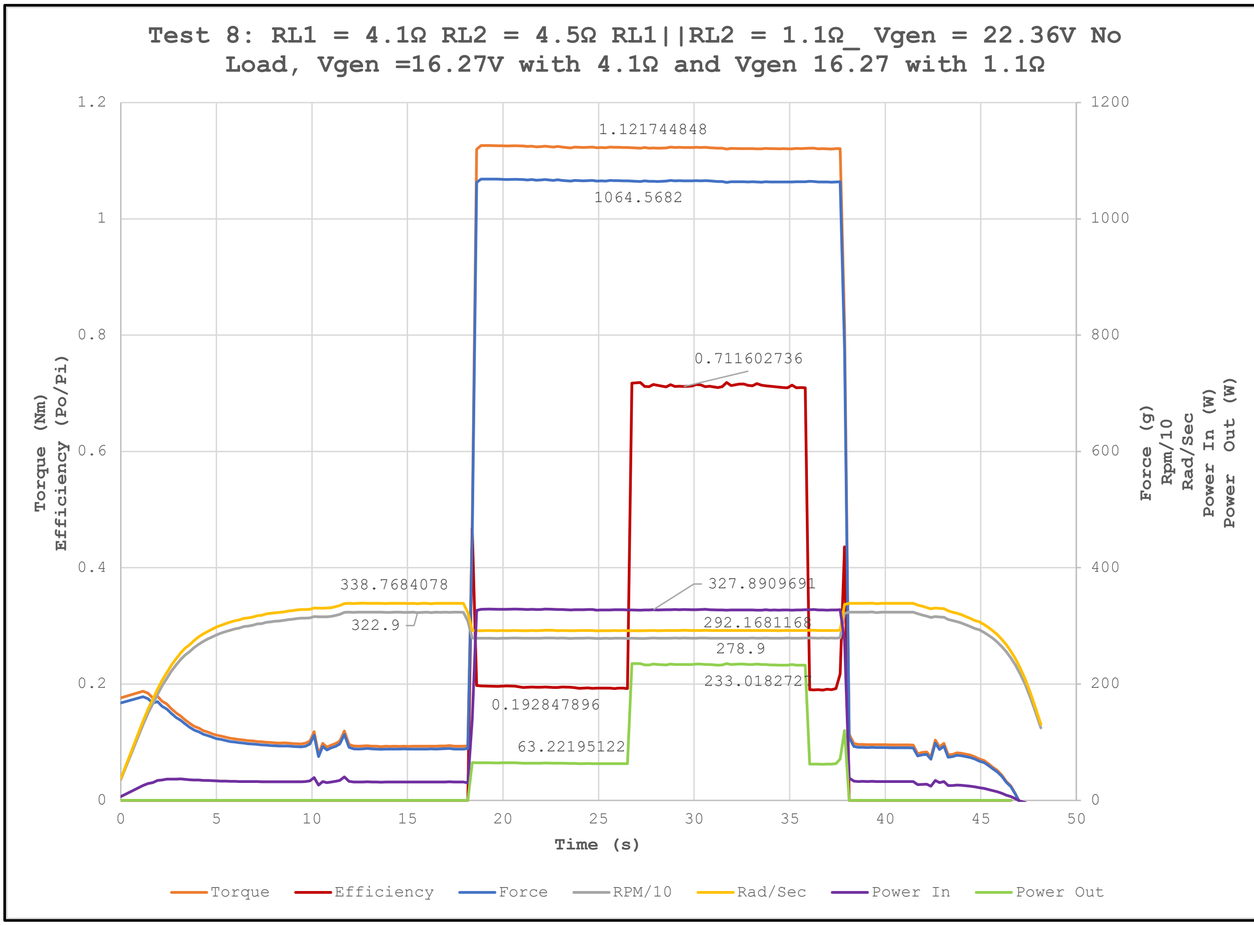


Fig 41: Test 8

Test 8 was conducted with the Dynamometer coupled to the generator and the results can be seen in Figure 41 above. The peak Power Output during this test was 233W at 16.27V. The highest efficiency calculated during this test was 71% with RL = 1.1Ω.

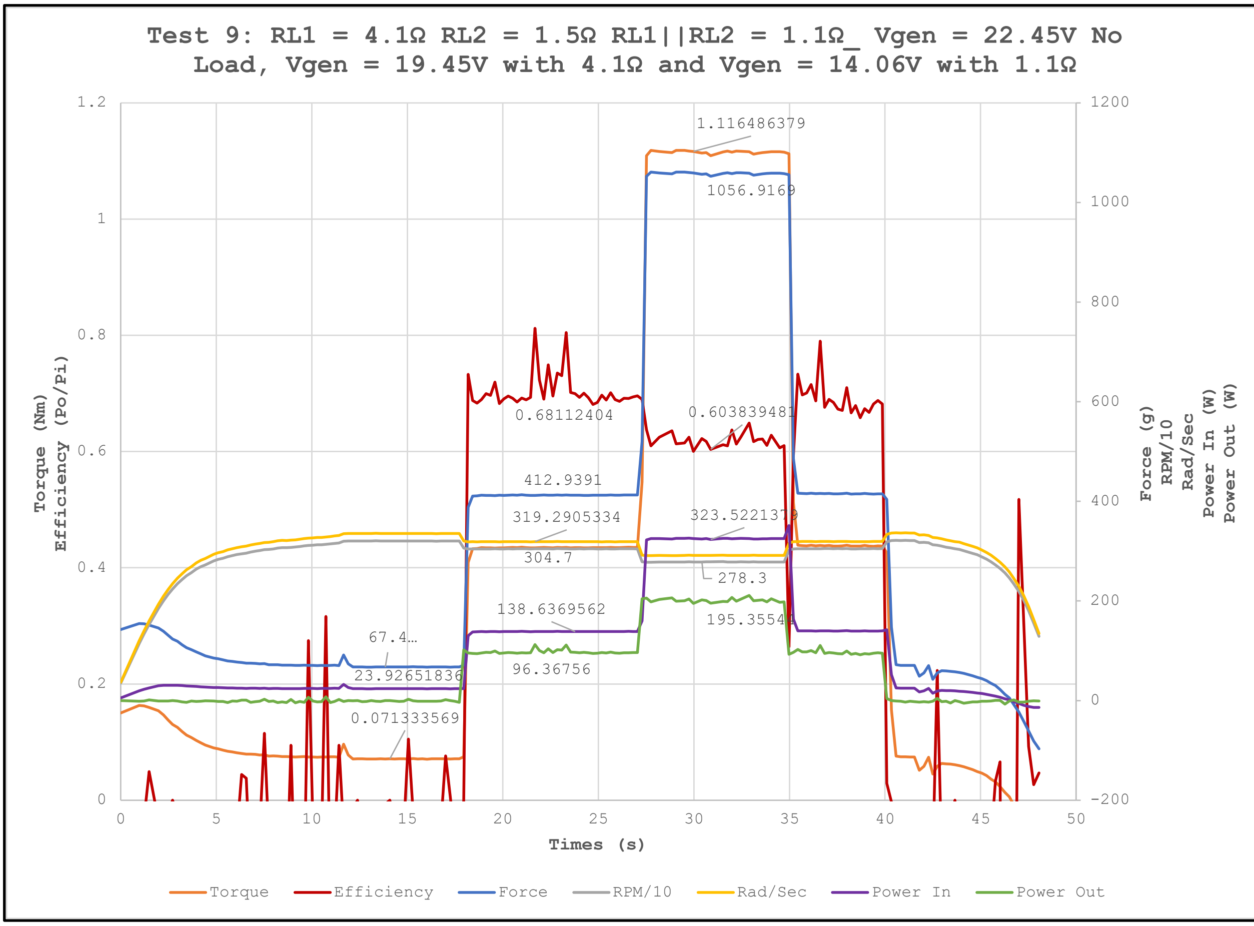


Fig 42: Test 9

Test 9 was conducted with the Dynamometer coupled to the generator and the results can be seen in Fig above. The peak Power Output during this test was 195W at 14.06V. The highest efficiency calculated during this test was 68% with RL = 1.1Ω.

	Test 7	Test 8	Test 9
Peak Power (W)	150	233	195
RL (Ω)	2.1	1.1	1.1
Vout (V)	17.76	16.27	14.06
Torque Required (Nm)	0.71	1.12	1.12
Efficiency (%)	68.82	71.16	60.38

Fig 43: Table of Test Results

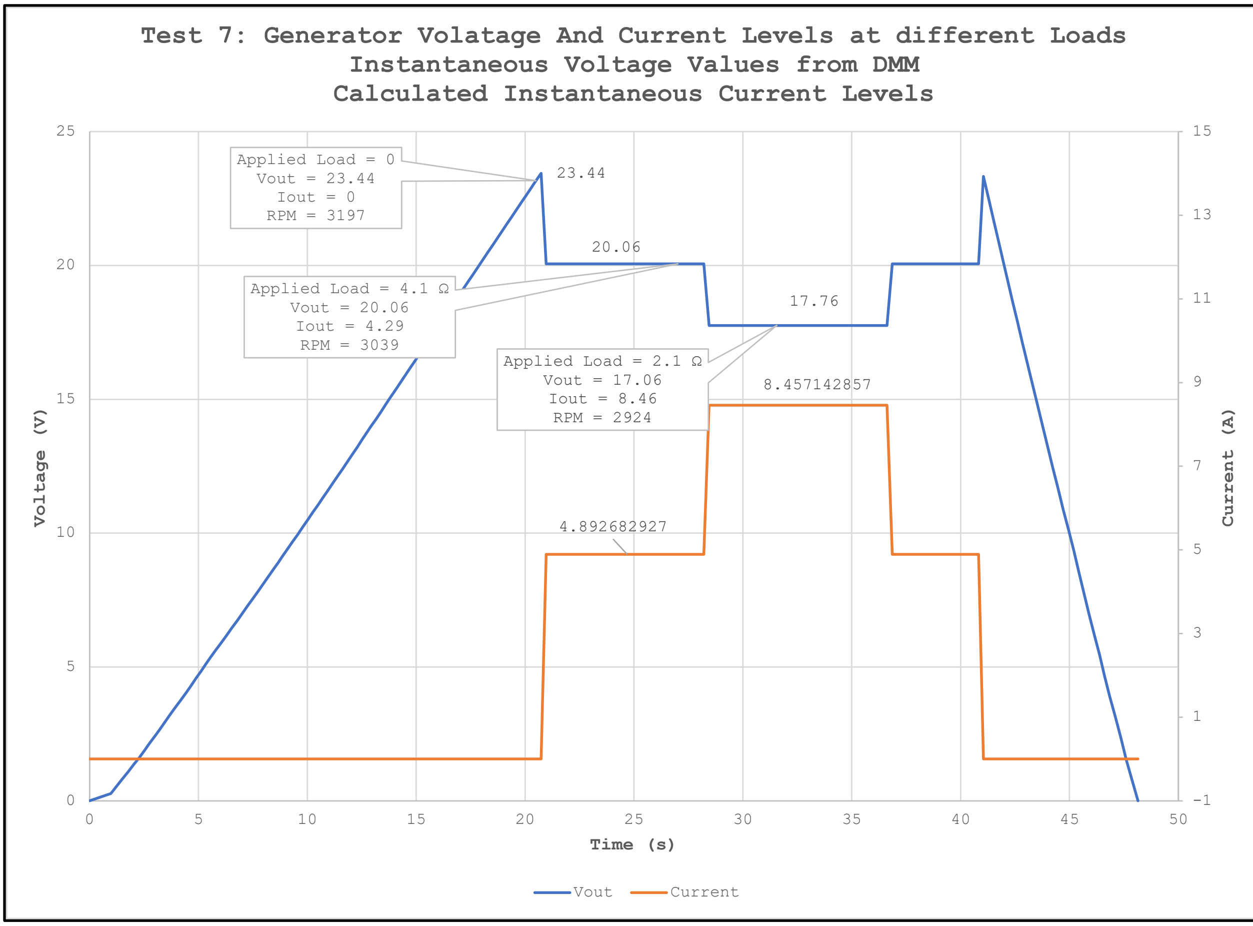


Fig 44: Test 7

The figure above shows the voltage and current outputs of the motor in response to different loads. The voltage of the generator was determined by using a DMM and recording the average DC output during the different load intervals. An output current can be calculated as $\frac{V}{R} = I$ where R was measured before the test beginning.

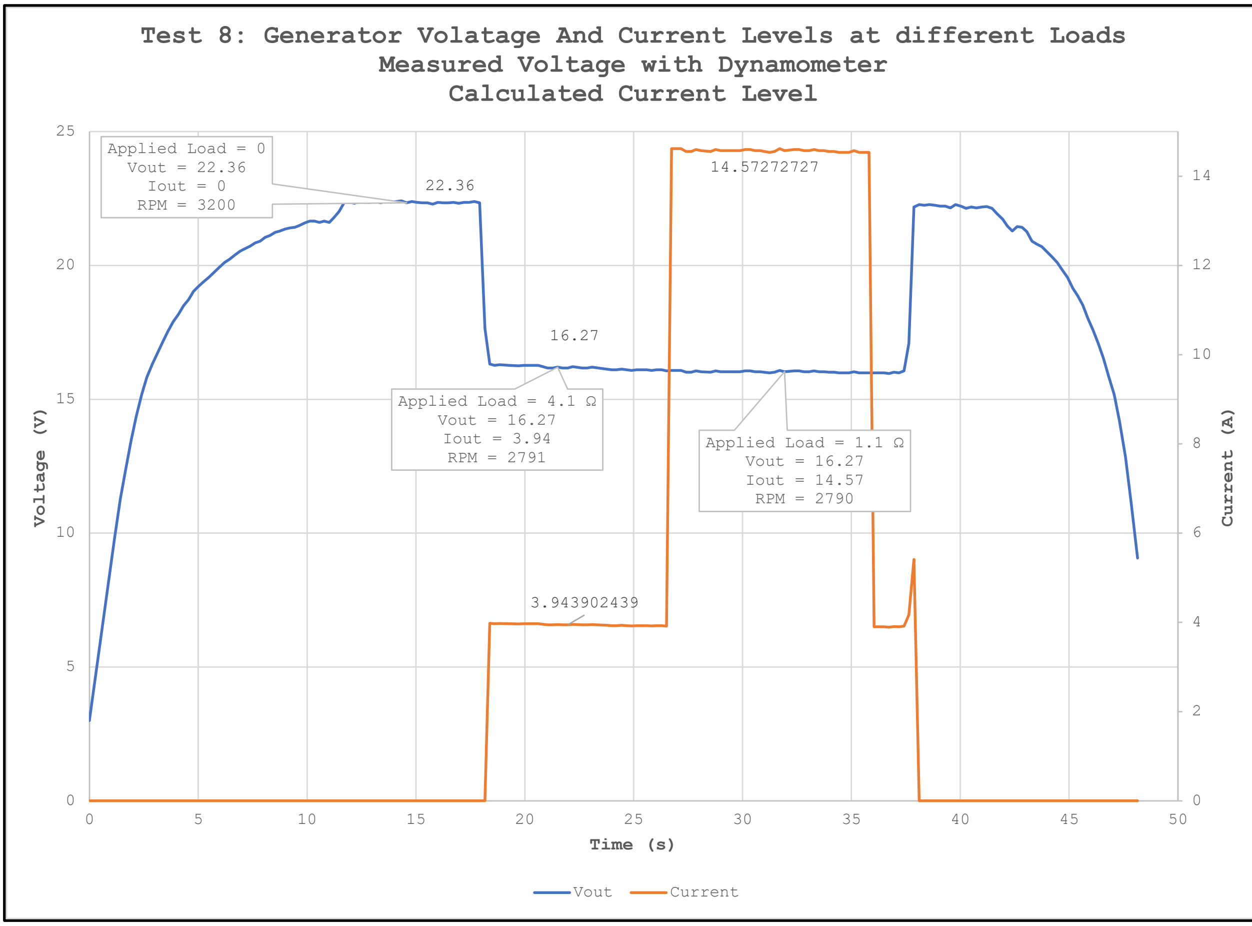


Fig 45: Test 8

The figure above shows the voltage and current outputs of the motor in response to different loads. The voltage of the generator was documented using a voltage divider and the Arduino's onboard ADC. The output current of this test was a calculated value. RL was measured before the test beginning.

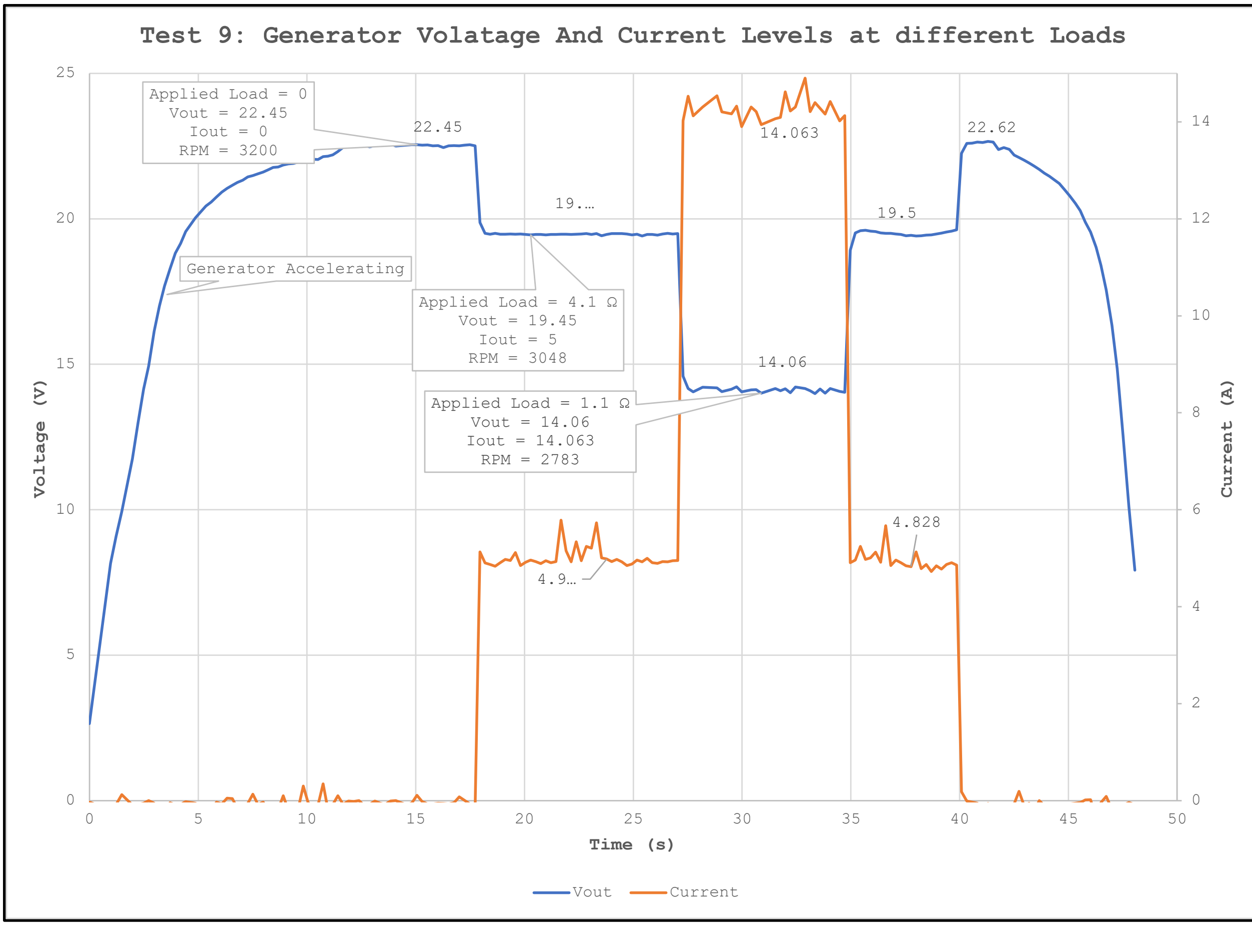


Fig 46: Test 9

The figure above shows the voltage and current outputs of the motor in response to different loads. The voltage of the generator was measured using a voltage divider and the Arduino's onboard ADC. The output current of this test was measured utilizing a hall sensor. RL was measured before the test beginning.

The electric load was applied to the generator at roughly the same time intervals for each of the three tests in Fig x-y. The load can be changed by flipping the switches as seen in Fig 47. The power resistors use a Large aluminum block to dissipate the power which peaks near 250W.

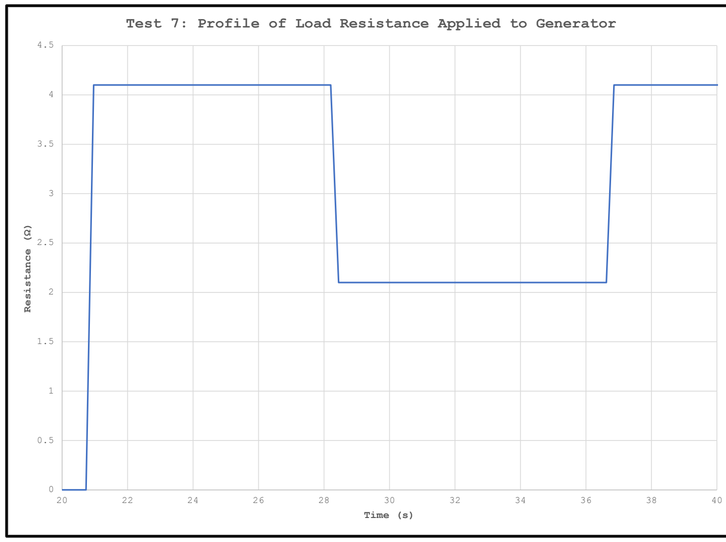


Fig 47: Test 7 Applied Load Resistance Profile

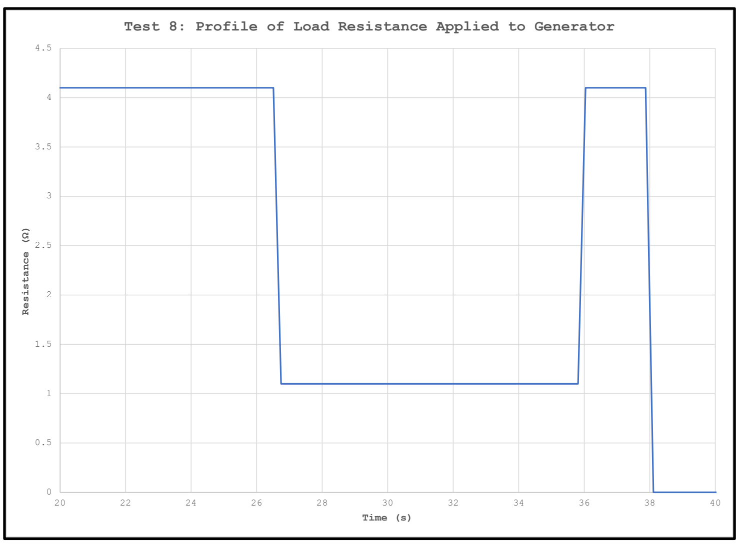


Fig 48: Test 8 Applied Load Resistance Profile

There are a total of five power resistors used for the electric load. The wiring diagram of the resistors can be found in Fig 49 of this report. The generator is connected to the two input terminals of the Dynamometer.

Fig 49: Electric Load and switches

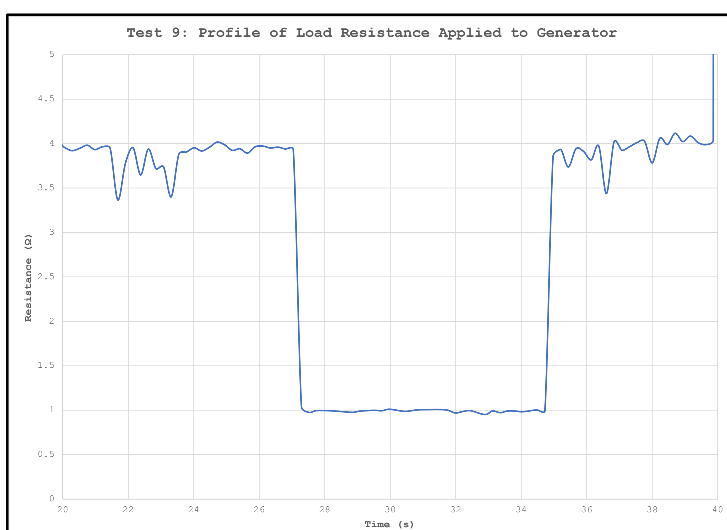


Fig 50: Test 9 Applied Load Resistance Profile

Conclusion

The generator purchased by the customer is capable of outputting 195W at 14.06V while rotating at 2783RPM. This should be more than enough power to charge a 12V DC system. The Dynamometer built for testing the customer's generators, functioned as intended. The machine is capable of evaluating torque required to spin a generator under loaded or unloaded conditions. The machine can be re-configured to measure the amount of torque produced by a motor/generator by swapping power/load leads on the machine. In the default configuration, the machine is able to compare power input at the shaft to the power output at generator terminals. The efficiency of the generator can the be found as $\frac{Pout}{Pin} = efficiency$.

The machine measures the following parameters while operating;

1) Torque
2) Temperature
3) RPM
4) Vout
5) Iout

In conclusion, the Dynamometer machine is capable of evaluating motors/generators through 5 different metrics and is considered a success. Future designs of the machine could include the use of an extruded aluminum frame for more rigidity. The electric load could also be automatically applied in future iterations to make for consistent time graphs.

References

How to Calculate Torque for a Motor – YouTube

How to Analyse the Performance of a Motor: Setting Up the Matrix Electrical Machines Test Equipment – YouTube

How to measure torque of a motor? | Torque Testing Stand (futek.com)

Digital Force Gauge & Weight Scale w/ Loadcell & Arduino - Arduino Project Hub

Load Cell 1kg | ElectroPeak

Electric Motors and Drives, Fifth Edition Austin Hughes, Bill Drury Ch2 Power Electronic Converters for motor drives Pg 45-