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MEASURING TORQUE AND POWER OF MINIATURE STEPPER MOTORS

Bachelor of Science Thesis
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ABSTRACT

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A stepper motor is a synchronous electric motor that, unlike many other types of motors, rotates only a certain number of degrees at a time rather than rotating continuously. This principle of operation makes it excellent for use in motion control systems. Measuring the torque and power of a stepper motor is an important part of a stepper motor's development process. Simulation software can be used to estimate the torque and power of a motor at an early stage of design work, but at a certain stage in the development process, it is necessary to measure performance in practice. A dynamometer is a type of device that can measure the torque and power of a motor or an engine. There are dynamometers on the market for measuring the performance of motors in all size and power classes. However, there are no inexpensive dynamometer options for measuring the torque and power of miniature-sized stepper motors.

The goal of this thesis is to design a dynamometer for measuring the torque and power of miniature stepper motors. The thesis is divided into two parts. The theoretical section introduces the basic principle of torque measurement, the most common types of dynamometers, and the calculation of power. The practical part introduces the built dynamometer and its operating principle, the torque and power of the three miniature stepper motors is measured at different pulse frequencies, and the torque measurement results are compared with the torque specifications reported by the stepper motor manufacturer.

The built dynamometer is sufficient for rough testing of miniature stepper motors based on the measurement results. The measurement results were close to the manufacturer's stated readings. However, there was variation in the measurement results, the causes of which are analyzed and a few changes to the structure of the dynamometer are proposed to improve the accuracy and repeatability of the measurement results in future measurements.

Keywords: dynamometer, stepper motor, torque, power

TIIVISTELMÄ

Nico Koski: Miniatyyri askelmoottorien vääntömomentin ja tehon mittaaminen
Tampereen yliopisto
Teknisten tieteiden kandidaattiohjelma
Kandidaatintyö
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Askelmoottori on synkroninen sähkömoottori, joka monista muista moottorityypeistä poiketen pyörii vain tietyn määrän asteita kerrallaan jatkuvan pyörimisen sijaan. Tämä toimintaperiaate tekee siitä erinomaisen käytettäväksi liikkeenohjausjärjestelmissä. Askelmoottorin vääntömomentin ja tehon mittaaminen on tärkeä osa askelmoottorin kehitysprosessia. Simulaatio ohjelmistojen avulla voidaan arvioida moottorin vääntömomenttia ja tehoa jo suunnittelutyön alkuvaiheessa, mutta tietyssä vaiheessa kehitysprosessia suorituskyvyn mittaaminen käytännössä on välttämätöntä. Dynamometri on laitetyyppi, jolla voidaan mitata moottorin tai koneen vääntömomenttia ja tehoa. Dynamometrejä on markkinoilla kaikenkokoisten ja tehoisten moottoreiden suorituskyvyn mittaamiseen. Miniatyyri-kokoluokan askelmoottorien vääntömomentin ja tehon mittaamiseen ei kuitenkaan ole edullisia dynamometrivaihtoehtoja.

Tämän työn tavoite on suunnitella dynamometri miniatyyri-kokoluokan askelmoottorien vääntömomentin ja tehon mittaamiseen. Työ jakautuu kahteen osaan. Teoriaosuudessa esitellään vääntömomentin mittaamisen perusperiaate, yleisimmät dynamometrityypit ja tehon laskeminen. Käytännön osuudessa esitellään rakennettu dynamometri ja sen toimintaperiaate, mitataan kolmen miniatyyri askelmoottorin vääntömomentti ja teho eri pulssitaajuuksilla, sekä verrataan vääntömomentin mittaustuloksia askelmoottorien valmistajan ilmoittamiin lukemiin.

Mittaustulosten perusteella rakennettu dynamometri riittää miniatyyri askelmoottorien karkeaan testaukseen sellaisenaan, sillä mittaustulokset olivat lähellä valmistajan ilmoittamia lukemia. Mittaustuloksissa oli kuitenkin hajontaa, jonka syitä analysoidaan ja muutamia muutoksia ehdotetaan dynamometrin rakenteeseen mittaustulosten tarkkuuden ja toistettavuuden parantamiseksi tulevissa mittauksissa.

Avainsanat: dynamometri, askelmoottori, vääntömomentti, teho

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LIST OF SYMBOLS AND ABBREVIATIONS

ω	angular velocity
$\mathbf{F}$	force
MC	microcontroller
$\mathbf{P}$	power
RPM	revolutions per minute
SI system	international system of units (Système international d'unités in French)
$\mathbf{T}$	torque

1. INTRODUCTION

Actuators are an essential component in all industries. There is an actuator to be found in almost all appliances in one's home.

A common type of actuator in motion control systems is a stepper motor. A stepper motor is a type of actuator that can turn electricity into rotational motion. Stepper motors are a special type of motor, as they only rotate a specific amount of degrees, a step, at a time rather than rotating continuously like many other motor types. (Atkins & Escudier 2013a) This makes them ideal for applications where accurate motion without closed–loop control is necessary.

Torque is an important characteristic when designing a stepper motor. Simulations can go a long way in the design process, but at some point, actual measurements need to be done to confirm the stepper motor's performance.

There are many different devices available to measure the torque and power of motors and engines with varying techniques. However, the selection of devices for measuring torque of miniature motors is extremely limited and the few available models are relatively expensive.

The objective of this bachelor's thesis is to research and develop a way of measuring the torque and power of miniature stepper motors and to verify the developed measuring system's accuracy by testing the performance of sample stepper motors.

In this bachelor's thesis, a dynamometer is built from readily available and 3D printed parts for measuring torque and power of miniature stepper motors. In the beginning, the theory of torque and power measurement methods is studied. Then the built measurement setup is described in detail and at the end of this thesis, measurement results are presented and discussed.

2. MEASUREMENT METHODS

In this chapter, the most common torque measurement methods are studied and discussed. Also, the definition and calculation of power are introduced.

2.1 Torque

In physics, the moment of a force is the turning effect of a force applied to an object. It is defined as the product of the force and the perpendicular distance to the axis of rotation. (Cooper 2006, p. 185; Garshelis 2014) When the situation is not stationary (e.g. a rotating shaft) it is common in physics to talk about torque ($\mathbf{T}$) instead of moment (Testbook 2024). The unit of torque and the moment of a force in the international system of units (SI system) is a newton meter (Nm) (Garshelis 2014).

Measuring the moment of a force is relatively straightforward. Only the applied force needs to be measured at a known distance from the axis of rotation and then the moment can be calculated. On the other hand, when measuring the torque of a rotating shaft things get more complicated. This can be done in many ways, but all of them have the same basic principle: the rotating shaft is loaded with some kind of brake and the braking force is measured at a known distance from the axis of rotation. These devices are called dynamometers and they are most often used for measuring torque and power of motors and engines. There are two main types of dynamometers: transmission dynamometers and absorption dynamometers. (Britannica 2024) Transmission dynamometers measure shear strains on the rotating shaft to measure torque (Atkins & Escudier 2013b). The dynamometer itself doesn't put any load on the shaft of the motor, it measures the transmitted torque/power. Absorption dynamometers absorb the power accumulated during the measurement and typically disperse that as heat (Mulligan 2024). The few most common types of absorption dynamometers are introduced below.

2.1.1 Eddy current brake

An eddy current dynamometer works by braking the rotating shaft with electromagnetic induction. The dynamometer consists of two main components, a stationary magnet or an electromagnet and a rotating disc/rotor made from a conductive material. (Sinaga et al. 2019) When the disc rotates near the magnet, circulating eddy currents are induced in the disc according to Faraday's law of induction. According to Lenz's law, these currents generate their own magnetic fields that are opposing to the field of the magnet. This results in a force opposite to the rotation of the disc which slows the disc down. A cross–section of an eddy current dynamometer is shown in Figure 2.1.

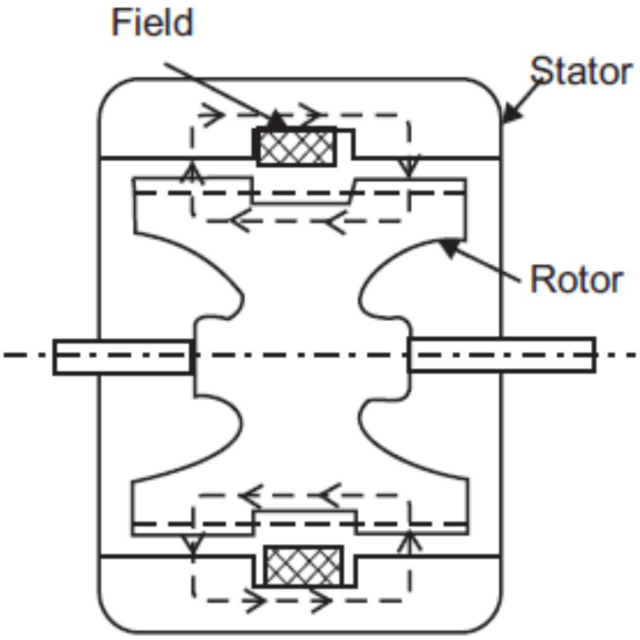

Figure 2.1. *An eddy current brake dynamometer (Mechtech Guru 2022).*

By altering the amount of current flowing in the electromagnet's coils the braking force can be accurately set for different applications. The downside of eddy current dynamometers is that they cannot provide braking force for a stationary shaft since the braking force is also proportional to the angular velocity of the rotating disc. (Martyr 2007, pp. 159–160)

2.1.2 Hydraulic brake

A hydraulic brake dynamometer uses water or oil to apply a braking force on the rotating shaft. The dynamometer consists of a cylindrical rotor attached to the shaft enclosed in the stator which is filled with water or oil. The rotor and the inside of the enclosure have thin sluice plates shaped in a way that generates toroidal circulation in the liquid. The toroidal circulations resist rotational motion. (Martyr 2007, pp. 154–157) Example of a hydraulic brake dynamometer is shown in Figure 2.2.

Hydraulic brake dynamometers come in two varieties: constant fill and variable fill machines. In constant fill machines, the braking torque is varied by altering the amount of sluice plates in the rotor and stator. Variable fill machine's torque is varied by altering the amount of water inside the casing. This allows the braking torque to be adjusted much more rapidly than with constant fill machines. (Martyr 2007, pp. 155–157)

Figure 2.2. *A hydraulic brake dynamometer (Taylor Dynamometer 2024).*

2.1.3 Hysteresis brake

A hysteresis brake dynamometer utilizes the hysteresis effect in magnetism to slow down the motor being tested. This type of dynamometer consists of two main parts: a steel rotor assembly and a stationary reticulated pole structure with a field coil or a permanent magnet. (mobac 2023) a Hysteresis brake structure is shown in Figure 2.3.

The field coil variant's rotor can spin freely when the coil is not energized. Once the coil is energized, a magnetizing force is applied to the pole structure which then turns the air gap between the rotor and the stator into a flux field, and the rotor becomes magnetically restrained. The applied torque is proportional to the current flowing through the coil. The permanent magnet variant provides a constant braking force without the need for energizing current but the braking force cannot be adjusted while in operation. The permanent magnet variant's torque can be adjusted to 30–40 % of the rated torque by physically changing the alignment of the pole structure in special designs. (mobac 2023)

Hysteresis brake dynamometers have a long life expectancy because they have no rapidly wearing parts. They have accurate and repeatable torque control and, a wide torque range from minimum (bearing friction) to 15–35 % over the rated torque limit. Many models can operate at speeds exceeding 10 000 RPM. (mobac 2023)

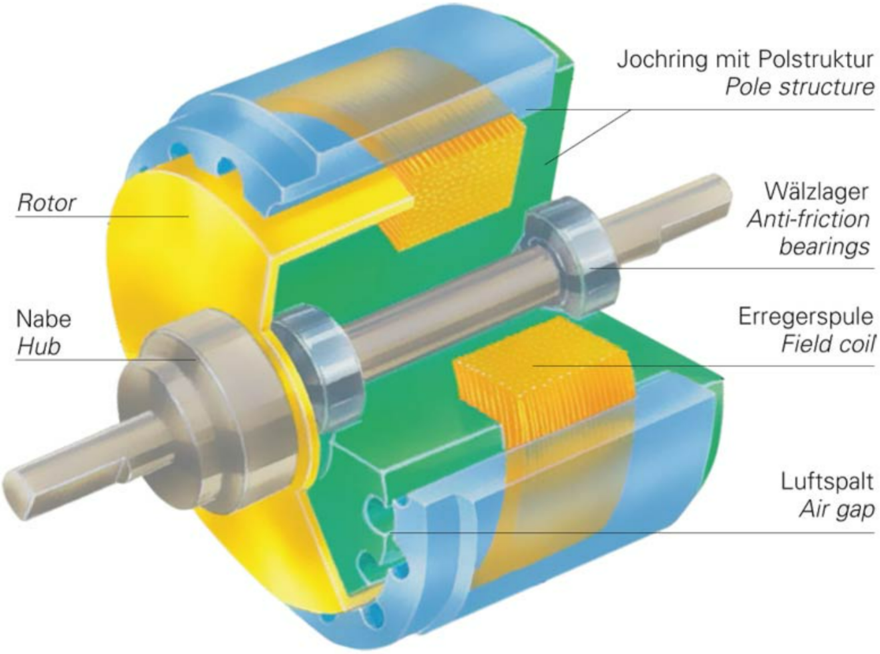

Figure 2.3. *A hysteresis brake dynamometer (mobac 2023).*

2.1.4 Prony brake

A Prony brake dynamometer was one of the first types of dynamometers to be invented. It was invented by a French engineer Gaspard–Francois–Clair–Marie Riche de Prony in 1821. Prony brake dynamometers use friction to put a load on the motor/engine being tested. An example of a typical early version of the Prony brake dynamometer is shown in Figure 2.4. It uses blocks tightened around the output shaft (A) (or around a pulley on the shaft) of the motor being tested. The blocks are tightened enough for the arm to stay in a horizontal position while the shaft is spinning. Then the torque of the motor can be calculated from the known hanging mass (E) and the distance from the hanging point to the center of the shaft. (Greenslade 1990, p. 340)

Another version of a Prony brake dynamometer is described by Morris and Langari (2012, pp. 491–492) to utilize a rope wrapped around the shaft of the motor. The top end of the rope is attached to a spring balance and the other end to a hanging mass, a dead load. This type of dynamometer is shown in Figure 2.5.

Prony brake dynamometers are not common anymore. The downside of friction–based dynamometers is that they generate a lot of heat which often requires active cooling. (Morris & Langari 2012, pp. 491–492) The benefits of a Prony brake dynamometer are simplicity, cost efficiency, and that they don't add any extra rotating mass to the motor being tested.

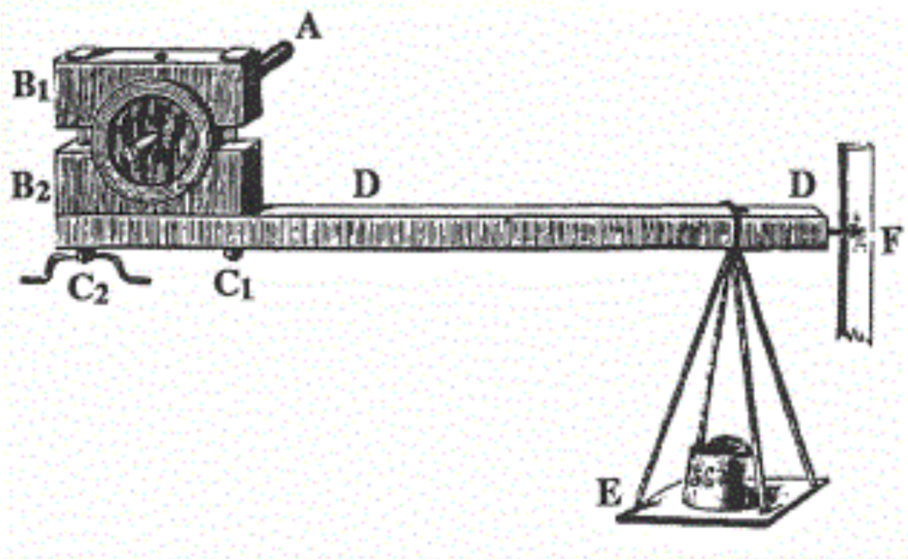

Figure 2.4. An early version of the Prony brake (Greenslade 1990, p. 340).

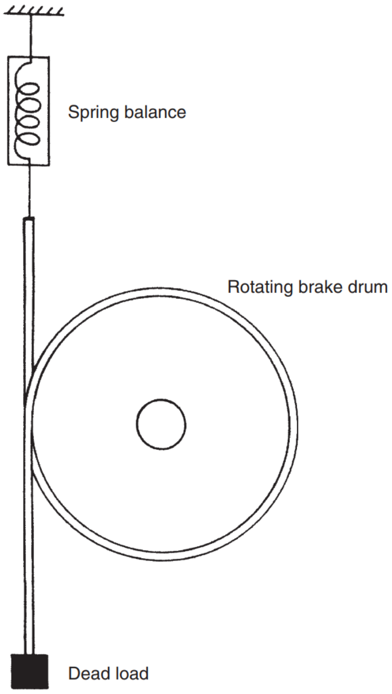

Figure 2.5. A Prony brake dynamometer (Morris & Langari 2012, p. 491).

2.2 Power

According to Garshelis (2014), power ($\mathbf{P}$) is the rate at which work is performed. The unit of power in the SI system is watt (W). 1 W = 1 J/s = 1 m · N/s. Before the definition of watt, power was measured in horsepower (Hp). 1 Hp is equivalent to 746 W. The formula to calculate power is

$$\mathbf{P} = \mathbf{T}\omega. \tag{2.1}$$

According to formula 2.1, only angular velocity (ω) needs to be measured alongside torque to calculate the power of a motor. Angular velocity can be measured with tachometers, optical sensors, Hall effect sensors, Wiegand effect sensors, and gyroscopes. The angular velocity of the motor's shaft is usually measured in revolutions per minute (RPM). (Pinney & Baker 2014) However, the unit of angular velocity in the SI system is radians per second (1/s) (IOMC 2024).

3. MEASUREMENT SETUP

The measurement setup to measure the pull–out and pull–in torque of small stepper motors is described in this chapter. The tested stepper motors are very small, only 6 mm in diameter and they don't have a lot of torque. Most dynamometer types add a lot of rotating mass to the shaft of the motor being tested. A large rotating mass on a small motor's shaft would affect the measurement results because of added inertia. The only dynamometer type researched that doesn't add any mass was the Prony brake dynamometer. A modern automated version of the Prony brake dynamometer was designed and built based on Sugawara Laboratories SMT–2 Stepper Motor Torque Tester (2024a).

3.1 General structure

The whole measurement setup was assembled on a Thorlabs breadboard which has an M6 threaded holes located every 25 mm in a rectangular grid pattern. The breadboard made it easy to mount every part of the system securely and precisely. Though all parts needed 3D printed adapter parts for mounting them to the breadboard. The dynamometer works using the same operating principle as the original Prony brake by applying a load to the motor with friction. Instead of a dead load hanging on an arm, a brake thread is wrapped around the shaft of the motor and attached to two force sensors from either end. One end of the brake thread is attached to a stationary force sensor and the other end to an identical force sensor mounted on a linear rail unit custom–made by Rollco. The linear rail unit is moved via a belt drive using a generic Nema 17 stepper motor to adjust the load on the stepper motor during measurements. The general structure of the measurement setup is shown in Figure 3.1.

The motor mount base was made from an aluminium extrusion cut to a V shape and the stepper motor was secured to the base with a 3D printed sleeve and an M3 bolt. The measurements can take up to 15 minutes so additional cooling for the motor is necessary to prevent overheating. The aluminium base does this by conducting heat away from the motor during measurements. The motor mount is shown in Figure 3.2.

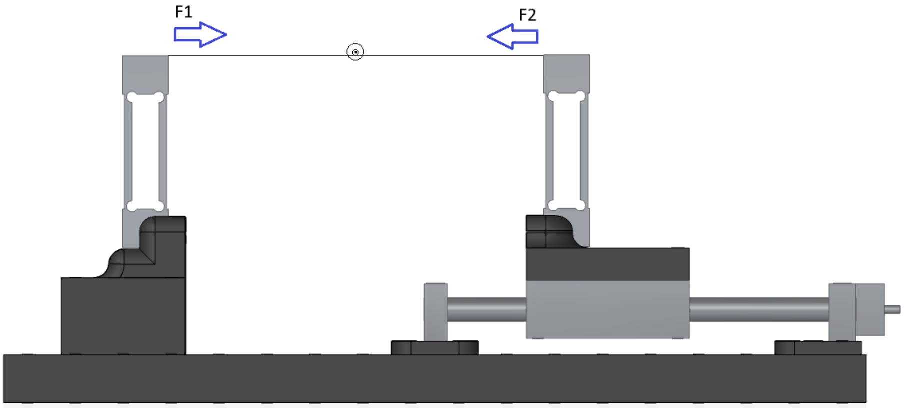

Figure 3.1. *The general structure of the dynamometer.*

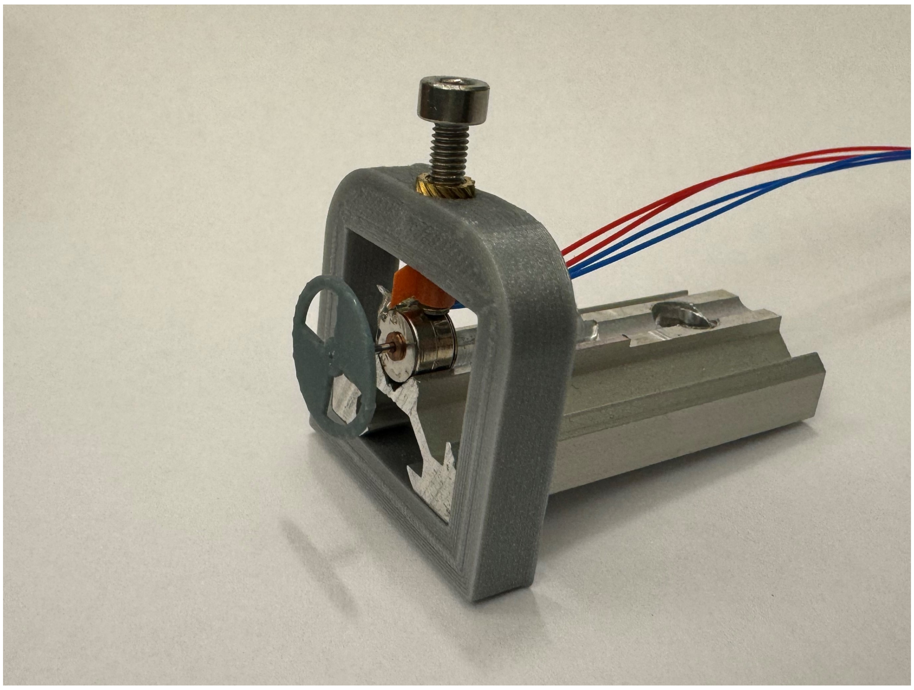

Figure 3.2. *A miniature stepper motor attached to the motor mount.*

3.2 Force measurement and calibration

The force is measured with two Variohm EuroSensor AL6B–L–0.3kg–0.4B load cells rated for about 3 N of force. The analog output from the load cells is amplified and converted to a digital signal with SparkFun HX711 load cell amplifiers.

Before measurements, the load cells were calibrated according to the manufacturer's instructions by mounting them horizontally and hanging a 200 g M1 class calibration weight from the end of the load cell. A raw reading was taken with and without the calibration weight. This provided ground truth measurement for a force equivalent to 1.962 N for all further measurements to be based on. The accuracy of the load cells in the lower range was also tested by hanging a 50 g M1 class calibration weight and confirming the correct reading.

3.3 Angular velocity measurement

Photo interrupters were used to measure the angular velocity of the tested stepper motors. Photo interrupters work by emitting light on one side and receiving it on the other side. They output a high or a low signal depending on whether the emitted light is received or not on the receiving side. (Aihara et al. 2021) An encoder wheel was placed on the shaft of the motor and the angular velocity could be calculated from the frequency of the photo interrupter signal and the amount of slits on the encoder wheel. The encoder wheel was designed and 3D printed to be as light as possible so it wouldn't add much inertia to the stepper motor's shaft and interfere with measurement results. The angular velocity measurement setup is shown in Figure 3.3.

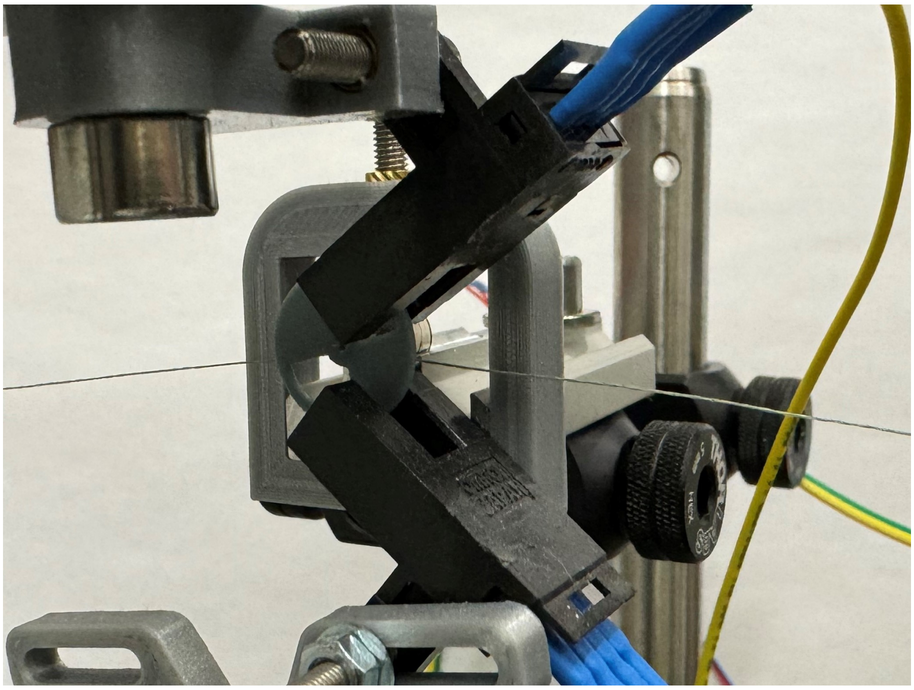

Figure 3.3. *The angular velocity measurement setup.*

Two photo interrupters were used instead of one because using only one would occasionally result in false angular velocity readings. The encoder wheel's slit edge would happen to be on the photo interrupter's sensing line and during torque measurement the stepper motor would vibrate the encoder wheel when trying to start rotating or after stalling, resulting in a high angular velocity reading even though it's not rotating. The two photo interrupters were positioned on the encoder wheel in a way that when the other is on the edge of a slit the other is not. This positioning eliminated all false angular velocity measurements.

3.4 Torque calculation

As discussed in Chapter 2, torque can be calculated by multiplying force by the distance from the force to the rotation axis. With this measurement setup torque is calculated as follows:

$$\mathbf{T} = (r + R)(\mathbf{F}_1 - \mathbf{F}_2), \tag{3.1}$$

where r is the radius of the brake thread, R is the radius of the stepper motor's shaft and $\mathbf{F}_1$ and $\mathbf{F}_2$ are force readings from the load cells.

Stepper motors have two types of torque characteristics: pull–out torque and pull–in torque. Pull–out torque is the amount of load the motor can handle when it's rotating without losing steps or stalling entirely. Pull–in torque is the amount of load that can be applied on the motor while it's stationary and it's still able to start rotating while the load is applied. Both torques are affected by the driving voltage and the pulse frequency the stepper motor is driven with.

3.5 Control system

The dynamometer's control system consists of a computer and three microcontrollers (Arduino Due, Uno and Micro) which control both stepper motors and read all the sensors. The computer is used to configure measurement parameters into the microcontroller (hereinafter MC) 1 via a serial connection. Measurement parameters include brake thread radius, motor shaft radius, and pulse frequency range to be measured.

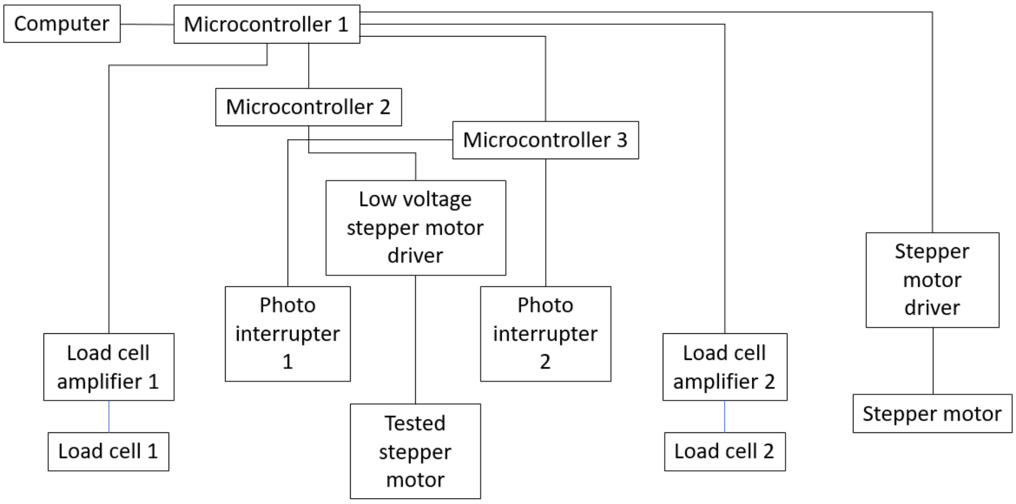

Figure 3.4. *A block diagram of the dynamometer control system.*

As seen in Figure 3.4 the MC1 functions as the main controller in the system. It communicates with both load cell amplifiers for force data, the load–adjusting stepper motor driver to control the load on the stepper motor being tested and communicates with MC1 and MC2. It also calculates and stores all torque measurement results and reports them back to the computer at the end of a measurement cycle.

MC2 and MC3 are dedicated to time–sensitive tasks; driving the tested stepper motor and measuring the stepper motor's angular velocity. The MC2 is used to command the STSPIN220 low voltage stepper motor driver to drive the tested stepper motor at a pulse frequency commanded by MC1. MC2 keeps driving the stepper until MC1 commands it to stop.

MC3 is used to measure the angular velocity of the tested stepper motor. It constantly monitors signals from the photo interrupters and calculates angular velocity. When measuring pull–out torque, MC3 sends a signal to the MC1 after it detects that the angular velocity has fallen below a set threshold. The threshold was set at 90 % of the target angular velocity. When measuring pull–in torque it signals MC1 if the stepper has started to rotate at the set pulse frequency or not.

Before starting the torque measurements, the measurement parameters are configured to MC1. After configuration, the dynamometer automatically measures pull–out and pull–in torque for all set pulse frequencies. A block diagram of the measurement process is shown in Figure 3.5.

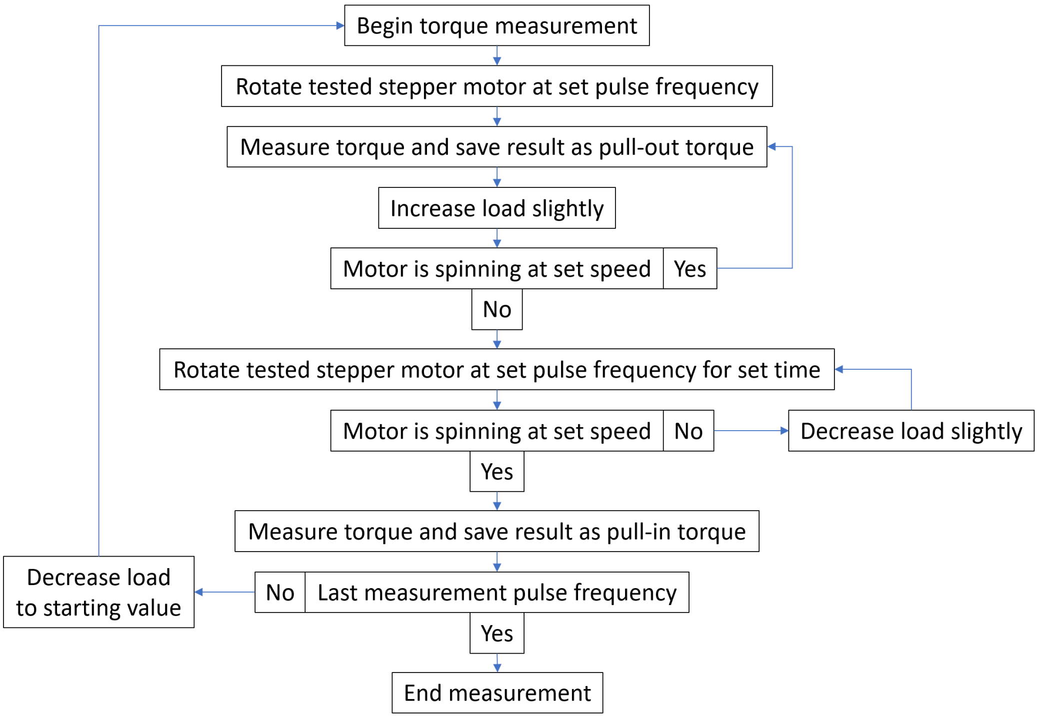

Figure 3.5. *A block diagram of the torque measurement process. Adapted from (Sugawara Laboratories 2024b).*

4. TESTS AND RESULTS

The torque and power of three miniature stepper motors was measured using the dynamometer introduced in Chapter 3. The measured stepper motor models were MinebeaMitsumi SMSSH6–F20, SMS6–F40 and SMH6–F20. The measurement results are presented and discussed in this chapter.

4.1 Torque

The torque of the stepper motors was measured in the pulse frequency range of 200-2800 Hz for SMSSH6–F20, 200–4300 Hz for SMS6–F40 and 200–2650 Hz for SMH6–F20. The driving voltage was 3 V for all stepper motors, as rated by the manufacturer. The torque measurement cycle was repeated four times for each stepper motor and an average of pull–out and pull–in torque was calculated for each pulse frequency. The torque measurement results are presented in Figures 4.1 - 4.3.

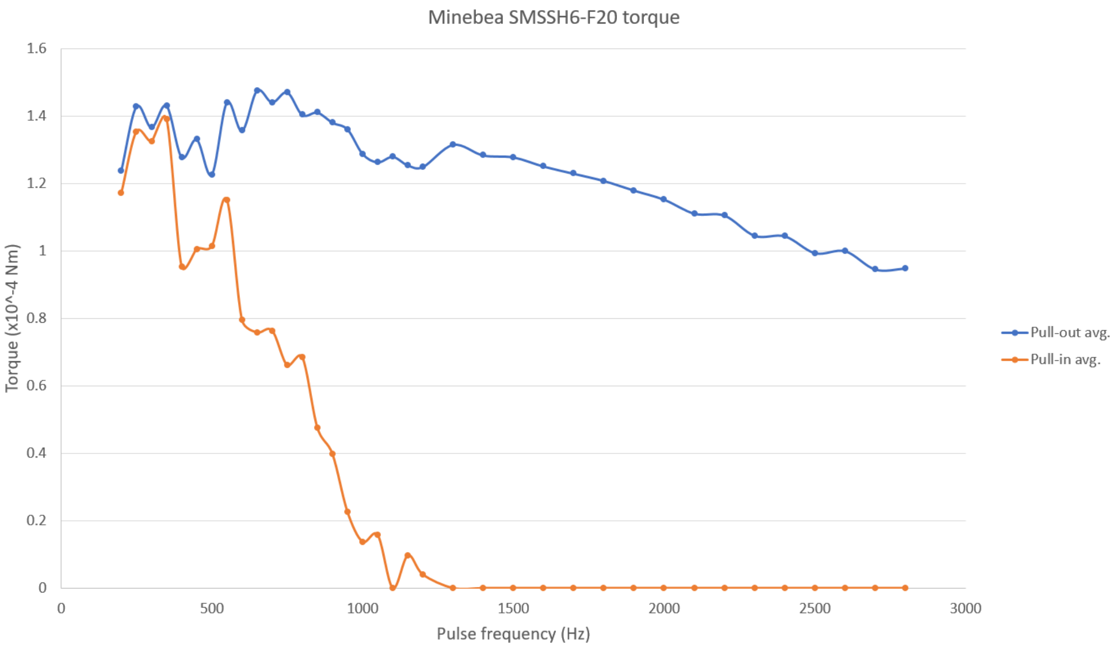

Figure 4.1. *The measured torque curves of MinebeaMitsumi SMSSH6–F20 stepper motor.*

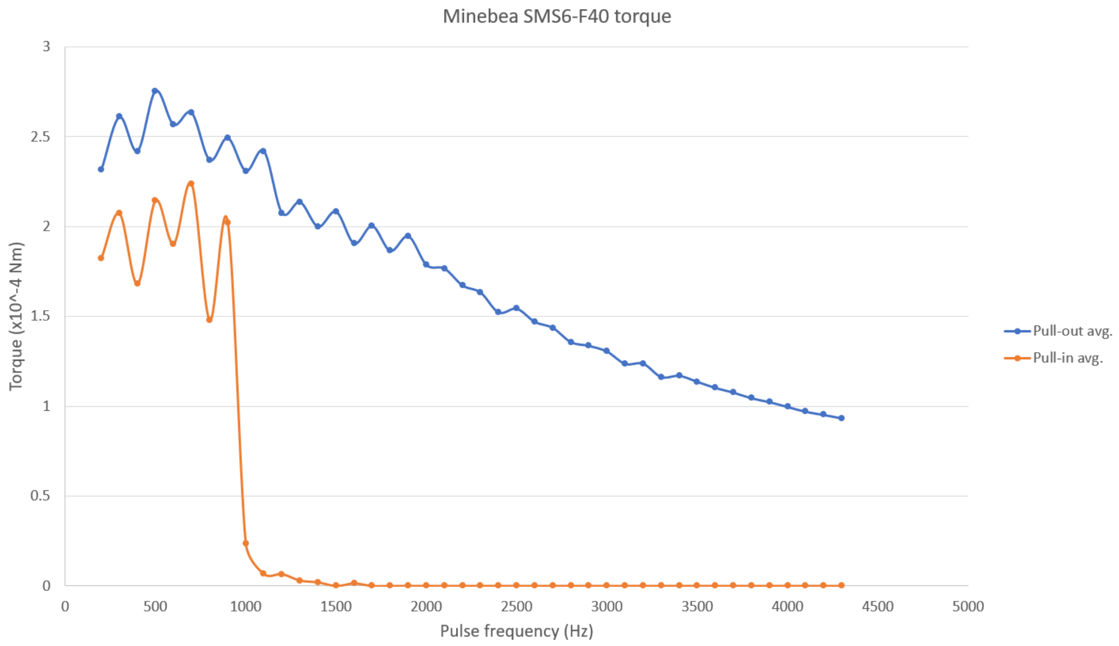

Figure 4.2. *The measured torque curves of MinebeaMitsumi SMS6–F40 stepper motor.*

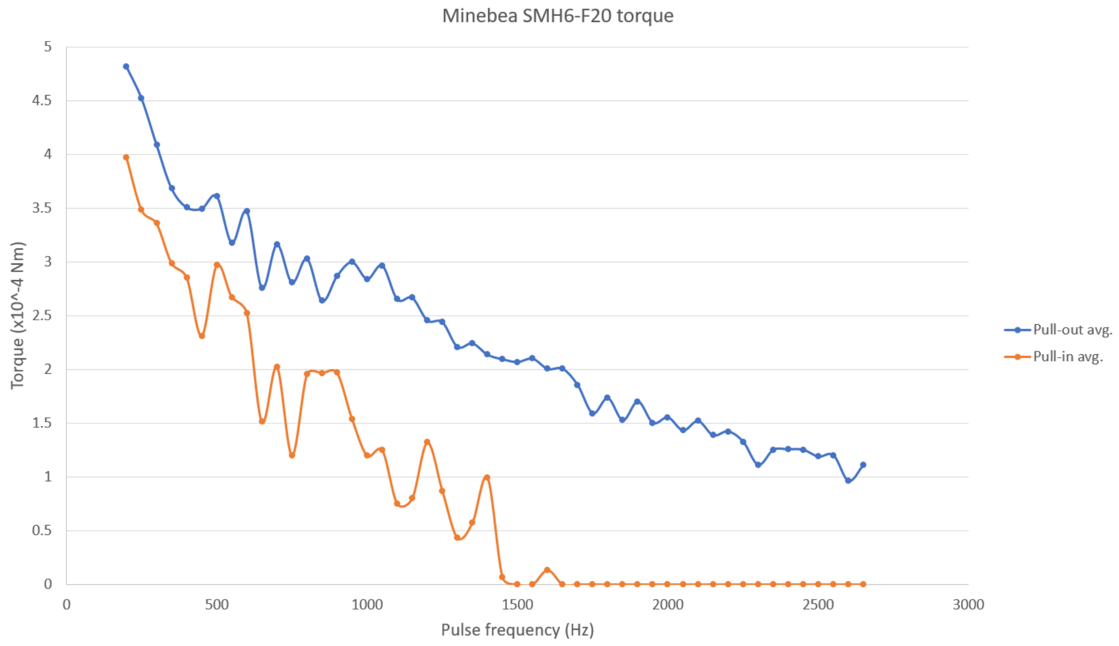

Figure 4.3. *The measured torque curves of MinebeaMitsumi SMH6–F20 stepper motor.*

4.2 Power

The power of the stepper motors was calculated from the measured average torque and pulse frequency. The power curves are presented in Figures 4.4 - 4.6.

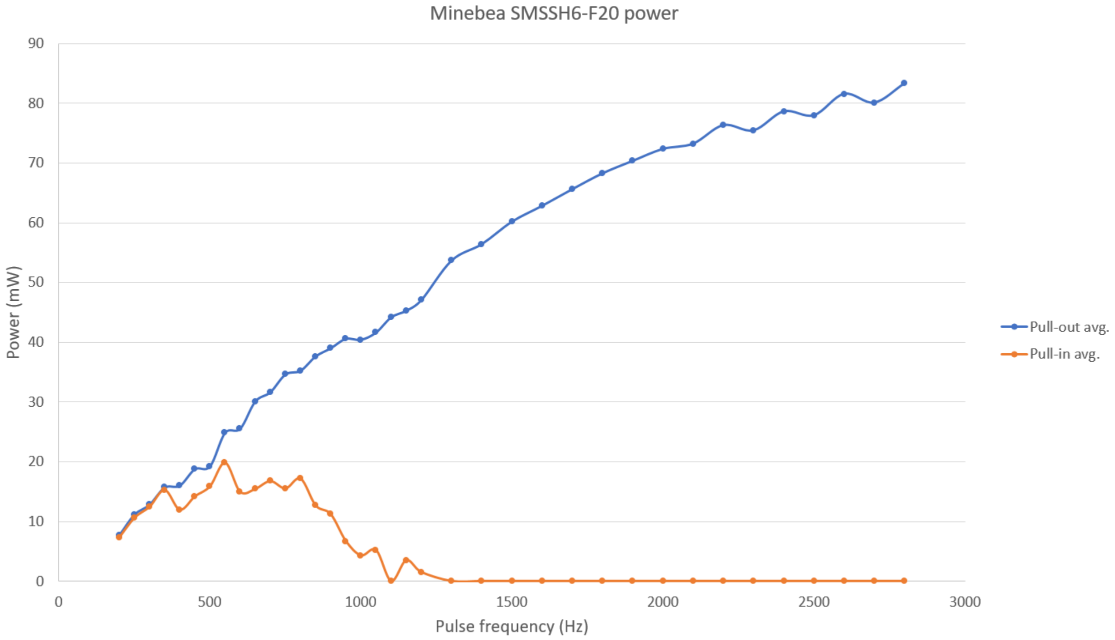

Figure 4.4. *The measured power curves of MinebeaMitsumi SMSSH6–F20 stepper motor.*

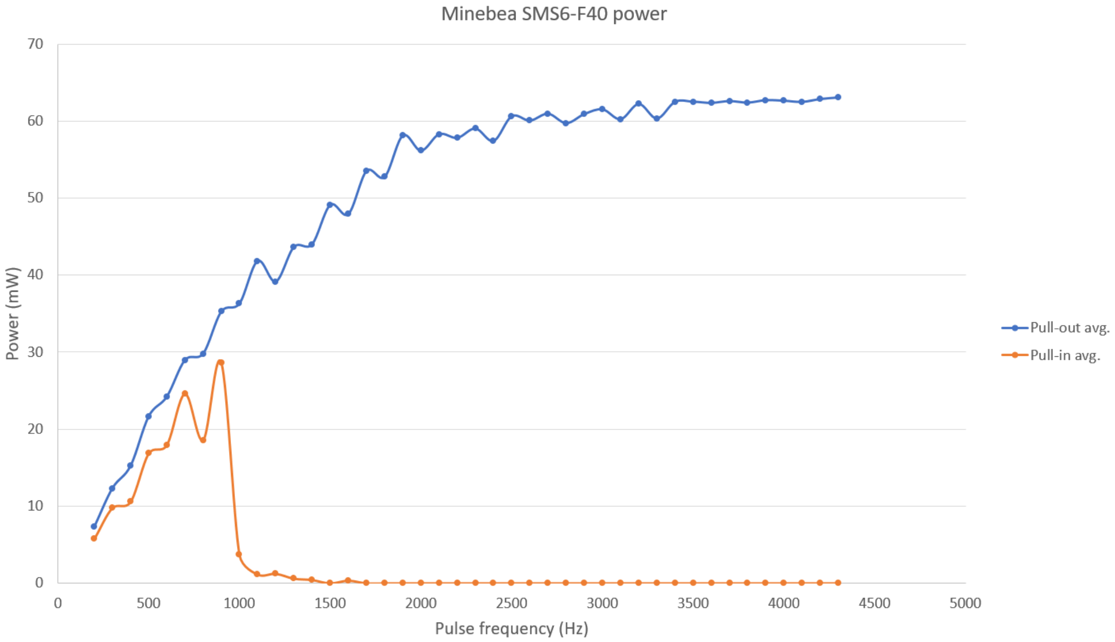

Figure 4.5. *The measured power curves of MinebeaMitsumi SMS6–F40 stepper motor.*

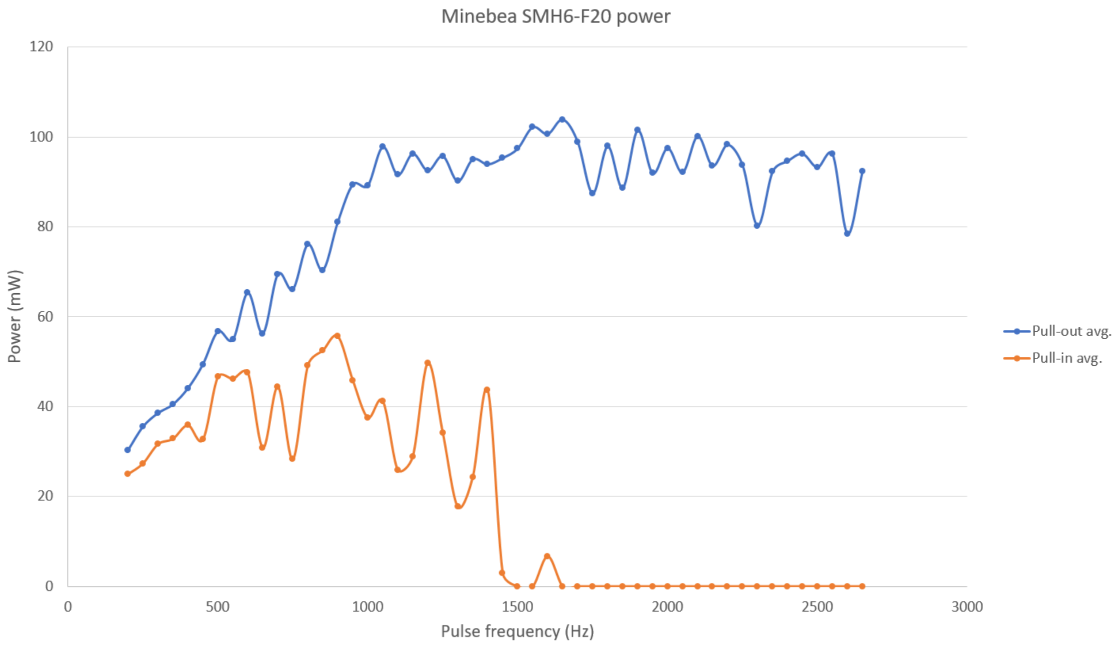

Figure 4.6. *The measured power curves of MinebeaMitsumi SMH6–F20 stepper motor.*

4.3 Discussion

The torque measurement results for the SMSSH6–F20 stepper motor showed some waviness in the pulse frequencies between 200 Hz and 1300 Hz. This was due to quite a bit of variance between the different measurement cycles, especially in the lower frequencies. In fact, all three stepper motor's torque measurement results displayed this same effect in the lower frequencies. When compared to the torque curve from the manufacturer's data sheet in Figure 4.7, the general shape and position of the pull–out torque curve match quite well. However, the pull–in torque curve slopes down to zero much earlier in the frequency range in the measured data.

Similar observations were made from the torque curves of the SMS6–F40 and SMH6–F20 stepper motors. When compared to the manufacturer's curves shown in Figures 4.8 and 4.9. The pull–out curve is similar to the manufacturer's curve, but peak torque is a bit higher in the measured data. The pull–in curve slopes down a lot earlier than on the data sheets also with these stepper motors.

The power curves of all three stepper motors show the same variations as the torque curves since they are calculated from the same data. The pull–out power curves increase as the pulse frequency increases. This indicates that stepper motors are more efficient when driven with higher frequencies because they use the same amount of electrical power regardless of the pulse frequency.

The variance in the measurement results between cycles could be caused by wear or overheating of the brake thread used to apply load on the tested stepper motors. The part of the thread that was around the shafts of the stepper motors looked polished after the measurements. This indicated that the coefficient of friction between the thread and the shaft didn't stay the same for the duration of the measurements. This issue could possibly be remedied for future measurements by changing the thread material to a different one and implementing a cooling solution to avoid the change in friction because of overheating.

The higher peak pull–out torque and early lowering pull–in torque of the stepper motors could be caused by the added inertia of the encoder wheel. Even though the encoder wheel is very light, it has a large diameter compared to the diameter of the stepper motors so the added inertia could be high enough to affect the results. To find out if the reason is inertia, a different method for measuring angular velocity would need to be implemented. A solution that doesn't add any inertia would be to use a stepper driver that can detect step loss. For measuring torque of stepper motors the angular velocity doesn't need to be measured. This is because stepper motors are synchronous motors so they rotate at the speed they are driven at as long as they are not overloaded. Unfortunately at the time of building the measurement setup, there were no stepper motor drivers available that could drive steppers at 3 V and detect step loss.

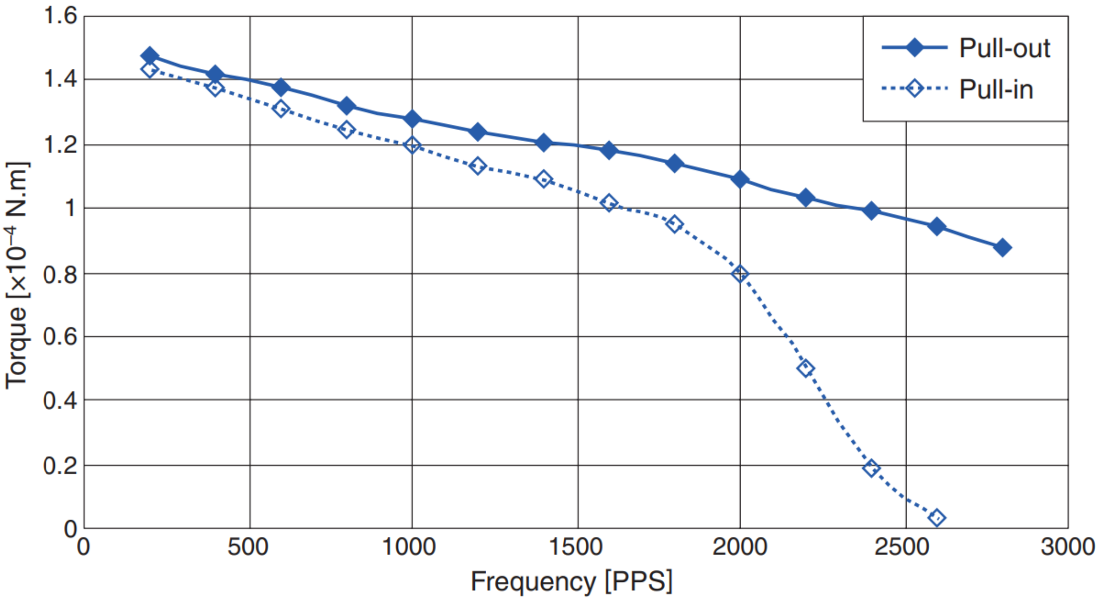

Figure 4.7. *The torque curves of MinebeaMitsumi SMSSH6–F20 stepper motor. (MinebeaMitsumi 2024)*

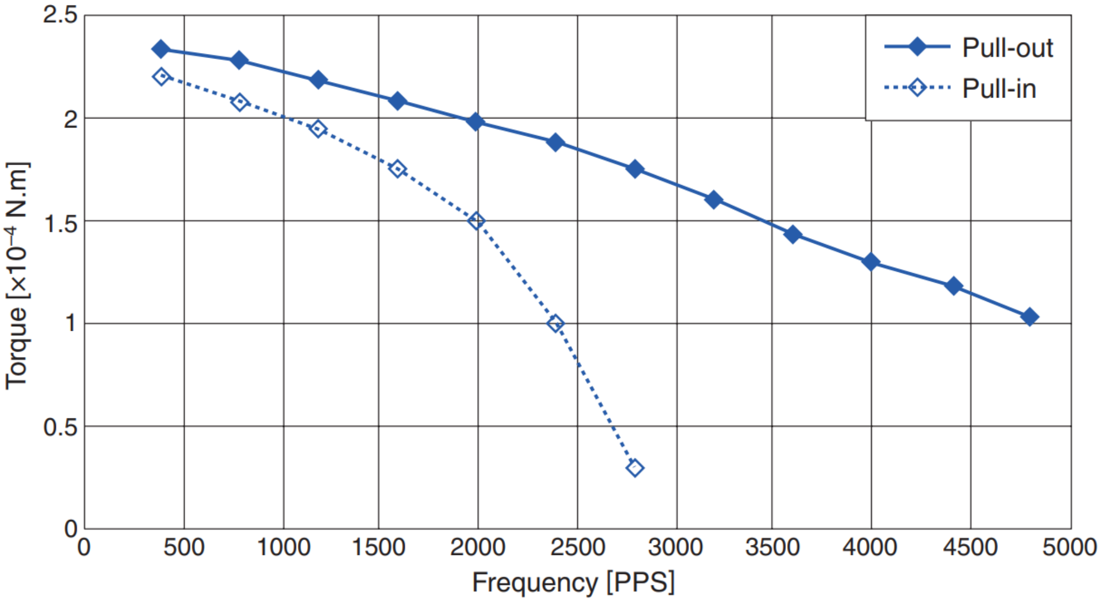

Figure 4.8. *The torque curves of MinebeaMitsumi SMS6–F40 stepper motor. (MinebeaMitsumi 2024)*

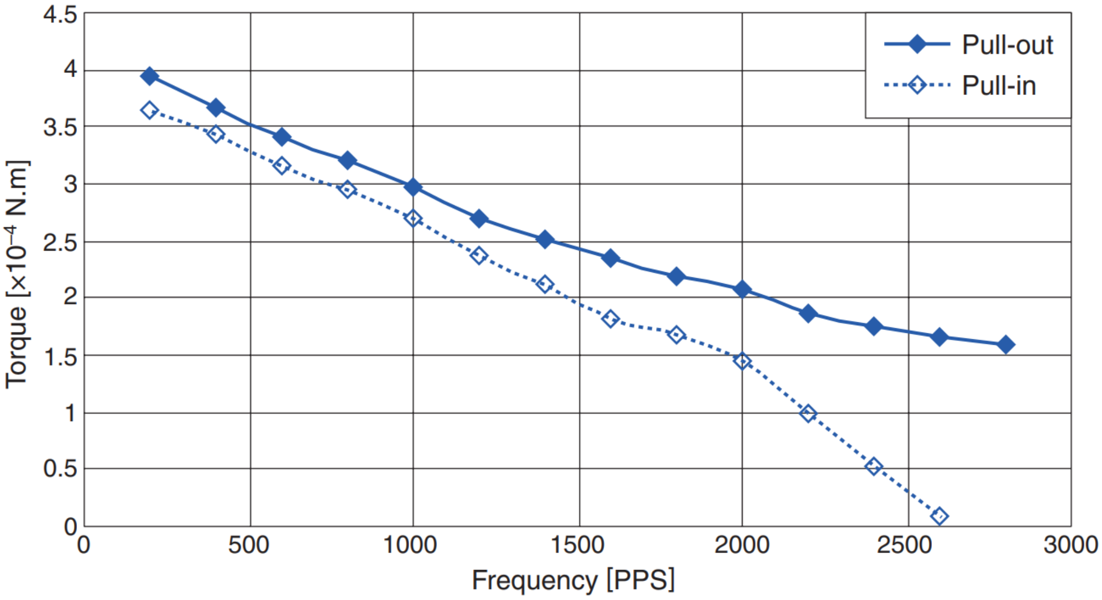

Figure 4.9. *The torque curves of MinebeaMitsumi SMH6–F20 stepper motor. (MinebeaMitsumi 2024)*

5. CONCLUSION

The designed and built dynamometer showed promising results for measuring the torque and power of miniature stepper motors. Because the measurement process was automated, the dynamometer was easy to operate. Although the measurement results did not line up exactly with the torque curves in the tested stepper motors' data sheets, the measurement setup could be used at its current state for getting a rough estimate of a stepper motor's torque and power.

In the future, the accuracy and repeatability of the dynamometer could be improved with a couple of hardware changes. The variance issue between measurement cycles could be fixed by changing the brake thread and adding a cooling solution. The accuracy could also be improved by changing the low–voltage stepper driver to a model with step loss detection.

Taking into account the amount of time and resources that were available for this study, it can be considered a success. Now there is an affordable and easily operable dynamometer that can be used for measuring the torque and power of miniature stepper motors.

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