

Mitigation of torque signal fluctuations in wear rig using digital filters and motor alternatives

Degree project report in Mechatronics Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
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Degree project report 2025
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Typeset in L^AT_EX
Gothenburg, Sweden 2025

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Abstract

In current modern industries, maximizing the lifespan and efficiency of machines is of a great importance to companies. A key factor in doing this is by understanding how different material influence the wear and performance on the machines. This is very important for Comminution Reimagined Sweden (CRS) since they work with machines that will experience change of material depending on where their machines are placed. To understand the effect of the material interactions, a torque sensor is used to gather data. That data is later on used for energy calculations. As of now, the torque signal is fluctuating in amplitude suspiciously much and this report investigates methods for reducing these torque fluctuations for CRS wear rigs, using digital filters and alternative motors as solutions. By analyzing frequencies and identifying the sources of these fluctuations, more precise solutions can be discovered. Various motors and digital filters are compared, to try and find a suitable solution to these fluctuations. The result of these studies indicates that a more suitable motor and digital filter in combination could significantly reduce the torque fluctuations. No real test have been done where a new motor and digital filter have been implemented and tested. The study therefore aims to provide a guidance for CRS on how future implementations can enhance the reliability of the torque signal.

Keywords: Torque ripple, magnetic cogging, cogging, fluctuations in torque signal.

Acknowledgements

We would like to express our sincere gratitude to all the employees at Comminution Reimagined Sweden (CRS) for providing us with such an engaging and insightful thesis experience. In particular, we extend our deepest thanks to Gustav Kolleby and Farshad Khorasani at CRS for their support in conducting tests and helping us grasp the complexity of the work.

Furthermore, we are grateful to our examiner, Magnus Evertsson, and our supervisor, Kanishk Bhadani, for their guidance in structuring the project and their support throughout the whole process. We would also like to thank Rob Maaskant and Godwin Peprah from Chalmers with their help with analyzing and confirming our data.

Anton Balder & Axel Magnusson , Gothenburg, June 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating current
BLDC	Brushless DC Motor
DC	Direct current
EMF	Electro magnetic field
FFT	Fast Fourier transform
LCM	Least common multiple
PMSM	Permanent Magnet Synchronous Motor
RPM	Revolutions per minute

Contents

List of Acronyms	ix
List of Figures	xiii
List of Tables	xiv
1 Introduction	3
1.1 Background	3
1.2 Purpose	4
1.3 Goals	5
1.4 Limitations / Demarcations	5
2 Theory	7
2.1 Operating Principles of Different Electric Motors	7
2.1.1 Direct current (DC) motors	7
2.1.2 Asynchronous motors (Induction motors)	9
2.1.3 Synchronous motors	10
2.1.3.1 Brushless direct current (BLDC) motor	10
2.1.3.2 Permanent magnet synchronous motor (PMSM)	10
2.2 Definition of torque ripple	12
2.2.1 Causes of torque ripple	12
2.2.1.1 Non-ideal back EMF	13
2.2.1.2 Magnetic circuit saturation	13
2.2.1.3 Magnetic cogging	13
2.3 MATLAB	14
2.4 Filters	14
2.4.1 Low-pass filter	14
2.4.2 Band stop/Notch filter	15
2.4.3 LabVIEW	15
3 Methods	17
3.1 Origin identification of torque fluctuation	17
3.1.1 Torque fluctuation frequencies	18
3.1.1.1 Mechanical rotation	18
3.1.1.2 Magnetic cogging	18
3.1.1.3 Electrical rotations	19
3.2 Researching different types of electric motors	19

3.3	Effect of signal enhancement	19
3.3.1	Torque ripple sampling	19
3.4	Methodology for choosing a new motor	20
3.4.1	Matrices used	20
3.5	Comparison of how different filters can be applied to improve the torque signal	20
3.6	Development of the customized filter	20
3.7	Test with a generated signal	20
3.8	Test with sampled raw data	21
4	Results	23
4.1	What caused the torque fluctuation?	23
4.1.1	Unknown frequency	26
4.2	Part 1	26
4.2.1	Motor design optimizations	26
4.2.2	Structured evaluation of motors using matrix methods	28
4.2.3	Elimination matrix	28
4.2.4	Pugh 1:5 matrix	29
4.2.5	Pugh 1:20 matrix	30
4.2.6	Pugh 1:2.5 matrix	31
4.2.7	Kesselring matrix	32
4.2.8	Which motor was best for our application	33
4.3	Part 2	34
4.3.1	Filtering techniques	34
5	Discussion	43
5.1	What can 280 Hz and its harmonics be?	43
5.2	Common problems in BLDC motors	43
5.3	Does the filter work too good?	43
5.4	The cost of a new motor compared to a customized filter	44
5.5	Further research	44
6	Conclusion	47
	Bibliography	49
A	MATLAB Code	I

List of Figures

1.1	Flow chart of the main components on the wear rig	4
2.1	Illustration of the basic construction of a DC motor [2].	8
2.2	Construction of two different types of PMSM [9].	11
2.3	Graph showing the periodic spikes in a fluctuating torque signal.	12
2.4	Frequency response of a bandstop filter, also known as a band reject filter [22].	15
3.1	Flow chart of methodology.	17
4.1	FFT of torque signal.	24
4.2	FFT of torque signal with high load intensity.	25
4.3	FFT of torque signal with low load intensity.	25
4.4	FFT of generated control signal.	34
4.5	FFT of filtered control signal.	35
4.6	FFT of torque signal based on small particles.	35
4.7	FFT of torque signal based on large particles.	36
4.8	Filtering out the mechanical noise and it's harmonics.	37
4.9	Filtering out torque ripple and its harmonics.	38
4.10	Filtering out the unknown/unwanted frequencies.	39
4.11	Original signal with low load intensity without filter.	40
4.12	Reduction of standard deviation when filter gets applied.	40

List of Tables

I	Frequencies causing problems	24
II	Motor Selection Criteria.	28
III	1:5 Gearbox.	29
IV	1:20 Gearbox.	30
V	1:2.5 Gearbox.	31
VI	Motor evaluation based on weighted criteria.	32
VII	Specifications for HDS6A-0104A.	33
VIII	Impact of occupancy-based adjustments on standard deviation, mean, and energy.	41
IX	Impact of particle size on standard deviation, mean, and energy. . . .	41

1

Introduction

This chapter introduces the project, outlines its objectives, and explains the underlying motivation.

1.1 Background

In today's industry, companies must maximize the usage and lifespan of their machines. An important factor in this regard is to be able to understand the wear characteristics in the components based on the material they are made of and the material they interact with during operation. This information gives insight into component wear, dimensioning of the components, a quantification of material losses, and specific energy requirements for the different material interactions. Besides potential performance improvements, this insight can help companies reduce cost, not only in the material selection but also by reducing maintenance costs due to knowledge of expected failure times, which can be used to perform service before an unplanned breakdown occurs.

This information is acquired by the use of sensors, which are used to measure the amount of torque that is affecting the drive shaft between the motor and the wear components. Besides the torque value measured, the torque signal can provide valuable insights into how the system performs in other regards, such as torque fluctuations generated from the motor and other types of oscillating components in the machine. This data is then used to evaluate the currently implemented motor to see if there are better motor options that would mitigate the fluctuating torque signal. In combination with potential motor alternatives, the effect of digital filters will be investigated to further be able to minimize the fluctuations. As shown below in Figure 1.1, a simple flowchart has been made to illustrate the main focus points for this project.

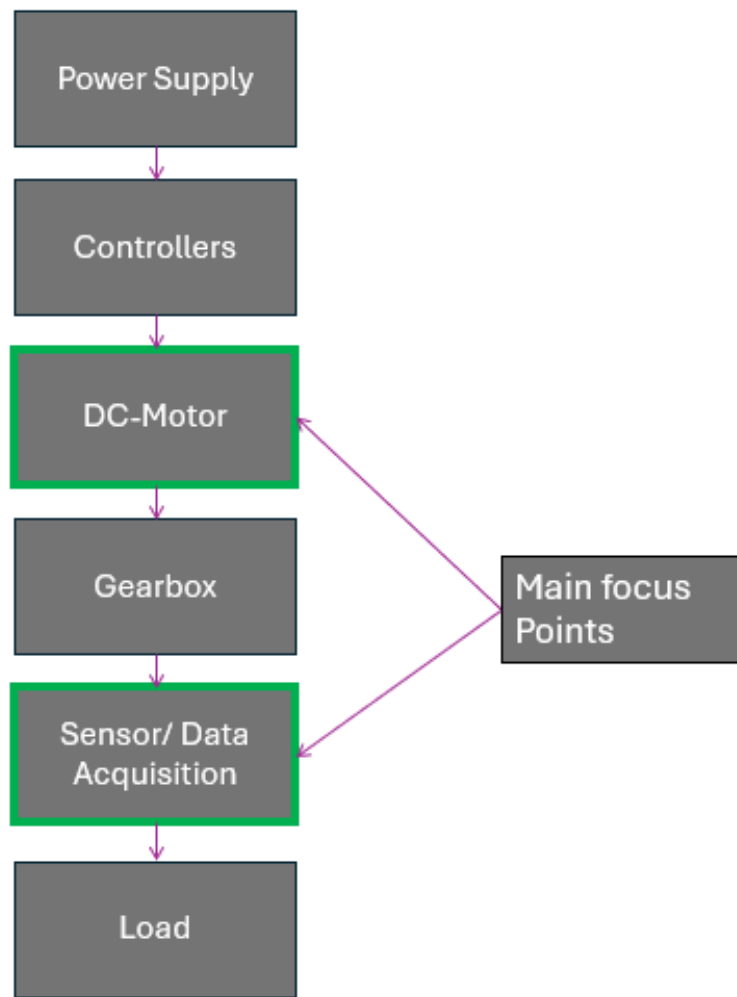


Figure 1.1: Flow chart of the main components on the wear rig

1.2 Purpose

The purpose of this project is to develop solutions that will ensure that the torque data gathered from the wear rig at Comminution Reimagined Sweden (CRS) is accurate and reliable without undesired fluctuation in the torque signal.

1.3 Goals

The goal is to identify and remove the undesired fluctuations in the torque signal and give CRS alternatives for a new motor that has the potential to further improve torque signal accuracy and provide them with insight on how to filter the signal going forward.

- Identify the sources of the torque fluctuations.
- Investigate electrical motor types that affect the torque signal with the least amount of fluctuation.
- Develop an approach for digital filtering of the torque signal.

1.4 Limitations / Demarcations

The project has been limited by a few points, which are as follows:

- Carried out during 20 weeks at a 50% work rate.
- Torque fluctuation investigation covers only the currently implemented BLDC motor.
- The digital filter provided will only give insight into what factors to consider and what filter types to use. Not a finished program.
- The proposed solution is intended solely for application in the existing wear rig setup and is not directly transferable to scaled or different systems.

2

Theory

This section will cover the background theory the this report, how different motors work, what problems they can experience, and also how a digital filter can alter signals.

2.1 Operating Principles of Different Electric Motors

This chapter presents an overview of the main types of electric motors that are most commonly found in industrial processes. This includes both Direct Current (DC) and alternating current (AC) motors.

2.1.1 Direct current (DC) motors

A direct current (DC) motor is a type of electric motor, like all electrical motors, that converts electrical energy to mechanical energy. A DC motor draws the electrical power through a direct current and converts this electrical energy into rotating mechanical energy. This type of motor is composed of the following main parts: an armature, stator, commutator, and sometimes also brushes [1]. The armature, also known as the rotor, is a cylindrical component that contains coil windings that are directly powered by the DC flowing through the motor. The rotor is the spinning part of the motor that rotates around the motor's axis, while the stator is a fixed part that either contains permanent magnets or electromagnetic windings responsible for creating the motor's magnetic field. It is the commutator's job to act as a switch for the current; it reverses the current direction in the rotor, altering the flux of the magnets, which in turn keeps the motor spinning in one direction cite . The last component is the brushes, which are carbon or graphite parts that transfer the current from an external circuit to the rotating commutator. All these components are illustrated in Figure 2.1 below.

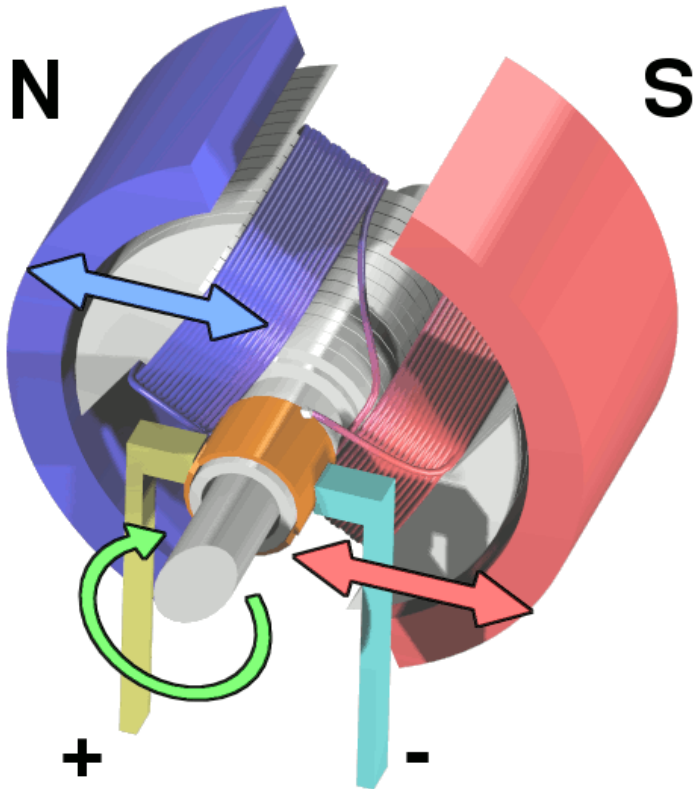


Figure 2.1: Illustration of the basic construction of a DC motor [2].

When an electric current is applied to the coils within the magnetic field from the magnets in the motor, the resulting magnetic force attracts and repels, which in different parts at different times, makes the rotor rotate [3]. This creates torque, which in turn leads to the DC motor starting to spin. It is the commutator that ensures that the current switches direction at the correct time depending on the rotor position. This keeps the torque moving in the same direction. The speed of the DC motor can be adjusted by altering the voltage applied to the motor. In the same way, the torque output of the motor can be adjusted by adjusting the current supplied to the motor.

2.1.2 Asynchronous motors (Induction motors)

An induction motor, also known as an asynchronous motor, is an alternating current (AC) motor that generates a magnetic field by running an AC current to the stator in the motor [4]. This will induce a current in the rotor, which in turn creates its own magnetic field in the opposite direction. The interaction between these magnetic fields results in a force that causes the motor to spin.

There are two different types of induction motors, single-phase and three-phase. The single-phase induction motor contains only two wire windings and only uses one alternating voltage to create a rotating magnetic field [5]. As the single-phase induction motor only has one magnetic field that constantly opposes itself, no resulting force is created, which makes the rotor remain stationary. This means the single-phase induction motor will need some type of external starting mechanism. Since this results in that they produce a quite low torque, they are most commonly used in household appliances, rather than in industrial settings.

The three-phase induction motors consist of three separate wire windings placed 120° degrees from each other. The three wire windings naturally produce a torque-generating magnetic field due to this offset in phase. They are therefore known as a self-starting motor. This improves efficiency and makes the design of the motor easier [5]. Three-phase induction motors produce a higher torque compared to a single phase motor, hence making them more suitable for industrial use.

2.1.3 Synchronous motors

The synchronous motor is a type of motor where the speed of the rotor is the same as the speed of the rotating magnetic field induced by the stator. A synchronous motor is very similar to an induction motor [6]. The main difference is the relative speed of the rotor and stator. The synchronous motor's rotor and stator have the same speed, whereas the asynchronous motor has a rotor that spins slower than the magnetic field generated from the stator. A synchronous motor is usually an AC motor, but there are exceptions, such as brushless direct current (BLDC) motors.

2.1.3.1 Brushless direct current (BLDC) motor

A brushless direct current (BLDC) motor is a synchronous motor that uses direct current (DC) as a power source. Compared to a normal DC motor, the BLDC does not use any type of brushes or commutators. The BLDC motor consists of three main parts: the stator, rotor, and the electronic controller. The stator is the stationary part of the motor, whilst the rotor is rotating within the motor [7]. The rotor is made up of magnets that rotate due to the interaction with the stator's magnetic field. Since the BLDC does not use any brushes or commutator, it needs an electronic controller to control the direction of the current [8]. This results in the motor having better control and lower energy consumption, compared to normal DC motors.

2.1.3.2 Permanent magnet synchronous motor (PMSM)

PMSM electric motors are also a type of synchronous motor, they are a three-phase AC motor. The rotor of a PMSM is made up of permanent magnets, or has permanent magnets attached to it [9], this is shown below in Figure 2.2. Since the permanent magnets provide a constant magnetic flux that the stator can interact with, the motor can produce torque, even at very low speeds. The most suitable processes to use a PMSM motor are where high-speed control and high efficiency are needed [10]. As a result of this, they are used in industries such as iron making and the petroleum industry [10].

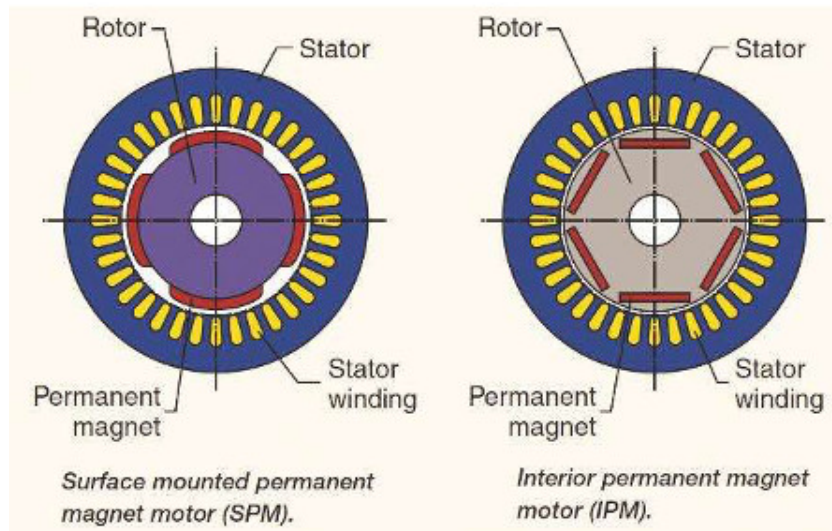


Figure 2.2: Construction of two different types of PMSM [9].

2.2 Definition of torque ripple

Torque ripple is a phenomenon where the torque output of an electric motor fluctuates while it is spinning. This can be seen if you plot the torque output as periodic spikes in the torque output, it is often referred to as a "non-constant torque signal" [14]. This is shown below in Figure 2.3 , where the torque is not constant and is fluctuating periodically. The torque ripple can be defined as the distance between the highest and lowest torque peaks in the signal. Torque ripple can be most commonly seen in a signal where the motor is running at low speed. This is because when the motor is spinning at a higher RPM, the higher inertia created by the speed will dampen the effect of torque ripple [14]. Torque ripple is, as described earlier, a form of undesired noise that can impact the readings for some applications. This can be seen very clearly where you have applications that require very precise and accurate torque measurements. Torque ripple can be reduced by improving the pole design of the motor. However, the more preferred method of reducing torque ripple is by implementing different types of control algorithms [15]. Since a redesign of the motor often comes at a higher cost and a delay in production.

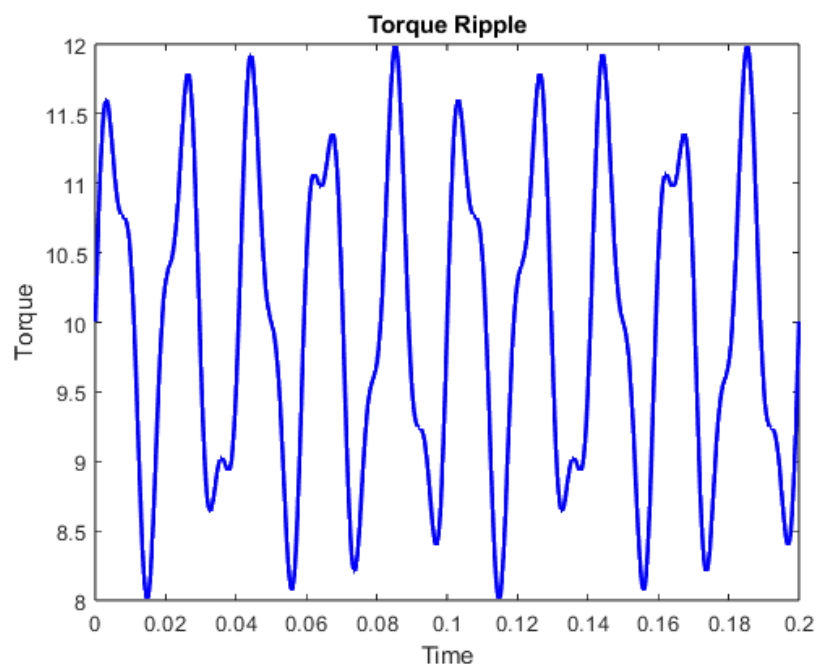


Figure 2.3: Graph showing the periodic spikes in a fluctuating torque signal.

2.2.1 Causes of torque ripple

Torque ripple is a form of noise that can come from many different types of sources. However, the three main causes of torque ripple are said to be [15], non-ideal back electromotive force (EMF) waveforms, saturation of the machine's magnetic circuit, and magnetic cogging. There can be different amounts of torque ripple in different types of motors, and the causes for torque ripple can also vary in different motors. Some types of motors are more prone to having torque ripple, due to their design

[15]. BLDC motors are one of these motor types that are known to experience torque ripple more than other others. Most of the torque ripple in the BLDC-motors comes from the cogging torque in the motor, and because of the trapezoidal back-EMF wave used to control the motor.

2.2.1.1 Non-ideal back EMF

Back EMF waves are voltages created that act in the opposite direction of the applied voltage [16]. The back EMF is generated when the unexcited coils in the stator are affected by the rotating permanent magnets in the rotor. This creates a force acting in the opposite direction, which in turn causes the fluctuating output torque. The back EMF voltage is always lower than the voltage applied to the motor.

2.2.1.2 Magnetic circuit saturation

Saturation of the machine's magnetic circuit is not as common a cause of torque ripple since the design of the motor is often built in a way to mitigate that as a potential source of ripple. However, when saturation in the magnetic circuit occurs, the magnetic flux has to find alternative ways to flow between the magnetic poles. This impacts the density of the magnetic flux and, therefore, the torque as well.

2.2.1.3 Magnetic cogging

Magnetic cogging is an undesirable effect on the torque output of electric motors. It originates from the interaction between the permanent magnets in the rotor and the stator teeth. [11]. This will result in fluctuations in the magnetic reluctance as the rotor is rotating. As the motor spins, the magnets in the rotor wants to align themselves with the stator teeth where the minimum reluctance occurs [12]. The torque fluctuations are more noticeable when the motor runs at lower speeds since there is less inertia from the rotor to overcome the magnetic "bumps." When the motor increases in speed, the inertia increases, and the effects from the magnetic cogging smooth out and become less noticeable. Besides making the torque output fluctuate, the cogging might also lead to faster wear of other components, such as bearings, due to the vibrations introduced in the system [12].

Magnetic cogging is common in motors, especially motors using permanent magnets, and over the years, multiple solutions have been implemented to reduce cogging in electric motors. The most common way is to use a reduction algorithm in the control unit to minimize the effect of the cogging by modulating the voltage depending on the rotor position. [11]. This may help with reducing the cogging, but not make it disappear. The best way is to redesign the motor itself. Optimizing the slot and pole combination will result in better performance in regard to the cogging effect. This is because some slot and pole combinations produce less cogging, but this can often lead to decreased performance in torque and speed [13]. Another method to reduce magnetic cogging is by reducing the strength of the magnets used in the motor. Since the magnetic cogging is directly connected to the magnetic field created by the magnets. However, these fixes come at a cost of lower torque output.

2.3 MATLAB

MATLAB is a programming language and environment designed to do numerical computing and data analysis. It can be used to simulate signals, plot data, and have many built-in toolboxes for specialized tasks such as signal enhancement and optimization [20].

2.4 Filters

A signal of any kind can be broken down into a range of overlapping frequencies with varying amplitudes. When sampling a signal, every frequency less than half of the sampling frequency can be recreated without distortion, this is called the Nyquist theorem. The ones outside of the range are going to be affected by aliasing [21]. It is the job of the filter to attenuate or completely remove the unwanted frequencies that are not a part of the system one wants to measure. These unwanted frequencies are often referred to as *noise*. A filter is defined by its cutoff frequency, pass band, transition band, and stop band. The pass band is the range of the unaffected frequencies, whereas the stop band is the range of frequencies that are attenuated. The transition band is the region between the pass band and the stop band where the cut-off frequency is where the attenuation is -3dB. There are a number of different types of filters in the following chapters; the band-stop filter and the low-pass filter are going to be explained [22].

2.4.1 Low-pass filter

A low-pass filter is designed in a way where lower frequencies pass through the filter unaffected, and the higher frequencies get attenuated [22]. There are two main types of low-pass filters, analog and digital filters. The analog filters are built using resistors, capacitors, or inductors, they are often used in hardware circuits. The digital filters are software-based and use algorithms to filter out unwanted frequencies.

2.4.2 Band stop/Notch filter

A band stop/notch filter is created by implementing two pass bands where the stop band is in between the two. This creates (depending on the design) a narrow region of frequencies that gets attenuated. This filter is very useful when filtering out specific frequencies in a signal [22]. As shown below in Figure 2.4 the bandstop filter attenuates a specific frequency range that the user chooses. Filtering out this specific bandwidth and allowing all the other frequencies to pass.

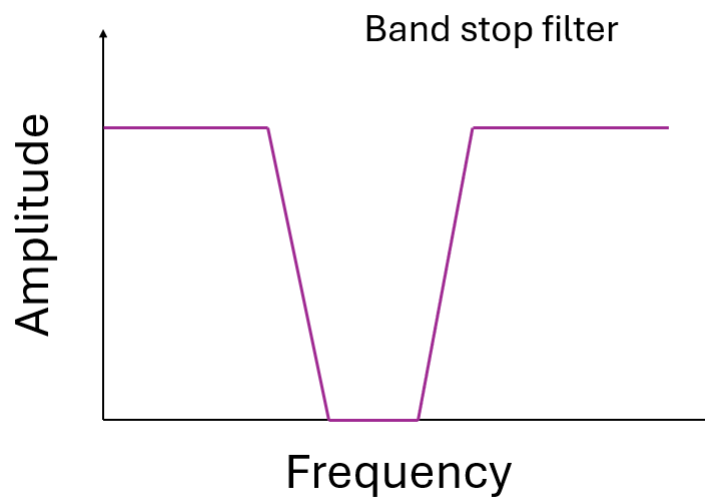


Figure 2.4: Frequency response of a bandstop filter, also known as a band reject filter [22].

2.4.3 LabVIEW

LabVIEW is a graphical programming environment designed by National Instruments, NI for short. It is mainly used for visualizing and analyzing data. It can also be used to perform tasks such as measuring and controlling different types of systems [23].

3

Methods

This chapter covers the an overview of which methods used in the project. This is also shown below in Figure 3.1, where a flowchart of the methods chapter is illustrated.

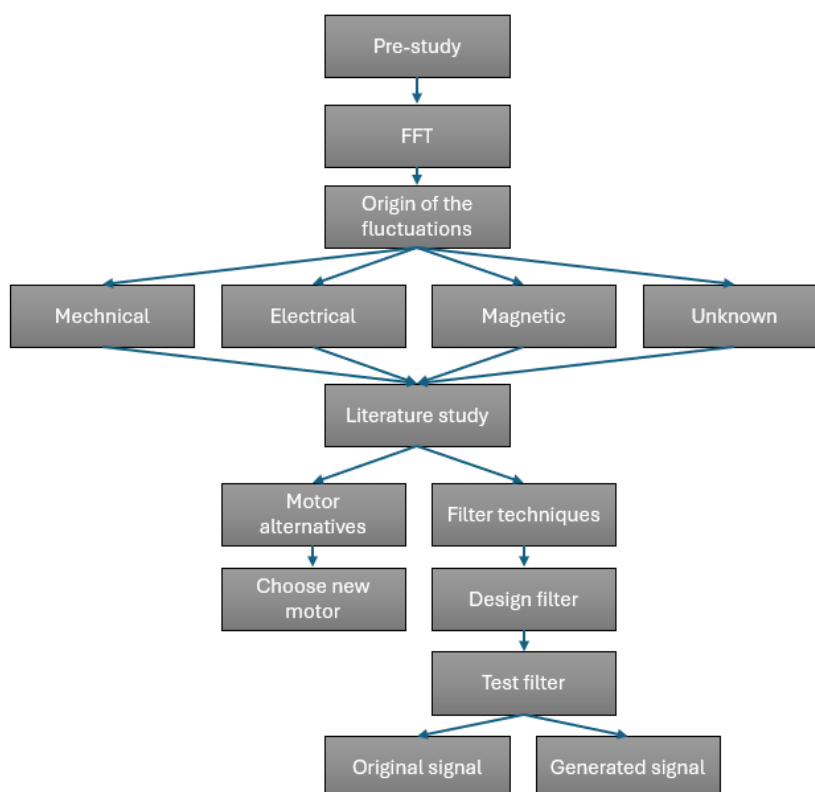


Figure 3.1: Flow chart of methodology.

3.1 Origin identification of torque fluctuation

As stated in chapter 2.2, the design of the electrical motor and the interaction of its components are the main contributing factors to the fluctuating torque in the motor and are an intrinsic effect in electrical motors. In the majority of cases, this is not an issue, but due to the very high precision goals for this application, these small but noticeable fluctuations in the torque signal needed to be dealt with.

The main process of identifying the unwanted frequencies in the torque signal was by utilizing the Fast Fourier Transform (FFT). By applying FFT on the sampled torque output signal, the signal gets converted from the time domain to the frequency domain. This breaks up the original signal into each frequency and their corresponding amplitude that the analyzed signal consists of and enables identification of the unwanted frequencies (noise).

The unwanted frequencies can be determined by running the wear rig in different scenarios (idle, with load, without gearbox, and idle without gearbox) and identifying the frequencies that was included with relatively high amplitudes in all of the FFT:s regardless of drive scenario (compensated for the gearbox reduction for those runs with gearbox mounted). These frequencies can, with relatively high confidence, be interpreted as noise since they are not a part of the signal that originates from the load, which is the relevant information this rig is built to investigate. When these frequencies have been identified, the next step is to research their origin by looking at the current motor design and how it is controlled.

3.1.1 Torque fluctuation frequencies

To determine the origin of the unwanted frequencies, there are some noise sources that needs to be investigated and is described in the sections below.

3.1.1.1 Mechanical rotation

In a perfect world without imperfections, the mechanical part of a symmetric component or system would not be an issue, but since that is not the case, it needs to be dealt with. If there is some part of asymmetry in the rotating shaft that the torque sensor is mounted on, or if the motor is slightly off center, the speed at which the shaft/motor rotates will show up in the FFT as a result of the imbalance. The frequency can be calculated using the following formula:

$$\text{Rotational frequency (Motor)} = \frac{\text{Revolutions per minute}}{60} \quad (3.1)$$

$$\text{Rotational frequency (Shaft)} = \frac{\text{Frequency (motor)}}{\text{Gear box reduction}} \quad (3.2)$$

3.1.1.2 Magnetic cogging

When the magnets in the rotor passes the windings in the stator, an electromotive force is generated and results in a fluctuating torque curve. The frequency this happens at, can be calculated by determining the least common multiple of the number of magnets in the rotor and the number of stator slots, and then multiplying that with the rotational speed of the motor [24].

$$\text{Cogging frequency} = \frac{\text{LCM}(\text{rotor magnets, stator slots})}{\text{rotor magnets}} \times \text{Rotational frequency (Motor)} \quad (3.3)$$

3.1.1.3 Electrical rotations

The imbalance in the mechanical rotations can give rise to fluctuations captured by the torque sensor, the same can happen due to the electrical rotations. In the motor, the stator turns on and off different stator windings in different ways to create an electromagnetic force that interacts with the rotor, which results in mechanical rotation of the rotor. It is therefore relevant to consider the stator activations when analyzing the FFT. The electrical rotational frequency corresponds to the number of magnetic poles in the rotor and can be calculated using the following formula [25]:

$$\text{Electrical frequency} = \frac{\text{Rotor magnets}}{2} \times \text{Rotational frequency (Motor)} \quad (3.4)$$

3.2 Researching different types of electric motors

The focus was put on researching different types of motors that would reduce the effect of the motor-related noise. This started by researching about how and why a signal can fluctuate and if the fluctuations originates from the mechanical system, the electronics or a combination of the two. These were some of the questions that were researched on when it comes to why a torque signal is fluctuating. This research was mostly done in google scholar and also using ordinary Google.

3.3 Effect of signal enhancement

At the beginning of the project, it was also determined that signal enhancement using digital filters could be a complement to motor alterations to reduce the noise seen in the torque signal. Since a cleaner filtered torque signal leads to a more reliable reading for torque measurement and data gathering. By using the data that was imported from LabVIEW and displayed in Matlab, the work started by using FFT as described in chapter 3.1.

3.3.1 Torque ripple sampling

Since the torque signal sampled in this application is far from a constant value, it is very difficult to know which values of the output signal are torque ripple and what the actual torque generated by the load is. It is therefore crucial to know what frequencies torque ripple occurs at. This is made possible by having a high enough sample rate on the torque sensor [17]. By following the Nyquist criteria, which states that the sample rate needs to be at least double the frequency of the sampled signal, it is possible to recreate the complete signal without aliasing [18]. Since torque ripple and its frequencies are hard to differentiate from the actual torque signal [19], it is also hard to determine the long-term effect that the oscillations will have on the life span of different rig components.

3.4 Methodology for choosing a new motor

To determine which new motor would be most suited for the wear rig, a structured decision-making approach was used, using multiple evaluation matrices. This will minimize personal bias and make the motor evaluation more systematic and transparent.

3.4.1 Matrices used

Elimination: Used as an initial screening tool.

Pugh: Provided a new perspective on how different gear ratios would impact the motor selection process.

Kesselring: Used to make the final evaluation between the motors.

3.5 Comparison of how different filters can be applied to improve the torque signal

At first, a lot of different filters were explored and evaluated to see which one would suit the application the best. Low pass, high pass, band pass, Butterworth, and band stop filters were evaluated. Some filters were dismissed quite early, since they would not fit the application, nor filter out just the unwanted frequencies. High pass and band pass were taken out of consideration by this criteria. Both low-pass and band-stop/notch filters were tested to see which one would perform the filtering of the signal the best. It was determined that a band-stop filter would suit this type of application best, since when using a band-stop filter, it is possible to control which frequencies to filter out and which ones to keep. The low-pass filters only remove frequencies above a certain threshold and leave the lower ones as unaffected as possible. The effect of the filter was measured by comparing the standard deviations of the signal and by comparing the energy using company-developed programs. The energy calculation program provided by CRS was primarily used to save time, but also to ensure that the results are only affected by the filtering, not the energy calculations process itself.

3.6 Development of the customized filter

To be able to pin point and just filter out the unwanted frequencies, a customized filter was created. This filter was designed by applying a band stop filter on just the undesired fundamental frequencies and their four first harmonics.

3.7 Test with a generated signal

To validate if the filter is working as intended, a fully generated signal was created to see how and which frequencies are being filtered out. This was done by using MATLAB and generating a signal consisting of all the frequencies from 0 Hz to half the

sample rate of the torque sensor, with all of them having the same amplitude. The filter was then applied to the generated custom signal to be evaluated by comparing the unfiltered signal to the filtered signal using FFT.

3.8 Test with sampled raw data

Multiple tests of the filter were performed, where the data came from multiple tests performed by CRS. The signals had different characteristics based on unique load cases and were used to determine filter performance based on reduction in standard deviation, and also to confirming correct frequency elimination using FFT.

4

Results

This chapter contains the results achieved throughout the course of the project.

4.1 What caused the torque fluctuation?

As covered in chapter 3.1, the mechanical imbalance, electronic rotations, and magnetic cogging were likely to be the main causes for the unwanted fluctuations in the torque signal. By using formulas 3.1-3.4 from the same chapter, their corresponding frequencies could be calculated. The calculations can be seen below:

$$\text{Equation 3.1} \Rightarrow \text{Rotational frequency (Motor)} = \frac{1000}{60} = 16.67 \text{ Hz} \quad (4.1)$$

$$\text{Equation 3.2} \Rightarrow \text{Rotational frequency (Shaft)} = \frac{16.67}{5} = 3.33 \text{ Hz} \quad (4.2)$$

$$\text{Equation 3.3} \Rightarrow \text{Cogging frequency} = \frac{\text{LCM}(14, 12)}{14} \times 16.67 = \frac{84}{14} \times 16.67 = 100 \text{ Hz} \quad (4.3)$$

$$\text{Equation 3.4} \Rightarrow \text{Electrical frequency} = \frac{14}{2} \times 16.67 = 116.67 \text{ Hz} \quad (4.4)$$

4. Results

In Figure 4.1, an FFT of an unfiltered signal is shown with calculated fundamental noise frequencies pointed out.

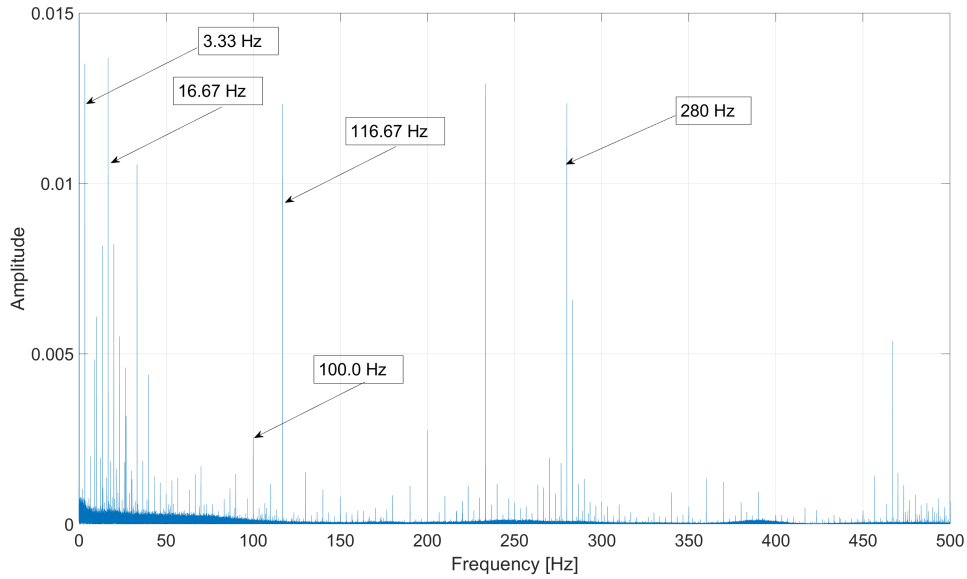


Figure 4.1: FFT of torque signal.

As can be observed in the figure, the calculated noise matches the frequencies with relatively high amplitudes in the FFT, which is a good indicator that these calculated frequencies are actual sources of noise in the system. 280 Hz is still unknown but is treated as a noise signal since 280 Hz was present in all of the tests performed with different load frequencies and characteristics. The harmonics of the fundamental frequencies of the sources of noise listed below in table I and fits in nicely on the FFT in 4.1.

Table I: Frequencies causing problems

Source	Frequency (Hz)
Mechanical noise (shaft)	3.33, 6.66, 9.99, 12.32...
Mechanical noise (motor)	16.67, 33.33, 50, 66.66...
Cogging	100, 200, 300, 400, 500...
Electrical rotation	116.67, 233.33, 350, 466.66, 583.33...
Unknown noise	280, 560, 840, 1120, 1400...

Multiple tests were performed where the only changing factor was the load intensity. During these tests, it was clear that the amplitude of the mechanical noise inflicted in the system had a great correlation with the load intensity and that the mechanical noise in most cases was the greatest noise contributor.

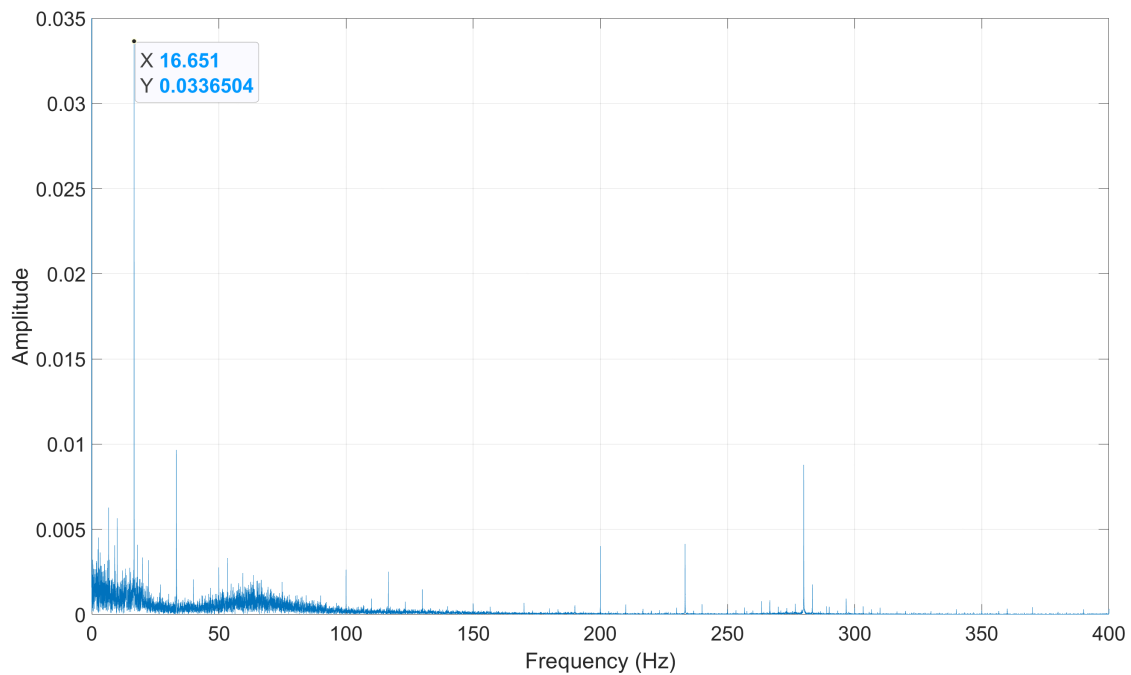


Figure 4.2: FFT of torque signal with high load intensity.

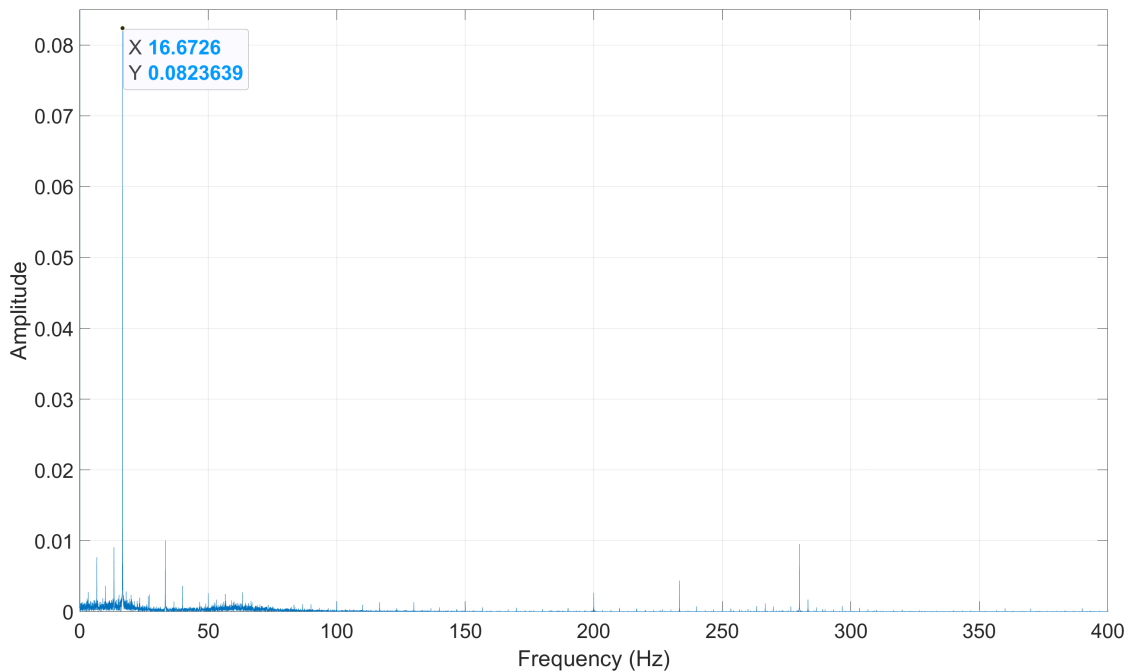


Figure 4.3: FFT of torque signal with low load intensity.

As can be observed in 4.2 & 4.3, the amplitude went down with 59% by increasing the load intensity. This is likely due to a dampening effect from the load it self. The other identified noise frequencies did not show a clear relation between frequency amplitude and load intensity, this is probably because they are created in the internal parts of the motor instead of the mechanical imbalance of the shaft.

4.1.1 Unknown frequency

280Hz is an unknown frequency has an undetermined origin, but still needs to be taken into account later in the filtering process and treated as noise since it appears as a constant frequency in all different test scenarios.

4.2 Part 1

In the following part of chapter 4 , the project were split into two directions. Part 1 focuses on the motor selection part of the project. Part 2 focuses on the effect of the digital filters used for signal processing.

4.2.1 Motor design optimizations

The literature study concluded that a BLDC motor works for almost all applications due to its simplistic design and efficiency. But in this case, where it is very important to have a stable torque signal, there are better options that do not inflict as much noise in the form of torque ripple. The torque ripple would effect the sampled torque signals' reliability negatively. As described earlier in chapter 2.1.3.1, a BLDC motor is known to produce torque ripple (especially magnetic cogging), but it is not considered to be a problem in most cases since very precise torque measurements are not needed.

As discussed in Chapter 2.2.1 and 2.2.1.3, there are several approaches to mitigating the impact of torque ripple and magnetic cogging. The most common solutions include improving the motor design itself, such as adjusting the rotor and stator geometry. However, while these approaches may help, they do not necessarily eliminate the noise entirely, especially in situations where very precise torque measurements are required. One other solution that potentially would work is to choose a different type of motor that will not experience torque ripple and magnetic cogging as much as other motor types.

After researching different ways of reducing torque ripple, it was found that a sinusoidally-controlled AC motor would suit this sort of application better. This is because in general, an AC motor can be operated at a much lower speed without losing any of its performance [26]. The sinusoidal commutation, when controlling the motor allowing the motor to generate smoother torque. Compared to a BLDC motor that uses a trapezoidal commutation, which can cause the magnetic cogging and torque ripple to worsen.

The motor currently in use features a configuration with 12 poles and 14 magnets, which is considered a highly favorable configuration regarding torque ripple mitigation for a BLDC motor. This configuration is designed to reduce torque ripple and improve performance. However, despite these improvements, it is important to note that this alone is insufficient to completely eliminate the fluctuations in the torque signal. Even with an optimized pole and magnet configuration, additional measures

may be necessary to achieve the desired level of accuracy in the torque signal.

4.2.2 Structured evaluation of motors using matrix methods

To be able to decide which of the motors would be the best for the wear rig, it was determined that the use of different matrices where needed. Matrices such as the elimination matrix, the Pugh matrix, and the Kesselring matrix were used to filter out motors that would not fit the criteria set. By using these matrices, the decision-making process becomes repeatable and transparent. This leads to more objectivity, since making decisions based on criteria will not be impacted by personal bias.

4.2.3 Elimination matrix

Table II: Motor Selection Criteria.

Motor	1000-3000 rpm	0.5-6 Nm	Servo motor	No gearbox needed	Shaft adapter not needed	Need A series adapter	Proceed
HDS60-0102A	+	+	+	?	-	-	No
HDS6A-0102A	+	+	+	?	-	+	Yes
HDS60-0104A	+	+	+	?	-	-	No
HDS6A-0104A	+	+	+	?	-	+	Yes
ESM04X-101-302	+	+	+	?	-	?	Yes
ESM06X-201-302	+	-	+	?	-	?	No
ESM06X-401-302	+	+	+	?	-	?	Yes
ESM013B-152-304	+	+	+	?	-	?	Yes
INNOMOTICS GP-71M	+	+	-	+	-	?	No

As seen above in the table II the elimination matrix was used as a preliminary screening tool. Motors that failed to meet the set criteria where discarded when the next matrix where used. The winners in the elimination matrix are those suggestions that will be taken forward in the next sets of matrices.

4.2.4 Pugh 1:5 matrix

To investigate how much different gear ratios would impact the result, it was determined that it would be best to create three separate Pugh matrices with different gear ratios.

Table III: 1:5 Gearbox.

Motor	REF	HDS5C-102A	HDS6A-104A	ESI MAX-401-302	ESI MAX-101-302	ESI HD1230-S3A
Torque	REF	0	0	0	-	-
Speed	REF	+	+	+	+	+
Price	REF	-	-	-	-	-
Potential torque ripple improvement	REF	+	+	+	+	+
can use same sensor	REF	+	+	+	+	-
inertia	REF	-	+	+	-	+
SUM		1	3	3	0	0
Rank		2	1	1	4	3

In table III a 1:5 gearbox was used to evaluate which one of the motors that would work best. The best suited motor in combination with this gear ratio was the HDS6A-104A and the ESI MAX-401-302. Both these motors was best in this case because of their high inertia which was determent to be an improvement from the BLDC motor currently being used.

4.2.5 Pugh 1:20 matrix

Table IV: 1:20 Gearbox.

Motor	REF	HDS5C-102A	HDS6A-104A	ESI MAX-401-302	ESI MAX-101-302	ESI HD1230-S3A
Torque	REF	-	-	-	+	-
Speed	REF	?	?	?	?	?
Price	REF	-	-	-	-	-
Potential torque ripple improvement	REF	+	+	+	+	+
can use same sensor	REF	-	-	-	+	-
inertia	REF	-	+	+	-	+
SUM		-3	-1	-1	1	-1
Rank		3	2	2	1	2

In Table IV, a bigger 1:20 gear ratio was used to see how much the result from the previous Pugh matrix would change. A 1:20 gear ratio would allow the motor to spin at a much higher RPM, therefore letting the motor spin closer to its rated speed, improving efficiency, enabling motors with lower torque output, and also decreasing the effect of magnetic cogging. The best motor in this case was the ESI MAX-101-302. This was the only motor with low enough torque to not damage the torque sensor with this gearbox configuration.

4.2.6 Pugh 1:2.5 matrix

Table V: 1:2.5 Gearbox.

Motor	REF	HDS5C-102A	HDS6A-104A	ESI MAX-401-302	ESI MAX-101-302	ESI HD1230-S3A
Torque	REF	-	-	-	-	+
Speed	REF	?	?	?	?	?
Price	REF	-	-	-	-	-
Potential torque ripple improvement	REF	?	?	?	?	?
can use same sensor	REF	+	+	+	+	+
inertia	REF	-	+	+	-	+
SUM		-2	0	0	-2	2
Rank		3	2	2	3	1

In Table V a smaller 1:2.5 gear ratio was used to see if there would be any significant changes in the result, since a lower gearbox would force the motor to spin at a much lower speed, and therefore enabling the use of slow-running motors with high torque and high inertia. With this gearbox the ESI HD1230-S3A suited the needs best for this application since the motor could run at a lower speed and still produce a small amount of torque.

4.2.7 Kesselring matrix

The last matrix, table VI is a Kesselring matrix that lists all the winners from the Pugh matrices and then gives them individual scores based on some predetermined criteria.

Table VI: Motor evaluation based on weighted criteria.

Criteria	Weight	Ideal Motor		HDS6A-0104A		ESM0x-401-302		ESM01-38-153-20	
		Result	Result	Result	Result	Result	Result		
Operates in optimal RPM range	0.3	5	1.5	3.5	1.05	3.5	1.05	2	0.6
Price	0.1	5	0.5	3	0.3	2	0.2	2	0.2
Inertia	0.15	5	0.75	2	0.3	2	0.3	3	0.45
Wear rig modifications needed	0.3	5	1.5	4 (7.0 Nm)		3 (15gb, 4.8Nm)		2 (2.5gb, 2x drop, 8Nm)	
Sum		4.25		2.85		2.75		2.15	2.6

4.2.8 Which motor was best for our application

As shown in the chapter, 4.2.2 matrices such as Elimination, Pugh, and Kesselring were used to narrow down the different motor suggestions. It was determined that the HDS6A-0104A won by a small margin. It is a small AC servo motor designed and manufactured by ABB. This motor belongs to their HDS series, which stands for High Performance AC PM servo motors. The HDS6A-0104A was selected due to its excellent performance characteristics, particularly in terms of low cogging torque and minimal torque ripple. According to the ABB product catalog, "the motor provides excellent performance at low speed and system control" [27], making it well-suited for applications where smooth and precise torque control is essential. This motor should, in theory, help reduce the noise generated by the torque ripple and magnetic cogging [27]. However, while the motor's theoretical performance suggests that it will reduce torque ripple due to better magnetic cogging performance, this can only be confirmed through actual installation and testing in the final system over a period of time.

Table VII: Specifications for HDS6A-0104A.

Parameter	Value
Input voltage	AC 230 V
Continuous stall torque T_0 (Nm)	1.4
Rated torque T_n (Nm)	1.27
Peak torque T_p (Nm)	4.46
Rated speed n_r (rpm)	3000
Maximum speed n_{\max} (rpm)	6000

Given the situation that this application requires the motor to operate at lower speeds, the HDS6A-0104A, is more well-suited for consistent performance at lower speeds, combined with its minimal noise characteristics. Makes it ideal for applications where accurate torque is desired. These conclusions are based on the technical documentation and product specifications provided by the manufacturer. This can be seen in Table VII, which contains the data provided by ABB's HDS-catalog. While this data aligns well with the requirements of our application, the performance increase is undetermined until installed and tested.

4.3 Part 2

This chapter covers the filtering process and the effect this will have on the torque signal.

4.3.1 Filtering techniques

During the testing phase, various filter designs and configurations were evaluated. The performance of each filter was assessed by comparing how the signal noise would be cleaned up by post-processing of the signal. It was concluded that a band-stop filter with a very tight stop band would be the most effective solution for removing unwanted noise while preserving the valuable data. As shown in appendix A , a specialized filter where created to remove just the unwanted noise without removing any of the valuable data. A test signal was generated to confirm functionality of the filtering algorithm, the results can be seen in the following figures:

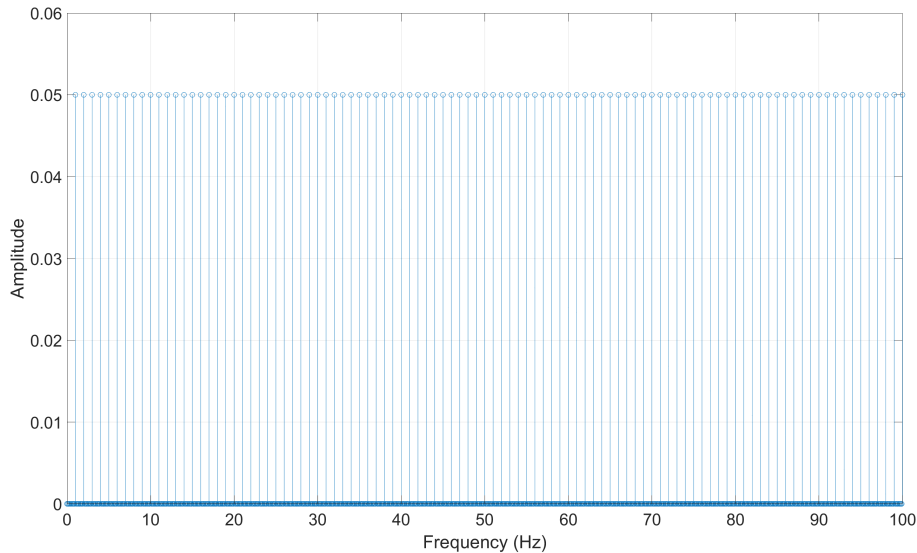


Figure 4.4: FFT of generated control signal.

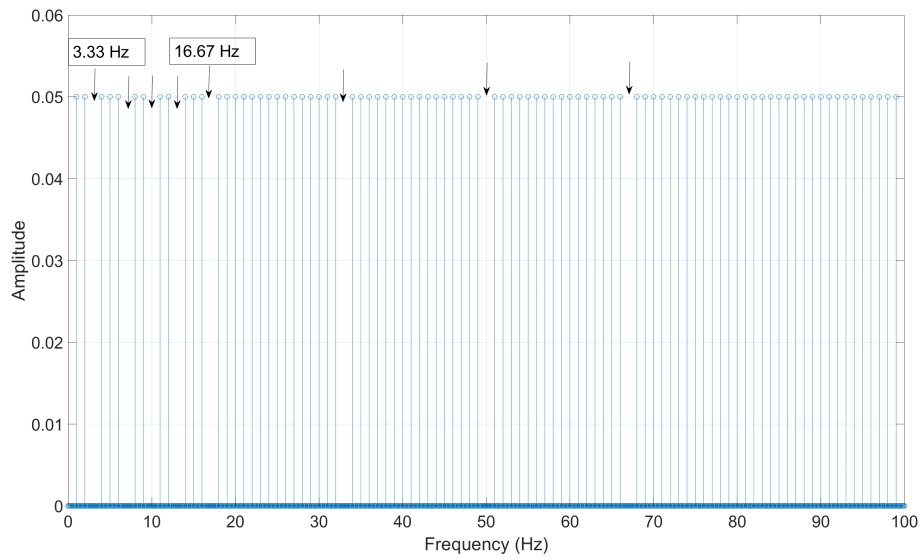


Figure 4.5: FFT of filtered control signal.

In Figure 4.5 , the filter can be seen in action, where it completely removes the impact of undesired frequencies and their corresponding harmonics.

An additional test was performed to determine if a low-pass filter could be used in combination with the stacked band-stop filter. This test used FFT:s to analyze at what frequencies the "bulk" of the energy of the signal where present. The hypothesis was that based on the particle size, the bulk would be placed at a higher frequency if the particles were smaller, and lower frequency if the particles were bigger. The test for the biggest and the smallest particle sizes can be observed below:

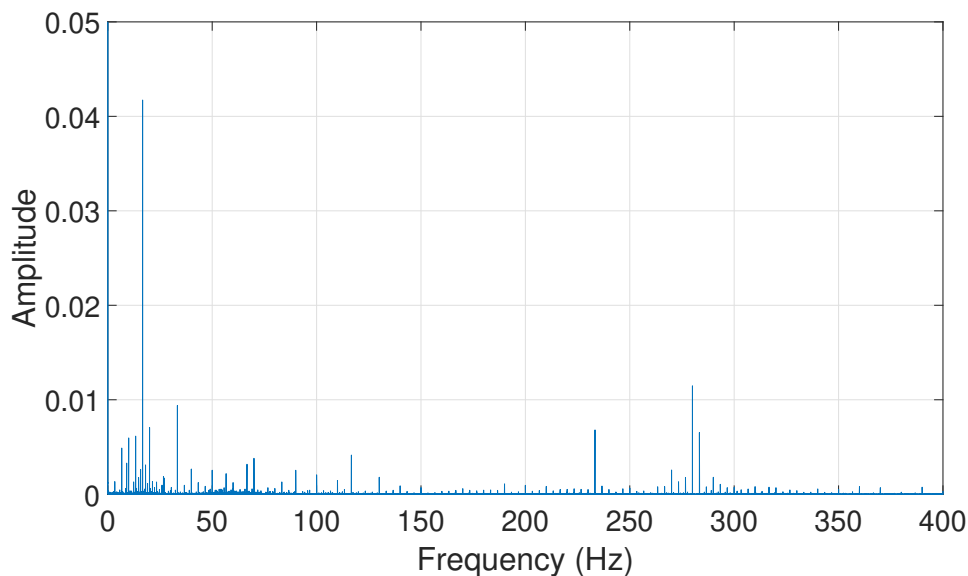


Figure 4.6: FFT of torque signal based on small particles.

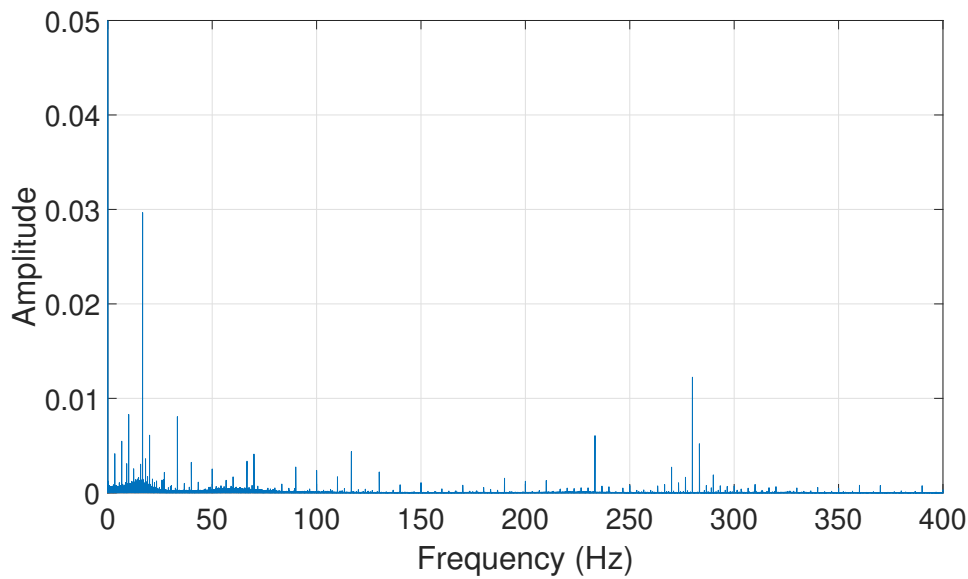


Figure 4.7: FFT of torque signal based on large particles.

Although a slight difference in amplitude of certain frequencies, now clear change in the frequency spectra could be observed. Therefore the implementation of the additional low pass filter was discarded since it was uncertain if the filter would remove important information of the load if applied.

In the following figures, the customized filter where done in steps to clearly and systematically filter out the unwanted frequencies one by one. In the first figure 4.8 the mechanical noise where filtered out. These sets of band-stop filters had the biggest impact on the signal when the motor was in idle mode, since the noise from the mechanical rotation was greatest at those tests. But since the data from idling is not of interest right now, the following figures illustrate just the motor under a load. In all the coming figures, the figure is split into four graphs. The first will show the original signal, the second will show the filtered part. The third will be an overlap of the first two; the green represents the filtered part, whereas the black is the original signal. The last graph illustrates the rolling mean that the two signals will have.

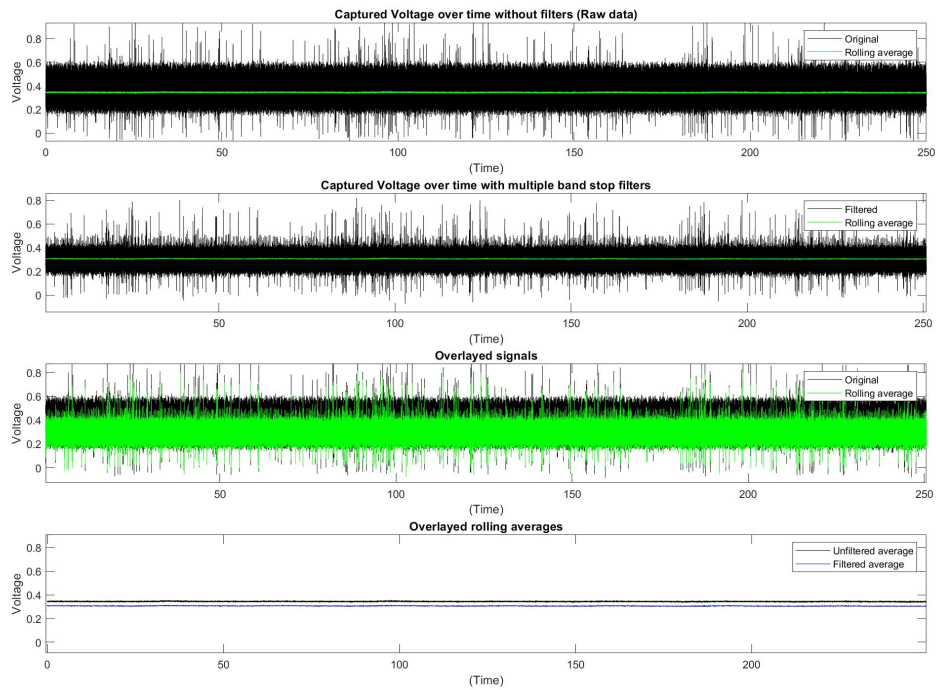


Figure 4.8: Filtering out the mechanical noise and it's harmonics.

As can be observed in Figure 4.8, the filtered signal is tighter and has a smaller overall variance.

The second figure 4.9 illustrates when the magnetic cogging is filtered out.

4. Results

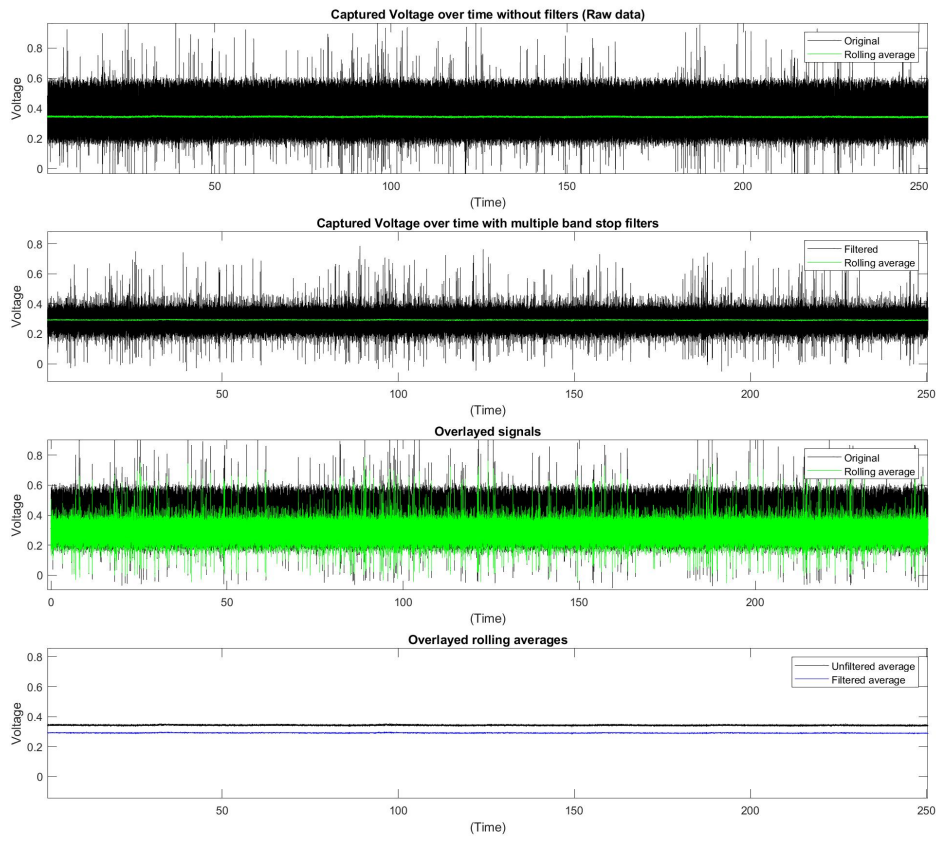


Figure 4.9: Filtering out torque ripple and its harmonics.

This is one of the bigger signals that can be seen creating fluctuations in the torque output signal. Again, by eliminating the frequencies connected to magnetic cogging, the signal became much "clearer".

The third figure 4.10 shows the signal where also the unknown frequencies (280 Hz) have been found are filtered out. This is the final signal in the initial developed filter.

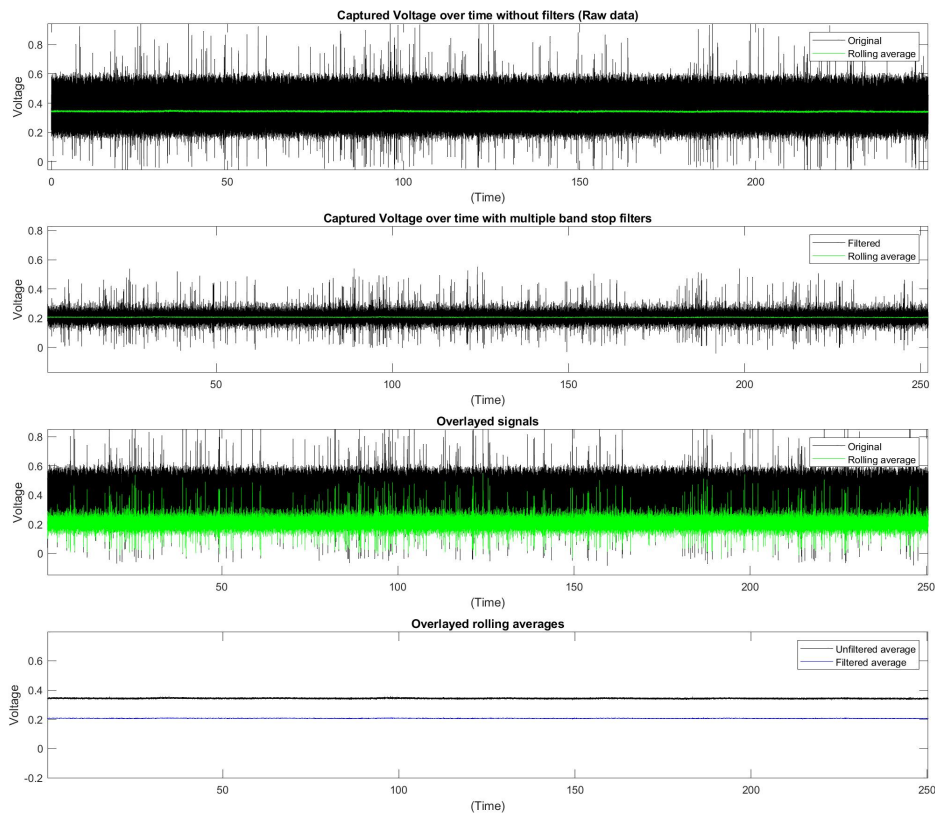


Figure 4.10: Filtering out the unknown/unwanted frequencies.

These signals, together with magnetic cogging, had the biggest impact on the signal, they fall under the same category as torque ripple. Since torque ripple is an "umbrella term" used to describe fluctuations in a torque signal, with unknown variables affecting signal output.

However, due to improper filtering techniques, the signal reading shifted down in energy unexpectedly. This was because the initial filters did not include preservation of the low-frequency baseline. Even though the signal is tighter with lower variance, the data does not represent the torque correctly, so preservation was later added to keep the data more accurate. This was done by eliminating the rolling average of the signal, applying the filter on the remaining signal, and then adding back the rolling average again to the filtered data. This resulted in the filtered signal having more or less identical mean values, which leads to a more correct representation of the actual torque data.

The effect of the finished filter can be seen in the figures below:

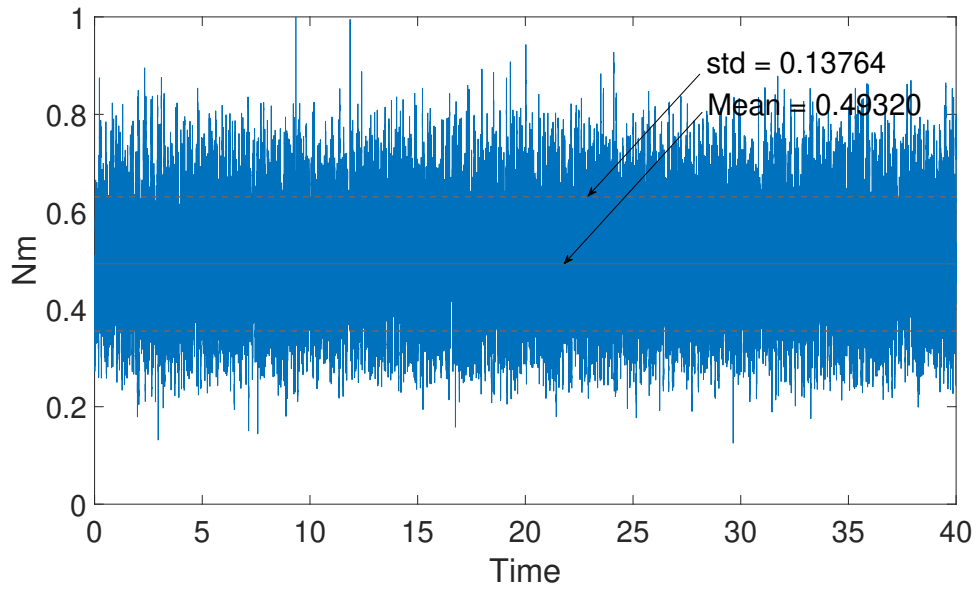


Figure 4.11: Original signal with low load intensity without filter.

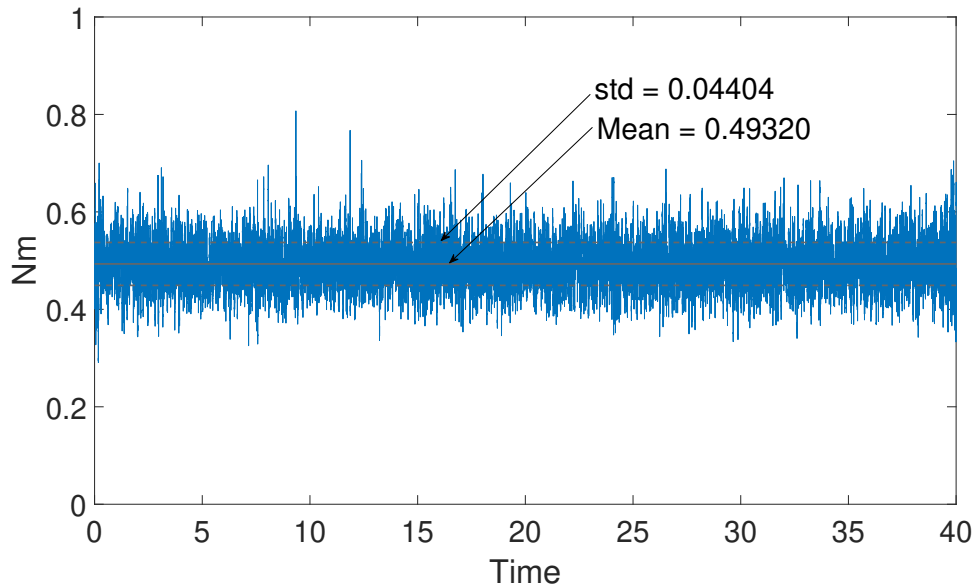


Figure 4.12: Reduction of standard deviation when filter gets applied.

When comparing the standard deviation of the filtered signal with the unfiltered signal, the standard deviation gets reduced by 68% as can be seen in 4.12. This suggests that the filter works in reducing the noise, confirming the effectiveness of the customized filter.

However, when applying the filter on a signal with different load intensity, in this case by adjusting the occupancy, the benefit of the filter varied as can be seen below in table VIII:

Based on occupancy	Standard deviation reduction	Changing mean	Change in energy
5%	68%	0%	Ongoing calculation
11%	20%	0%	–
15%	29%	0%	–
21%	41%	0%	–

Table VIII: Impact of occupancy-based adjustments on standard deviation, mean, and energy.

The effect of the filter based on occupancy is varying, but based on this test, one can conclude that the filter seems to decrease the standard deviation in the torque signal with at least 20%. The effect of the filter was a bit clearer when comparing the standard decrease in standard deviation based on particle size, as can be observed in table IX below:

Based on particle size [mm]	Standard deviation reduction	Changing mean	Change in energy
0.25	45%	0%	Ongoing calculation
0.32	30%	0%	–
0.5	48%	0%	–
0.78	23%	0%	–
0.98	24%	0%	–

Table IX: Impact of particle size on standard deviation, mean, and energy.

Here, the trend points to the filter having a greater effect on the decrease in standard deviation the smaller the particles are. The energy calculations in table VIII & IX have as of the writing of this report not yet been calculated, but the preliminary results based on the calculations performed by CRS point to a slight decrease in total energy, which is expected since the total removal of some frequencies removes information which is used for energy calculation.

5

Discussion

This chapter discusses the possible source of the 280 Hz disturbance, common issues related to BLDC motors, and whether the applied filter may be performing too aggressively. It also discusses future research points.

5.1 What can 280 Hz and its harmonics be?

280 Hz does not correspond to any known cause; it is not torque ripple or any kind of mechanical noise. There is a possibility that this frequency comes from the gearbox being used. It is also a possibility that this is some sort of noise coming from within the motor. It might be motor mounts or even something else entirely.

5.2 Common problems in BLDC motors

As described in earlier chapters, most BLDC motors are notorious for experiencing torque ripple and magnetic cogging. These problems can lead to more than just an unclear signal, the vibrations created by the motor can reduce the lifespan of the motor and other connected components. If this is quite a common problem, why is it not addressed more? This is most likely because using a BLDC motor is very cost-effective for companies, and investing in a new motor design or a control algorithm is too expensive for them. It is cheaper for them to just run the motors as they are and experience a small loss in accuracy. If they want a more accurate reading, it is most likely that they will choose another type of motor, possibly a PMSM motor.

5.3 Does the filter work too good?

Since the filter works by completely eliminating the chosen frequencies, it is possible that some valuable data gets lost. For example, if the load applied to the motor has the specific frequency 16.67 Hz, which matches the frequency of the noise created by the mechanical rotation of the motor, that data would be lost. Since the load frequency is unknown, extra analysis is needed to confirm load frequencies so the potential data loss could be determined.

5.4 The cost of a new motor compared to a customized filter

The challenge of torque fluctuations is an undesirable outcome for our application and, therefore, needs careful consideration when developing suggestions on fixing these fluctuations. One way of doing this is by implementing the new motor described in chapter 4.2.8. Since this is a PMSM motor that is designed to reduce cogging torque, which can lead to torque ripple and magnetic cogging, this motor should, in theory, reduce fluctuations, leading to better performance. However, while this solution shows promise, it is important to note that it cannot guarantee the complete elimination of torque fluctuations. Since the only way of knowing this is by testing the motor over a period of time.

In comparison, our other solution is a customized filter that has been developed to target just the unwanted frequencies and nothing more. This is a promising way of reducing the torque fluctuations and leaving the other valuable measuring data intact. But while this customized filter can effectively smooth out the signal and reduce the impact of the undesirable fluctuations in the signal, it does not provide a permanent solution. Rather, it acts as a means of dampening the problem, filtering out specific unwanted frequencies without eliminating the root cause of the problem.

When comparing these two approaches, it becomes clear that they both have advantages and disadvantages. A new motor would, in theory, have the potential to more accurately resolve torque fluctuations, but this comes at a higher cost, both in terms of development and potential implementation time. Additionally, there is no certainty that such a solution would fully eliminate the fluctuations due to the complex nature of the underlying torque fluctuations.

On the other hand a customized filter is a more cost effective and quicker to implement solution to this problem. Since it will reduce the unwanted noise in the signal but this will not fix the issue just dampen it and mask it. Ultimately the decision between these two approaches may come down to a balance between the desired level of torque fluctuation control, available resources, and long-term goals. It may also be prudent to implement them both in some sort of way.

5.5 Further research

Further research would be to actually test a new motor and seeing if it works as intended. This can be done by performing experiments over a longer period to see that we get the same result over a long period of time. If a new motor does not work, further research is necessary to see if the problems we are experiencing right now can not be fixed by a new motor. Or if it will force us to design a new motor from the ground up, optimized slot and pole combinations, and other solutions. If that does not work as well, it might be necessary to look into creating a specialized control algorithm to help reduce the torque fluctuations.

Further research can be done in the energy consumption of the motor. Some motor design allows the motors to be more efficient. However some of these designs can come with some disadvantages. Investigating these disadvantages and finding an optimal balance between efficiency and performance could be a valuable area for future research.

6

Conclusion

As shown in earlier chapters in this report, the torque fluctuations are not caused by a single issue but rather by multiple factors. The BLDC motor that is used right now works for most applications. However, since CRS's application requires the torque output to be as steady as possible, it is not well suited for this. As also discussed and discovered earlier, both magnetic cogging and torque ripple are notorious for being problems in BLDC motors. Both of these problems causes, can be found in its design and control system. Over the years, quite a few advanced control algorithms have been developed to handle some of the unwanted noise created by these problems. These algorithms work good and are widely used, but they can only reduce noise up to a certain degree and cannot fully resolve the issue.

We have therefore come up with a filter that entirely filters out the frequencies created by magnetic cogging and torque ripple. It works on the thought that we can manually calculate all the frequencies that are created by these problems and then by using a bandstop filter, filter out all these frequencies.

Therefore, we suggest that CRS use a combination of these solutions: a customized filter and a change in the motor type. The motor we recommend is as described in chapter 4.2.8, HDS6A-0104A or any motor from this series. They are one of ABB's most high-performance motors and should, in theory, help reduce most of the noise the motor currently being used is experiencing.

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A

MATLAB Code

```
1 time=%insert time vecotr here%(:,1);           %% time
   vector
2 volt=%insert data vector here%(:,2);           %% data
   vector containing volts (1V=1Nm)
3
4 fs=25000;                                       %%
   sampling rate
5 dt=1/fs;                                       %%
   sampling period
6 rpm=1000;                                       %%
   rotational speed / minute
7 L=length(volt);                                %%
   Length of signal
8
9
10 windowSize=1000;                               %% moving
   average window size
11 SignalMovMean = movmean(volt, windowSize);    %% Moving
   average calculation
12
13 %% removal of idle values
14 NoDCOffsetVolt=volt-mean(volt);                %% removal of
   mean value
15 Tsignal=timeseries(NoDCOffsetVolt,time);      %% converts
   to timeserier
16
17 %% filtering
18 rps = rpm/60;                                  %% rotational
   speed/second
19 poles=12;                                       %% rotor magnets
20 magnets=14;                                    %% stator "
   magnets"
21 gearboxRatio=5;
22
23
24 extra=0.5;                                      %% filtering
   window
25
26 remove=rps*(poles/2);                          %%
```

A. MATLAB Code

```
27 removenext=remove;
28
29 for i=1:4 %Magnetic cogging (all harmonics (100,200,300,400))
30     interval=[remove-extra , remove+extra];
31     tsout = idealfilter(Tsignal,interval,'notch');
32     remove=remove+removenext
33     Tsignal=tsout;
34 end
35
36 remove=(((poles*magnets)/2)*rps)/gearboxRatio;
37 removenext=remove;
38
39
40 for i=1:4 % Unknown noise (all harmonics (280,560))
41     interval=[remove-extra , remove+extra];
42     tsout = idealfilter(Tsignal,interval,'notch');
43     remove=remove+removenext
44     Tsignal=tsout;
45 end
46
47 remove=rps;
48 removenext=remove;
49 for i=1:4 %rotational noise from motor (all harmonics 16,67 +
50     33 + 49 + 66 )
51     interval=[remove-extra , remove+extra];
52     tsout = idealfilter(Tsignal,interval,'notch');
53     remove=remove+removenext
54     Tsignal=tsout;
55 end
56 remove=rps/5;
57 removenext=remove;
58 for i=1:4 %rotational noise from after gearbox (4 harmonics 3
59     6 9 12)
60     interval=[remove-extra , remove+extra];
61     tsout = idealfilter(Tsignal,interval,'notch');
62     remove=remove+removenext
63     Tsignal=tsout;
64 end
65 remove=rps*(magnets/2);
66 removenext=remove;
67 for i=1:4 % electrical rotations (116, 233, 466, 933)
68     interval=[remove-extra , remove+extra];
69     tsout = idealfilter(Tsignal,interval,'notch');
70     remove=remove+removenext
71     Tsignal=tsout;
72 end
73
```

```
74 Tsignal=Tsignal+mean(volt);
```

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