Electrification of rock drills
- An initial study of an electromagnetic percussion concept

Jakob Smith Siljestrånd
Sai Shridhar Chebolu

Supervisor: Robert Braun
Examiner: Magnus Sethson
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Abstract

The world is looking for greener solutions and so is the mining industry. This quest has led to the question whether it is possible to have a completely electric rock drill. This work carries out an initial exploration of completely electrified percussion. Furthermore, it compares the preliminary performance of an electrified rock drill against a hydraulic counterpart.

A mathematical model for an electromagnetic linear motor was developed and simulated as a component in the simulation software Hopsan. This component was then incorporated into a electromagnetic rock drill model which uses components from Epiroc’s in-house developed library. The electromagnetic rock drill model was then optimised and used to obtain the performance characteristics such as impact energy and frequency which were compared against one of the hydraulic rock drill models, COP 1838. The results show that it is possible to reach the same performance as the COP 1838 with enough input current. The characteristics were then studied with respect to variation of physical parameters of the electromagnetic linear motor and input current.

Finally some limitations and strengths of the electromagnetic rock drill concept are discussed and some conclusions are presented.
Acknowledgments

This thesis work is a culmination of years of learnings from our time in Linköping University and these learnings would not have been possible without the FLUMES faculty. We would like to express our gratitude towards all who have helped and supported us along the way.

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Acronyms

**EM** - Electromagnetic
**EMF** - Electromotive force
**FEM** - Finite element method
**MMF** - Magneto motive force
**MEC** - Magnetic equivalent circuit
**PM** - Permanent magnet
**TLPM** - Tubular linear permanent magnet motor

Nomenclature

**Stator** - The stator is the outermost casing of the linear motor which holds the current carrying conductors

**Mover** - In this work mover is defined as a cylindrical core with magnets mounted on the surface. It is the moving part of the linear motor.

- **z** - Coordinate in axial direction on the mover.
- **r** - Coordinate in radial direction on the mover.
- **x** - Axial coordinate of the mover with respect to origin of the stator.

Definitions

**Free hammering** - Free hammering occurs when the rock drill is hammering without being in contact with rock. Meaning, there is no rock to absorb the stresswaves.

**Impact velocity** - The velocity of the mover at the moment of impact.

**Impact energy** - The energy that is transformed from the movers kinetic energy when it hits the shank. It is calculated from the mover mass and impact velocity.
Epiroc Rock Drills AB is a manufacturer active in the mining and infrastructure industry with about 17000 employees worldwide. They produce drill rigs, rock excavation and construction equipment, and tools for both underground and surface applications. All industries are undergoing electrification of some sort, and the mining and construction industry is no exception. This means new challenges for Epiroc, but also new possibilities. Many of their current line of machinery can be purchased with either a conventional diesel engine or with battery powered electrical motors. Their rock drills are powered by a hydraulic system driven by an electrical motor. Epiroc is now looking into the possibility of powering these rock drills directly with electricity, without using hydraulics. This thesis investigates the possibilities for replacing the hydraulic hammer. More specifically, it looks into tubular linear motors and how these can perform as a hammer and whether they can have the same performance as the hydraulic counterpart.
1.1 Percussive drilling theory

Drilling a hole in a material is typically performed by a combination of a rotation and a forward feed motion. To improve this further, an impact force can be added to the above motion which results in faster drilling, called percussion.

![Feed force + percussion](image)

Figure 1.2: Illustration of rotation of buttons after impact

Instead of cutting rocks, the buttons on the bit (illustrated in figure 1.2) create strain in the rock followed by an impact by the piston on the shank. Rotation is then used to move the buttons to a different position between impacts. To achieve this, high powered drills are required because rock formations are tough and difficult to break. The energy and frequency required to break the rock are determined by the type of rock and the required hole diameter (figure 1.3).

![High frequency Low energy](image) ![Low frequency High energy](image)

Figure 1.3: Ways to achieve the required power

If the feed force is absent then it results in free hammering and zero drilling rate which may reduce the life of the rock drill. A more detailed explanation of percussive rock drilling is given in section 4.1.

1.2 Rock drills

Currently, a majority of commercially available rock drills utilise hydraulics to obtain the percussion motion. To reverse the motion of the piston a hydraulic 'On - Off' valve is used. The valve keeps switching position between the end states to connect the forward and reverse percussion pressure lines. An example of a hydraulic rock drill is shown in figure 1.4.
1.3 Electrification

1.2.1 Hydraulic mechanism

As mentioned above the rock drill uses a 'On - Off' valve to control the piston movement. A switching motion between end states is created using the 'On - Off' valve, which then leads to the piston making an impact onto the shank.

![Diagram of piston movement for impact stroke in a rock drill]

1.2.2 Hydraulic rock drill performance

Epiroc offers hydraulic rock drills which can operate at different frequencies, energies and power rates depending on the application [21]. For instance,

- COP 4038 can produce a power of 40 kW with an impact frequency of 140 Hz
- COP 5060 is the most powerful rock drill which can produce a power of 50 kW with an impact frequency of 47 Hz.
- COP 1838 is a 15 kW rock drill with an impact frequency of 50 Hz.

The model COP 1838 has been used as comparison in this thesis. Various performance parameters of the electrified model will be compared against the parameters of this rock drill.

1.2.3 Losses and problems in hydraulic rock drills

Hydraulic rock drills excel in performance owing to the inherent high power density. However there are many flow restrictions in the hydraulic system, which lead to pressure drops and losses as heat.

1.3 Electrification

A piston motion using only electrical machines can help mitigate the shortcomings of using hydraulics. This could be achieved by using electromagnetism which facilitates direct conversion of electrical power to mechanical power. Unlike hydraulics, this eliminates an intermediate conversion resulting in potentially more efficient system.
Another solution is a rotating electrical motor which is connected to a crankshaft to produce a linear motion. This concept can rotate fast and it is possible to make the rock drill more compact. However, the stroke length would be fixed and a challenge with this concept would then be to produce a variable stroke length.

1.4 Aim and Purpose

The aim of this thesis is to investigate the feasibility of an electromagnetic percussion mechanism concept by means of a simulation study.

The purpose is to investigate the advantages, disadvantages and theoretical performance metrics of this percussion concept to see if an electrified rock drill is a viable substitute for a conventional hydraulic rock drill.

1.5 Research Questions

The research questions for the thesis are as follows:

- What is a suitable electromagnetic percussion concept?
- How does the electromagnetic concept compare to its conventional hydraulic equivalent in terms of performance?
- What is the characteristic behaviour of the electromagnetic percussion concept?

1.6 Scope and delimitations

Some delimitations need to be set due to the time constraint of the thesis. Stress limitations on the construction of the electromagnetic motor are not considered. The report also does not investigate any thermal effects. Same goes for irreversible demagnetisation of the permanent magnets. Effects due to magnetostriction are also ignored and so is the structural strength of the rock drill and mover. These are all crucial factors that will have to be investigated in the future. Instead, this report focuses on the feasibility in terms of performance and limitations of the functionality of a concept for an electromagnetic percussion mechanism rather than an actual intricate design. For a more detailed description of the approach, see chapter 3.

It is also assumed that a digital commutator or current control is present. Current control is not investigated further in this thesis because it is tedious to implement and has potential to become a focus area in itself. Another delimitation is that the effect of Eddy currents will not be investigated. Eddy currents will affect the motor performance but a mathematical implementation is complex and does not fit within the time frame of this thesis. Finally, vibrations and rotation in the rock drill will not be considered.
The idea of electrified rock drills have been around for a long time. In a paper from 1892 written by Harry N. Marvin \cite{35}, he presents his ideas for an electric percussion drill. He mentions the extreme requirements such as being soaked in mud, being able to withstand the roughest of handling, incapable of burning and easy to repair by a mechanic. As mentioned in chapter 1, rock drills which were earlier powered by pneumatic sources are now being powered by hydraulic systems. Conventionally, hydraulic systems are known to have high power densities compared to their pneumatic or electromagnetic counterparts.

Recently however, much of the research has focused on development of high power density electromagnetic linear motors. Many solutions utilise permanent magnets in a tubular construction. Having permanent magnets in the linear motor results in lower power factor, increased thrust and higher efficiency compared to traditionally used linear inductance machines \cite{45}.

### 2.1 Current state of rock drills

The first mechanized rock drill was invented by Burton in 1844 which relied on compressed air for delivering percussive load to strike the drill \cite{31}. Then in 1900, Wacław Wolski improved the rock drill by utilising hydraulic percussion \cite{25}. Until today the rock drills have been mostly hydraulic owing to the high power density.

The next step up in rock drilling according to Konya \cite{31}, could be an increase in efficiency of drilling, reduction in cost of ownership and more robust equipment. These would be the area for competition in the market. Furthermore, according to Konya, drilling is more likely to be electric powered in the future. This might take 15-30 years more for the use to be widespread. At the moment, all commercially available rock drills are powered either pneumatically or hydraulically. However, there have been recent developments in the field of electric hammers.
2.1.1 Recent developments

As mentioned in chapter 1, the mining industry is undergoing an electric transformation. Parallelly, there is also a digital transformation. Wróblewski et al. [51] writes that there is great potential for increased efficiency and safety with these transformations and the alternative to today’s hydraulic hammer would be a fully electric hammer. It would come with benefits such as energy savings, increased performance and no pressurised and toxic hydraulic oils. The energy savings comes from the fact that it does not require any secondary energy converters like pumps, compressors and hydraulic lines and is instead directly powered. An electric hammer allows for dynamic control of parameters like frequency and impact force, which in traditional hydraulic hammers are limited.

There exist many patents with a variety of solutions for electric hammers, but they have yet to reach the commercial market. As of writing this, there exists one commercially available fully electric hammer; a rock breaker which has the purpose of breaking large pieces of rock into smaller pieces, usually after blasting. It utilises a tubular linear motor with permanent magnets (see section 2.2.5) attached to the mover. The manufacturer claims it is programmable and therefore certain parameters can be varied. The advertised frequency of the percussion is between 1-15 Hz with an impact energy of 500-1500 J [51].

2.2 Linear motors

The principal behind a linear electric motor is the same as a rotational electric motor. It has a stator and a mover but instead of rotating, they are laid out flat to produce a linear motion. They move in a linear motion without any mechanical couplings. Wróblewski et al. [51] write that linear electric motors can be classified as either a DC motor, induction motor, synchronous motor, oscillating motor or hybrid motor. The most common type of these today are PM linear synchronous motors and linear induction motors.

The stator of a linear motor can be either slotted or slotless [13]. Slotted means that the stator is having “teeth” to focus the electromagnetic flux towards the mover. The coil is wrapped around these teeth. Slotless means that there are no teeth present and instead the coil is held together by epoxy or similar and is placed in the airgap between the mover and the stator.

2.2.1 Linear reluctance motors

A linear reluctance motor is a type of linear motor that does not use permanent magnets [8]. The principle behind it is that the mover is made of a ferromagnetic material that is not magnetised but has a magnetic reluctance. The stator has sets of coils which are separated by non-magnetic spacers. The mover is slotted and these slots try to align with the excited phases of the stator and therefore there is a longitudinal force exerted on the mover. The lack of PM makes the reluctance machine easy to assemble and less expensive [2]. It also makes it more robust and increases fault tolerance.

2.2.2 Permanent magnet linear motors

The mover of a linear motor can be fitted with PMs, either surface mounted or integrated in to the mover [5]. This topic is further explored in section 2.2.4. By using PMs it is possible to improve the performance of the linear motor. This is also reinforced by Polinder et al. [38] who claims that PM linear motors have a high efficiency and high force density compared to other linear motors.
2.2.3 Linear motors in industry today

The use of linear electric motors spans across many industries and applications. Some examples include industrial automation, robotics, pick and place systems, high voltage breakers and actuators for door movements [51].

Since linear motors can achieve high forces there are also a lot of high force applications. For example, many amusement rides make use of linear motors. An example of this is the roller coaster Maverick in Sandusky, Ohio, USA [46]. It uses linear synchronous motors to launch the train up steep inclines. Another example is a developing area where linear electric motors is of potentially great use. The United States navy is currently in the late stages of implementing an electromagnetic aircraft launch system to propel aircrafts from their aircraft carriers [39][37]. It is expected to be more efficient and produce a higher force than the conventional steam piston technology [36][37]. The high power density, efficiency and power factor of a PM linear motor makes it a good contender for use in a aircraft launch system [14].

2.2.4 Permanent magnet arrays

As mentioned before, a lot of research has been performed recently in development of high force linear motors. Most of them utilise an array of permanent magnets to achieve the high thrust combined with high efficiency. Wang et al. [48] present a framework for analysis of different constructions of tubular linear motors with permanent magnet arrays. They vary from using radially magnetised and axially magnetised to Halbach arrays. These different types of magnetised PM arrays also produce different properties of the magnetic field. Halbach arrays are good at creating a strong field on one side of the array while reducing the intensity of magnetic field on the other side [33], see figure 2.1.

![Figure 2.1: A strong onesided field created due to a Halbach array. Flux density increases from blue to red.](image)

2.2.5 Tubular linear permanent magnet motors

A tubular linear permanent magnet motor is working on the same principle but has a cylindrical mover made of a ferromagnetic material [44]. Wrapped around this mover is one or more solenoids, which produce a magnetic field when a current is passed through it. This magnetic field interacts with the mover which causes it to move linearly along the length of the cylinder. Bolognani et al. [8] have concluded that a tubular reluctance linear motor has about 60% lower force/volume ratio than a TLPM. This thesis has therefore focused on TLPM.

The research on TLPM is extensive and comes in various forms. Ummaneni et al. [47] propose a high power linear motor to be used in oil drilling applications. They make use of a axially magnetised magnet array. Research on radially magnetised TLPM has been done by Bianchi [4] where he also proposes a methodology for analytical modelling of the same. Bianchi et al. [6] also propose a design guide for these actuators in one of their works.
Jang et al. [27], Moon et al. [32] and Ci Yong et al. [12] present different approaches to a TLPM with a single Halbach PM array. Furthermore, Yan et al. [25] and Consolo [14] have worked on development of a TLPM utilising a dual Halbach array. The dual Halbach array has a self-shielding effect and thereby reduces the magnetic flux leaking out of the machine.

Yan, et al. [25] state that only radial magnetic field can create an axial thrust on the mover. So, for this thesis owing to the complexities in manufacturing a Halbach array and the fact that strong permanent magnets often utilise rare earth elements, which are costly, it was decided to use a radially magnetised array of permanent magnets. This ensures that the solutions generated, although non-conventional, still remain practical enough to be utilised from industry’s point of view.

2.3 Losses

Electromagnetic systems, just like any other system, suffers from power losses. These losses reduce the maximum thrust force available in the linear motors and thereby limit their performance. Many of these losses vary with input current which makes it difficult to incorporate them into mathematical models. For this reason, losses are often not included in mathematical models for linear electric motors. Some of these losses are described below.

2.3.1 Saturation

Saturation losses take place when the relative permeability of the core reduces when placed in an increasing magnetic field. This leads to diminishing increase in flux density in the core on increasing current. Because of this phenomenon the thrust force of a linear actuator is not always proportional to a linearly increasing applied current.

Saturation losses cannot be avoided and are dependent on the material of the core. A B-H curve is often used to deduce the varying relative permeability of the material. The research on how to analytically model saturation in a linear motor is limited, but a common approach is to use a magnetic equivalent circuit (MEC) [11, 38, 43]. The approach differs between them but the idea is to model the magnetic elements as equivalent electrical components such as capacitors, resistors and batteries. Using this circuit it is then possible to incorporate saturation into the model.

2.3.2 Eddy currents

Similar to saturation, Sheikh-Ghalavand et al. [43] model Eddy currents with a MEC. The authors approximates it by making it a function of flux density in the time domain. The result is corrected by using a predetermined coefficient. Chen et al. [11] also use a MEC approach but make the eddy current losses a function of flux density as well as frequency. In these functions they also use loss coefficients which have been experimentally determined. Both approaches are complex and require experimental data, and according to the presented results, lack accuracy when compared against a FEM solver.

2.3.3 Hysteresis

Chen et al. [11] and Sheikh-Ghalavand et al. [43] both use a MEC approach and have formulated expressions, which similar to eddy currents, depend on frequency, flux density and experimentally determined coefficients.
This section presents the approach used to meet the aim of the thesis. It is divided into two sections where it is first described how the mathematical formulation and simulation model was developed. Second section describes how the simulation and testing were approached.

3.1 Modelling

The first requirement to meet the aim was to have a mathematical model which can predict the behaviour of the TLPM. As mentioned in section 2.2.3, multiple mathematical models relating to the TLPM were available. The mathematical model presented by Bianchi \[4\] was chosen to be implemented owing to the relative simplicity in implementation and enough evidence from other available research stating that the model was accurate, some examples being \[14\], \[28\], \[29\].

As mentioned in section 1.6, this report does not investigate the effects of eddy currents, hysteresis, demagnetisation, vibrations and thermal effects of the model. Thermal effects and demagnetisation are difficult to mathematically model as a continuous phenomena and can be only calculated with numerical iterations. Bianchi et al. \[6\] however present formulations to circumvent these limits, but it falls outside the scope of this thesis. Eddy currents and hysteresis are a lot more complicated to deal with and require experimental data in the formulations. Eddy current losses are for example affected by material properties, design and frequency of alternating current which make them hard to evaluate analytically. Given the time frame of this thesis, it is not possible to formulate a model of continuous losses from Eddy currents. Vibrations will be present in a rock drill and will have to be considered at some point, but it also falls outside the scope of this thesis.

As mentioned in section 2.3, many mathematical models of linear motors do not consider losses in the formulations. Bianchi’s model is no exception and assumes a lossless motor. This thesis however has taken saturation into account and implemented it in the mathematical model. If not accounted for, the force would keep increasing with the rise of current which results in an unrealistic force output from the TLPM upon application of increasing current. The method proposed by Chen et al. \[11\] is used for correcting the force value. The method requires solving a lumped parameter model of the magnetic circuit to calculate the returning
3.2 Debugging and optimization

flux in one pole pitch of the TLPM and taking the ratio of the flux linkage due to current calculated with non linear values of permeability and a constant value. The non linear values of permeability were taken from the experimental test data of a material from Epiroc.

The computational software Mathematica (see section 4.7.3), was used to model the mathematical formulations. Mathematica offers a range of tools which makes implementation and plotting of various mathematical functions simple and allows for validation of the plots against the EM field solver Ansys Maxwell (see section 4.7.1). Initially, to verify Bianchi’s results a FEM model without losses and ideal permeability values were considered. Later, the total force plot is compared against FEM using a mover of certain length. After achieving satisfactory correlation the mathematical model was transferred to a Hopsan component.

To transfer the TLPM model to Hopsan the mathematical formulations have to be converted into C++ code. The calculations in Hopsan for magnetic field distribution and forces are performed about a million times per second owing to a small time step required for stress wave calculations. This means that the computational time of the components would need to be kept to a minimum. The mathematical model uses Bessel functions which are computationally expensive and therefore they had to be replaced with two approximations, see section 5.3. This will be a trade off against model accuracy as the approximation may not work well for certain small geometry inputs which will be seen in upcoming sections.

3.1.1 Hopsan model

Epiroc has a custom library with components required to simulate rock drilling equipment. As was alluded to in the previous section, there were stresswaves that needed to be calculated in the model. To incorporate these waves into the simulation model, a piston component from the custom library was modified to become the mover of the TLPM. The TLPM mathematical model was therefore incorporated into one component which outputs the thrust force as a signal which was sent to the separate mover component. This, together with components from the Epiroc library and some custom subsystems complete the TLPM rock drill model in Hopsan. This model could then be used to test and analyse the electromagnetic percussion concept.

3.2 Debugging and optimization

The Hopsan model allows for simulation and testing of the electromagnetic percussion concept. To ensure the model was working, a series of checks were performed to ensure all parameters, which if varied, would not result into a non-physical solution. System parameters such as different radii of the mover geometry were defined in relation to one another to avoid, for example, a hole radius larger than the outer radius. Furthermore, some metrics to test performance were used, like frequency, energy and stress in drill steel. These metrics were implemented as target functions written as scripts.

To find a suitable geometrical design, model parameters were determined using optimization. There are a lot of parameters that can be controlled in the model and they had to be tuned to the most optimal value. The optimisation was performed with a set of weight functions for some target values which were multiplied together to make a total objective function. The optimization process then runs a number of iterative cycles to minimize this total objective function. With the optimisation complete it was possible to conduct performance tests on the rock drill and also investigating the effect that certain parameters have on said performance.
4 Theory

This chapter describes the theoretical background for topics relevant to this report. It also includes descriptions of the different softwares used.

4.1 Percussive rock drilling

The main principles of rock drilling as of today is piston impact force, feed force, rotation speed and flushing. An illustrative example of this can be seen in figure 4.1 below.

![Figure 4.1: The four main drilling functions in percussive rock drilling.](image)

The piston impact force is what is used to crush the rock. It is performed by a hydraulic hammer with a certain frequency. This is called percussion. The hammer impact will generate a shock wave which will travel through the extension rod to the drill bit and will break the
4.2 Magnetism

Since the work presented in this thesis considers the use of TLPM, the mathematical model makes use of formulations relating to magnetism. Quantities that are used throughout this work are magnetic flux density, magnetic field strength, permeance and permeability.

The equation relating magnetic flux density and magnetic field strength is given as,

$$B = \mu_0 \mu_r \cdot H$$

4.2.1 Flux density

Magnetic flux density is a measure of the amount of magnetic flux per unit area passing through a section perpendicular to the direction of magnetic flux. It is usually denoted by \( B \) and has tesla (T) as SI unit [40].

4.2.2 Field strength

Magnetic field strength, also called magnetic intensity or magnetic field intensity, is the part of the magnetic field that arises from an external current and is not intrinsic to the material itself [40]. It is expressed as the vector \( H \) and is measured in units of amperes per metre (A/m) which is the SI unit.

4.2.3 Permeance

Permeance is the inverse of reluctance in magnetism [23]. It can be defined as the quantity of flux passing through the length of a given cross section component at certain ampere turns of applied current. A larger cross section allows more flux to pass through while a smaller cross section restricts it; similar to a fluid flow through an orifice. It is expressed in units of Weber per Ampere turns, (Wb/AT).

4.2.4 Magnetomotive force

Magnetomotive force (MMF), like a voltage source, drives the flux to flow through a magnetic circuit [22]. Since, magnetic fields do not require a medium to flow through, a magnet or an electric conductor always has magnetic flux flowing around and through it. Magnetomotive force is expressed in Ampere turns (AT).

4.2.5 Permeability

Magnetic permeability is a property of a material that measures how easily it can support the formation of a magnetic field within itself [40]. It is equal to the ratio of the magnetic flux density \( B \) to the magnetic field strength \( H \) in the material. Higher permeability means more magnetic flux can pass through the material. The permeability of free space, or vacuum, is a constant denoted by \( \mu_0 \) and has a value of about \( 4\pi \times 10^{-7} \) Henry per metre (H/m).

Relative permeability is the ratio of absolute permeability of the material to the permeability of free space. Diamagnetic materials have relative permeabilities slightly less than 1,
meaning they weakly oppose the external field. Paramagnetic materials have relative permeabilities slightly greater than 1, hence they weakly enhance the external field. Ferromagnetic materials, on the other hand have relative permeabilities much greater than 1 so they strongly enhance the external field and can retain their own magnetization even after the external field is removed. 

Permeability of a material changes with the applied magnetic field strength and thereby affects the flux density in the material. This results in a characteristic curve called the B-H curve (shown in figure 6.3) which may be thought of as a visual representation of a material’s behaviour under applied magnetic field.

### 4.3 Lumped-parameter magnetic circuit model

A magnetic circuit model is required to be solved for taking saturation into account in this work. Similar to an electric circuit, a magnetic circuit also contains a source for the field, resistances which oppose it and conductors which allow its flow. For magnetic circuits the source or MMF can be a current carrying conductor or permanent magnet. The resistance to the MMF is offered by permeance of various mediums in the way. Instead of current, in a magnetic circuit flux is imagined to be flowing across the loop.

### 4.4 Modified Bessel functions

Two Bessel functions have been used in the mathematical formulation, namely Bessel function of first and second kind of orders 0 and 1. These functions are used in describing various physical phenomena such as heat transfer, electromagnetism and quantum mechanics. These functions, according to, are mathematically given as:

\[ I_v(z) = \left( \frac{1}{2} \right)^v \sum_{k=0}^{\infty} \frac{\left( \frac{1}{4} z^2 \right)^k}{k! \Gamma(v+k+1)} \]

\[ K_v(z) = \frac{\Gamma(v + \frac{1}{2})}{\sqrt{\pi}} \left( \frac{2}{z} \right)^v \int_0^{\infty} \frac{\cos lt dt}{(t^2 + z^2)^{(v+\frac{1}{2})}} \]

where \( v \) is the order of the Bessel function and \( \Gamma \) is the gamma function given as:

\[ \Gamma(n) = (n-1)! \]

### 4.5 Fourier Series

A Fourier series is a sum of sine and cosine terms with coefficients which can be used to approximate a function provided it is periodic. A Fourier series for \( f(x) \) is according to given as:

\[ f(x) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} a_n \cos(nx) + \sum_{n=1}^{\infty} b_n \sin(nx) \]

where,

\[ a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) dx \]

\[ a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos(nx) dx \]
4.6. Optimisation algorithms

\[ b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin(nx) dx \]

A Fourier series is particularly useful when a function is difficult to evaluate or is unknown. It acts a close enough replacement for the original function thereby simplifying the evaluation.

4.5.1 Gibbs phenomenon

Gibbs phenomenon is an oscillating or ringing effect seen when a Fourier series is used at a discontinuity. This is due to the usage of continuous terms being used to describe a non-continuous function. It is not possible to get rid of Gibbs phenomenon, which is evident in the forthcoming chapters. An example of Gibbs phenomenon is shown below in figure 4.2:

![Figure 4.2: Shows the effect of increasing number of terms in Fourier series](image)

A point to note is that increasing the number of Fourier terms leads to an increase in computational time so it is a trade off against accuracy.

4.6 Optimisation algorithms

Often in engineering problems, there are situations where a system in focus has a number of parameters, which if tweaked to have appropriate values, results in the overall performance of the system to be maximized. Since, manually varying all the parameters is not only tedious but can also result in a local maximum rather than a global maximum. Hence, an optimization algorithm is preferred to be used. Optimization algorithms utilise mathematical formulations which vary the parameters over a number of function evaluations to obtain a set of values which results in a global maximum for the given objective function. In this work the following algorithms have been used.

4.6.1 Complex-RF

Complex-RF is based on the simplex method and works by having a certain amount of parameters to be optimised. The key settings are a reflection coefficient, a randomisation factor and a forgetting factor. Then it has a number of points, usually double the amount of parameters, and each point gets assigned a random value. A simulation is then performed and the objective function is evaluated for each point. The worst point then gets reflected through the other points and afterwards the algorithm checks for convergence in the function and parameter values. If it has not converged it employs the forgetting factor and lessens the non-mirrored points objective value with it. Then it simulates again and repeats until convergence is achieved.
4.6.2 Particle swarm

Particle swarm is a population based optimisation method. It is slower than Complex-RF but has higher chance of convergence \[26\]. It works by spreading random particles in the parameter space and then assigns them a local point which is the best known point. Every particle keeps track of its own coordinates and will travel with a velocity that is determined by a weight factor. This weight factor depends on the best local point and the globally known best point. The working procedure is that it simulates each particle and evaluates the objective function. Then it updates the particle velocities according to the weight factor. The weight factor keeps changing since the particles move. The local best point and the globally best point update when a better one is found. This will repeat until convergence is achieved \[19\].

4.7 Software

Here follows a short description of the softwares used in this thesis.

4.7.1 Ansys Maxwell

Ansys Maxwell is an EM field simulation software used to simulate and electro-mechanical devices \[1\]. It uses FEM and it is possible to do both 2D and 3D EM field simulations, transient and steady-state analyses, and coupled EM and thermal analyses. A library of components and materials is included in the software.

4.7.2 Hopsan

Hopsan is an open source simulation software developed at the division of Fluid and mechatronic systems at Linköping university \[10\]. It has a wide range of system real-time simulation possibilities in domains like mechanics, hydraulics, pneumatics, and electrical circuits. Included in the software is a set of component libraries for all previously mentioned domains. Hopsan also includes a C++ code editor which allows the user to create their own custom components and libraries.

4.7.3 Mathematica

Mathematica is a computational software used for calculations in domains like mathematics, engineering and science in general \[41\]. It has some key features like symbolic and numerical computation, data visualisation, programming and machine learning.
Modelling of tubular linear motor

To create a Hopsan model for a TLPM, a mathematical formulation describing magnetic fields, forces and current density was required. The following sections show the mathematical modelling and verification of the TLPM. These equations were later converted to C++ code to be implemented into a Hopsan model.

5.1 Mathematical formulation of TLPM

N. Bianchi proposes in his paper a method for analytical calculation of magnetic fields and forces for a radially magnetized PM array in a linear motor. The model uses Bessel functions of first and second kind for the solution of the Laplace equation. This thesis has made use of this mathematical model for the TLPM concept. The model is presented below.

The linear motor was modelled as shown below in figure 5.1.

Figure 5.1: Piece of a linear motor model with infinite length. Recreated from Bianchi

Assumptions made by Bianchi in the model:

- Relative permeability of PM \( \mu_r \) is considered 1.
- Iron parts are considered to be infinitely permeable.
- The motor is considered to have infinite length.
- When modelling magnetic flux density and field strength distribution due to PM, it is assumed that there are no currents in conductors.
• When evaluating the magnetic fields due to the coil, the magnets are considered inert.
• Magnetisation $M_r(z)$ is considered to be a rectangular function in radial direction and is approximated using a Fourier series equation.
• The current is assumed to flow through an infinitesimally thin sheet at $r = r_s$.

Then, with the assumptions applied, the flux density for the permanent magnets can be written as:

$$B = \mu_0 (H + M)$$

Now, to calculate the magnetisation of the permanent magnet, a function is needed to describe the magnetisation direction and magnitude. This function can be obtained by using a Fourier analysis.

Since only radial magnetic field is assumed, $M_r(z)$ can, according to Bianchi, be written as:

$$M_r(z) = \sum_{n=1,3,5...}^{\infty} \hat{M}_n \sin(\omega_n z) \quad (5.1)$$

where,

$$\omega_n = \frac{n\pi}{\tau}$$

$$\hat{M}_n = \frac{4B_{res}}{n\pi \mu_0} \sin \left( \frac{n\pi}{2} \right) \sin(\omega_n \tau_m)$$

and $z$ is the axial coordinate on the mover. Figure 5.2 below shows the correlation between the Fourier approximation in equation 5.1 and the actual piecewise function.

![Figure 5.2: Comparison between direction of magnetism and approximated function](image)

Note that due to difficulties in evaluation, Bianchi proposes to use an approximation for $M_r(z)$ by multiplying an additional term which is shown in 5.3.

Since the structure is tubular and has cylindrical symmetry, B and H have only radial and axial components respectively. Also, due to the absence of currents $\nabla H = 0$ then the field equations are expressed as magnetic potential $\psi(r, z)$ which results into the Poisson’s equation:

$$\nabla^2 \psi = \frac{1}{r} \frac{\partial}{\partial r} (r M_r)$$
Then, equations for distribution of radial magnetic flux density due to PM in the region 1 and 2 are given by,

\[ B_1^r(r_s, x) = \mu_0 \sum_{n=1,3,5,...} \infty \omega_n (-A_n^1 I_1(\omega_n r) + B_n^1 K_1(\omega_n r)) \sin(\omega_n x) \]  \hspace{1cm} (5.2)  

\[ B_2^r(r_o, z) = \mu_0 \sum_{n=1,3,5,...} \infty \omega_n (-A_n^2 I_1(\omega_n r) + B_n^2 K_1(\omega_n r)) + \left( \frac{c_1}{r} + c_2 r \right) \tilde{M}_n(z) \sin(\omega_n x) \]  \hspace{1cm} (5.3)  

where, K and I denote Bessel functions of second and first kind, and where r is the coordinate in radial direction. The number in subscript represents the order for them.

Furthermore, Bianchi solves the Laplace equation and uses the boundary conditions at \( M_r = 0 \) to get the solution for axial field strength and radial flux density due to effect of the current carrying coil. The permanent magnets are considered to be inert here.

\[ H_z(r, z) = \sum_{n=1,3,5,...} \infty \omega_n (I_0(\omega_n r) + \beta_n K_0(\omega_n r)) \gamma_n \tilde{J}_n \sin(\omega_n z) \]  \hspace{1cm} (5.4)  

\[ B_r(r, z) = \mu_0 \sum_{n=1,3,5,...} \infty \omega_n (-I_1(\omega_n r) + \beta_n K_1(\omega_n r)) \gamma_n \tilde{J}_n \cos(\omega_n z) \]  \hspace{1cm} (5.5)  

The equations 5.4 and 5.5 are used for correlation of results obtained from the Hopsan simulation against Ansys Maxwell.

For calculation of total force on the mover, at a mover position \( x \) for a infinitesimal length \( dz \) the force \( df_z \) is, according to Bianchi, given as:

\[ df_z(x) = 2\pi r_s J_\theta(x) B_1^r(r_s, x)dz \]  \hspace{1cm} (5.6)  

where,

\[ J_\theta(x) = \sum_{n=1,3,5,...} \infty \tilde{J}_n \sin(\omega_n x) \]

\[ \tilde{J}_n = \frac{4N_s i}{n\pi} \]

\( B_1^r \) is the flux density distribution due to the permanent magnets in region 1 that is the area above radius \( r_m \) in fig. 5.1, given by 5.2. In this equation the effect of flux density by the current conductor is ignored. \( J_n \) is the coefficient of current density while \( J_\theta \) is the current density on the infinitesimal current sheet.

The purpose of the functions which are not listed but used in the above formulations are given in Table 5.1.
### 5.1. Mathematical formulation of TLPM

<table>
<thead>
<tr>
<th>Function</th>
<th>Function type</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{M}_n(z)$</td>
<td>Magnitude of Magnetization</td>
<td>Used to calculate the magnitude of magnetization</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>Helper function</td>
<td>Used to divide $\pi$ over the pole pitch to have the sine wave oscillate with pole pitch</td>
</tr>
<tr>
<td>$\hat{J}_n$</td>
<td>Current density coefficient</td>
<td>It calculates the magnitude of current density throughout the conductor which is utilised by $J_\theta$</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>Helper function</td>
<td>Used to incorporate the effects of air gap radius in the generalized equation 5.5 for flux density due to the coil</td>
</tr>
<tr>
<td>$\beta_n$</td>
<td>Helper function</td>
<td>Used to incorporate the effects of PM inner radius in the generalized equation 5.5 for flux density due to the coil</td>
</tr>
<tr>
<td>$A_n^1, A_n^2, B_n^1$ and $B_n^2$</td>
<td>Helper functions</td>
<td>Used to establish a relationship for variation of magnetic flux density distribution with varying values of $r_o, r_m$ and $r_s$ in equation 5.2 and 5.3</td>
</tr>
<tr>
<td>$c_1r + c_2r$</td>
<td>Approximation</td>
<td>To make computation of the field distribution easier, Bianchi altered the function $\hat{M}_r(z)$ to be a function of both axial and radial coordinates. This is used in equation 5.3. $c_1$ and $c_2$ are coefficients selected in a way to reduce modification of $\hat{M}_r(z)$ as much as possible.</td>
</tr>
</tbody>
</table>

### 5.1.1 Limits on Fourier series terms

A perfect Fourier series evaluation sums up the sine and cosine terms up to infinity, see equation 5.5. This is not computationally feasible when running the code a million times per second in a simulation. A solution to this was to limit the number of Fourier terms in the series to 13 terms. It is observed that on increasing the number of terms, the oscillations become smaller (see figure 5.3). It would make more sense to use 31 terms if accuracy was the only factor, but since the computational time has to be considered, 13 terms was found to be a reasonable trade off between the two.
5.1. Mathematical formulation of TLPM

(a) Total Force with 13 Fourier terms
(b) Total Force with 31 Fourier terms

Figure 5.3: Comparison of plots for total force on the mover with 13 terms and 31 terms

5.1.2 Total force

To obtain total force, equation 5.6 needs to be integrated over entire length of the mover. This was implemented in C++ using the explicit Euler integration method. The mover length $L$ is divided into chunks of $dz$ and the force $df_z$ is summed over to get the total force.

$$F_{n+1}(x) = F_n + df_z(x)$$

where $x$ is the axial coordinate of the mover with respect to origin of the stator. Since, $F_n$ is summed from $dz$ up to $L$ and is $L/dz$ times the small force $df_z$, then it is possible to write,

$$F(x) = \left(\frac{L}{dz}\right) df_z(x)$$

Then on integrating and multiplying an additional sin term to get a sinusoidal profile, the resulting final equation is given as

$$F(x) = 2\pi r_s J_0(x) B^1_\nu(r_s, x) \sin \left(\frac{\pi}{\tau} z\right) L$$

(5.7)

As mentioned in section 5.1.1, it is assumed that current control is present. In figure 5.3 it can be seen that the force has oscillating nature across the x-axis. To avoid the negative part of the force the polarity of current is changed such that the actuator ends up with a positive force. Since current control is assumed to be set up already, to achieve the positive force the values of $\sin\left(\frac{\pi}{\tau} z\right)$ are passed through an absolute function which converts negative values to positive.

5.1.3 Base parameters

Bianchi [4] has defined some parameters which are used to prove the equations presented in the paper. These parameters are initially used in this thesis as well to test and compare the implementations. The parameters are presented in table 5.2 below.

Table 5.2: Parameters used to verify the paper. Table is recreated from a table in [4]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [Unit]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>24 [mm]</td>
<td>Pole pitch</td>
</tr>
<tr>
<td>$\tau_m$</td>
<td>16 [mm]</td>
<td>Pole pitch of PM</td>
</tr>
<tr>
<td>$r_o$</td>
<td>15 [mm]</td>
<td>Inner PM radius</td>
</tr>
<tr>
<td>$r_m$</td>
<td>20 [mm]</td>
<td>Outer PM radius</td>
</tr>
<tr>
<td>$r_s$</td>
<td>21 [mm]</td>
<td>Outer airgap radius</td>
</tr>
<tr>
<td>$B_{res}$</td>
<td>1 [T]</td>
<td>Residual PM flux density</td>
</tr>
<tr>
<td>$N_s$</td>
<td>13 [-]</td>
<td>Coil windings per pole</td>
</tr>
</tbody>
</table>
5.1.4 Mathematica model

The mathematical model described by Bianchi [4], see section 5.1, was translated into a Mathematica model. The values in table 5.2 were used and the plots that Bianchi presents in his paper can be confirmed. Figure 5.4 below shows the flux density caused by the magnets. The plots for the radial distances match well with equivalent plots presented by Bianchi. There is some sinusoidal behaviour (Gibbs phenomenon) present in the Mathematica plots due to the limits used (see section 5.1.1), but if that is disregarded they align well, both in incline and peak value.

Figure 5.4: Plots of PM flux density from Mathematica with the implemented mathematical formulation. \( B_r \) is measured in T. a) \( r = r_o \) b) \( r = r_m \) c) \( r = r_s \)

The flux density due to the current is confirmed with Mathematica. Figure 5.5 shows this for the radial distances \( r_o \), \( r_m \) and \( r_s \). Again, Gibbs phenomenon is present in some of these plots as well. There is a discrepancy in 5.5c where the peak is \(~30\%\) smaller than the one Bianchi presents, but otherwise they match well. This discrepancy is further investigated in section 5.2.3.
5.1. Mathematical formulation of TLPM

(a) \( r = r_o \)  
(b) \( r = r_m \)  
(c) \( r = r_s \)

Bianchi [6] does not present a total thrust force plot from single phase current and it is therefore not possible to compare against that paper. However, it is possible to model it in Ansys Maxwell and make a similar plot. This plot is presented in section 5.2.4. The resulting total thrust force plot is presented in figure 5.6 below. It is assumed to be a \( 2\tau \) mm long mover which is being moved across a distance of \( 0 - 2\tau \) mm.

Figure 5.6: Total force acting on a \( 2\tau \) mm long mover plotted over a distance of \( 0 - 2\tau \) mm.
5.2 Verification with FEM

The FEM software Ansys Maxwell (section 4.7.1) was used to verify the results of the mathematical model proposed by Bianchi in section 5.1. The geometrical dimensions in the paper were used to create a 2D-model, see figure 5.7. Similar to the paper, it is an ideal model with the exception that the relative permeability of the iron were set to $40 \times 10^9 \, \text{H/m}$, to represent the infinite permeability assumption in the paper. The surrounding area was set as vacuum. The coil is divided into two parts, one for each pole. This allows for setting the current in two different directions.

![Figure 5.7: Ansys Maxwell 2D-model, the numbers represent: 1. Iron core, 2. Permanent magnets, 3. Outer iron, 4. Copper coil](image)

5.2.1 Boundary Conditions

In the FEM model a geometry called 'Region' was used to encapsulate the entire TLPM model. Since magnetic field lines can stretch out quite far from the vicinity of the FEM model, it is necessary to restrict the mesh area given to the solver, up to a certain limit. 'Region' is a feature used to demarcate the area of study.

As the solution was set to 'cylindrical about z', the outer edges of the 'Region' were given 0 vector potential. 0 value for vector potential forces the field to be 0 beyond the region of study. A image showing the 'Region' is show below in figure 5.8.

![Figure 5.8: 0 vector potential boundary condition in Maxwell](image)

5.2.2 Radial flux density from the PM

The PM flux density was verified with the 2D-model without any current in the coil, similar to the mathematical formulation. Each plot was made along an axial line, at the radial distances, $r_o, r_m$ and $r_s$. 

24
The resulting plots in figure 5.9 match with the equivalent plots from 4 to a high degree and therefore confirm the PM radial flux density. Figure 5.4 has the equivalent plots.

5.2.3 Radial flux density from the current

To verify the radial flux density from the current carrying coil, same 2D-model was used with some minor changes. The PMs were set as vacuum to model them as inert similar to the mathematical formulation and a current was added to the coil. The parameters from 4 were used, a current of 1 A and a winding of 13 turns per pole was added. One positive and one negative direction, for the two parts respectively.

The resulting plots in figure 5.10 match the characteristics of the paper results with the exception of the peak for \( r = r_s \). This is the same characteristic that was observed in the plot from Mathematica in figure 5.5c. It is then a fair assumption to assume that the mathematical model in Mathematica is correct.
5.2. Verification with FEM

5.2.4 Thrust force on the mover

To verify the total thrust force on the mover there needed to be a slightly different model. What was found to work is a 48mm long mover with a coil that extends through the entirety of a performed motion by the mover. It can be viewed in figure 5.11 below. Note that the coil is very thin (0.1mm) compared to the rest of the geometry and is attached to the outer iron.

As mentioned, the total thrust force plot was created by assigning a variable to the mover position in z-direction. This variable was then used to perform a step by step motion from z-position -12.5 mm to 35.5 mm with a step size of 0.2 mm. Then, for each step, the solver calculated the total thrust force that acted on the mover. The resulting plot is shown in figure 5.12. The plot is very coarse due to initially using a coarse mesh.
5.2. Verification with FEM

Later, the plot was recreated with a finer mesh, see figure 5.13. If compared against figure 5.6 in section 5.1.4, it is apparent that the total force produced in Ansys Maxwell is slightly lower than the mathematical model. A difference between the mathematical and FEM was expected due to the assumptions. For example, the assumption of infinite permeability was not possible to recreate in Maxwell. The coil is also assumed to infinitesimally thin, which also is not possible to model in Maxwell. Furthermore, the material properties in Maxwell might not be entirely comparable. Boundary conditions and mesh density might also affect the results.

Another factor could be that the mathematical model assumes that the B-field and H-field are purely radial and axial respectively. In reality, these might not be strictly one dimensional. Another factor could be the Bessel approximations (see section 5.3). One, potentially, major factor is the total force equation 5.7 which was presented in section 5.1.2. It is an approximation of equation 5.6 which was presented by Bianchi. This equation originally had an infinite summation which had to be limited. It also required some alteration which could have had an effect on the result.

Figure 5.12: Plot of the total thrust force before a full Ansys Maxwell licence was obtained.

Figure 5.13: Plot of the total thrust force with finer mesh.
5.3 Approximation of Bessel functions

Since the mathematical model need to be implemented in Hopsan, it is not suitable to use Bessel functions due to their computational complexity. Instead they have been simplified with a partly modified polynomial approximation by Culham [13]. The result is two expressions $BK(x)$ and $BI(x)$, one for BesselK and one for BesselI respectively. It was found that the approximations were suitable for both zero and first order and therefore same approximations are used for all orders.

$$BI(x) = \frac{e^x}{\sqrt{2\pi x}}$$

$$BK(x) = \sqrt{\frac{\pi}{2x}} e^{-x}$$

Comparing the plot results of the regular Bessel functions against the approximated ones shows that the approximations are working properly. Figure 5.14a shows the magnetic flux density in radial direction $B_r$ for both. It is plotted at $r = r_o$. The parameters used are the same that Bianchi used in his paper [4]. As can be seen, the plot lines are close to perfectly aligned. The result is the same in 5.14b which shows the magnetic field strength in axial direction, $H_z$. Also for both regular and approximated Bessel functions.

![Comparison of Bessel functions](image)

Figure 5.14: Shows a comparison between the regular and approximated Bessel functions for the geometry used by Bianchi [4]. The dotted lines represent the value that was calculated with the approximations.

Plotting the magnetic flux density at $r = r_s$ shows the weakness of the approximation. Figure 5.15a below shows that the plot lines do not align perfectly. A consequence of this is that the force per pole also becomes inaccurate. This can be seen in figure 5.15b which shows a comparison between the regular and approximated Bessel functions.
5.4 Saturation

As mentioned in section 5.1, the model presented by Bianchi assumes the mover iron to be infinitely permeable, meaning it can be infinitely magnetised by an increasing applied magnetic field (H). If this was the case, the force would proportionally scale with the current and could in theory go towards infinity if the current applied does the same. In reality there is a saturation limit of the magnetisation that occurs when a material is exposed to a magnetic field.
Chen et al. \cite{11} proposes a method to analytically correct for saturation in a mathematical model. They achieve this by calculating a correction factor with the use of a linear and a non-linear value for permeability. The non-linear value comes from a BH-curve for the material. To calculate this correction, the authors create a lumped-parameter magnetic circuit (see section 4.3) of the linear motor.

The value for linear permeability of the material is chosen such that it is maximum on the BH curve. This means that since it is a constant it would exhibit a linear relationship between flux density and field strength starting from origin.

### 5.4.1 Lumped-parameter magnetic circuit

Similar to electrical circuits, magnetic circuits can be formed by expressing individual components in the system as generators, conductors and consumers of magnetic flux. Since, saturation is closely linked to the amount of flux passing through a component in focus, a lumped parameter model is appropriate be used for modelling it. Chen et al. \cite{11} propose a method wherein they express electric coils and magnets as sources of MMF in a lumped parameter magnetic model. All other components, for example air, stator and core are treated as resistances. They use this lumped parameter model to calculate the return flux $\lambda_2$. Once an equation is obtained for $\lambda_2$ they use it with both linear and non linear permeability, to have a ratio of $\lambda_2$ in non linear and linear form. This results in a correction factor $k_{cf}$ which can be multiplied to force and radial flux density to account for saturation.

The model used by Chen et al. is not directly applicable to the TLPM used in this thesis. They use a slotted design with a quasi-Halbach PM array and this thesis has made use of a slotless design with only radially magnetised PM. It is therefore necessary to model the lumped-parameter magnetic circuit slightly differently. Figure 5.17 below shows a section of the TLPM which the magnetic circuit was modelled from. It highlights the magnetisation direction of the PMs and the flow of flux.

![Figure 5.17: Flux flow for the TLPM magnetic circuit](image)

Using figure 5.17 and the fact that the slotless topology of the TLPM has coils and no teeth, the magnetic circuit can be drawn as shown below in figure 5.18.
ϕ and λ are related to each other in way such that \( \lambda = N \cdot \phi \), where \( N \) is the number of turns. \( \phi \) has units 'Wb' while \( \lambda \) has units 'Wb turns'. So, the magnetic flux generated by a single turn of wire is given by \( \phi \) while flux linkage gives the amount of flux due to multiple turns of wires forming a coil \( \lambda \).

Table 5.3: Explanation of the components in the lumped-parameter magnetic circuit.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_a )</td>
<td>Air gap permeance</td>
</tr>
<tr>
<td>( P_m )</td>
<td>Magnet permeance</td>
</tr>
<tr>
<td>( P_{bs} )</td>
<td>Stator permeance</td>
</tr>
<tr>
<td>( P_{bm} )</td>
<td>Mover core permeance</td>
</tr>
<tr>
<td>( F_m )</td>
<td>Magnet MMF</td>
</tr>
<tr>
<td>( F_w )</td>
<td>Winding MMF</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Magnetic flux</td>
</tr>
</tbody>
</table>

5.4.2 Mathematical model

By solving the lumped-parameter magnetic circuit it yields the following expression:

\[
\lambda_2 = \lambda_j - \left( P_a - F_m P_m - F_m \left( P_m + \frac{1}{P_a} + \frac{1}{P_{m1}} + \frac{1}{P_{m2}} \right) \right) + F_m P_m + F_m + P_m - J_\theta(z) P_a
\]

which can be simplified into

\[
\lambda_2 = \lambda_j + \frac{|F_m(z)|}{\frac{1}{P_a} + \frac{1}{P_{m1}} + \frac{1}{P_{m2}}} \quad (5.8)
\]
where $\lambda_j$ is the flux linkage due to the winding. For this, the expression presented by Bianchi \[4\] was used and can be seen below.

$$\lambda_j = \sum_{n=1,3,5,...}^{\infty} \frac{32 \gamma_n r_s N_s^2}{n \omega_n} \frac{\mu_0}{\tau^2} \left[ I_1(\omega_n r_s) - \beta_n K_1(\omega_n r_s) \right]$$

Just as in section 5.1, there is an infinite summation present which will be limited by a certain number of terms. The permeances and the magnet MMF in equation 5.8 was calculated using the equations given by Chen et al. \[11\]. They are presented below with our adaptation of them indicated by the arrow.

**Airgap permeance:**

$$P_{nk} = \mu_0 \frac{2 \pi \tau_{nk}}{\ln \left( \frac{R_s}{R_m} \right)} \rightarrow P_a = \mu_0 \frac{2 \pi \tau_m}{\ln \left( \frac{r_s}{r_m} \right)}$$

**Stator back-iron permeance:**

$$P_{bm} = \mu_0 \mu_{rbm} \frac{\pi \left( R_s^2 - R_i^2 \right)}{\tau_{eq}} \rightarrow P_{bs}(\mu_{rbs}) = \mu_0 \mu_{rbs} \frac{\pi \left( r_s^2 - (r_{bs} - h_{bs})^2 \right)}{\tau}$$

**Mover core permeance:**

$$P_{bm} = \mu_0 \mu_{rbm} \frac{\pi \left( R_s^2 - R_i^2 \right)}{\tau_{eq}} \rightarrow P_{bm}(\mu_{rbm}) = \mu_0 \mu_{rbm} \frac{\pi \left( r_s^2 - r_{oi}^2 \right)}{\tau}$$

**Magnet MMF:**

$$F_{mk} = \frac{B_r (R_m - R_i)}{\mu_0 \mu_{rpm}} \rightarrow F_m(z) = \frac{B_r(r,z)(R_m - r_o)}{\mu_0 \mu_{rpm}}$$

Equation 5.8 are then used to calculate two flux linkages, one for linear permeability and one for non-linear \[11\]. The quotient of them becomes the correction factor, $k_{cf}$.

$$k_{cf} = \frac{\lambda_{2,non-linear}}{\lambda_{2,linear}} \quad (5.9)$$

Most of the parameters used are explained in section 5.1 and figure 5.1, but there are some specific ones that are only used for saturation model. They can be seen in table 5.4 below. The implementation of the mathematical model for saturation is written in section 6.1.1 and 6.1.2.

**Table 5.4: Additional parameters used in the saturation model.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{rpm}$</td>
<td>Permeability of the PM</td>
</tr>
<tr>
<td>$\mu_{rbc}$</td>
<td>Permeability of the mover core</td>
</tr>
<tr>
<td>$\mu_{rbs}$</td>
<td>Permeability of the stator</td>
</tr>
<tr>
<td>$r_{bs}$</td>
<td>Radius to where the stator starts</td>
</tr>
<tr>
<td>$h_{bs}$</td>
<td>Thickness of the stator</td>
</tr>
</tbody>
</table>
6 Hopsan model for rock drilling

This thesis has made use of the simulation software Hopsan. To model the EM rock drill it was required to convert the mathematical model, described in section 5.1, into a Hopsan component. The Hopsan components are written in C++ and therefore the equations in the Mathematica document have to be manually rewritten into C++ code. This chapter shows how the rock drill simulation model with a TLPM was built in Hopsan by creating some custom components and subsystems while, also making use of Epiroc’s extensive custom Hopsan component library.

6.1 Custom components

After finalising the code for the TLPM, it was separated into two components in Hopsan. One component is the mover of the TLPM. The other supplies the calculated force to the mover and may be visualised as the coil winding and the stator. Two subsystems were also created, one for the non-linear permeability and one for the controller. Subsystems in Hopsan’s context are a bunch of components encapsulated into a block so that the main model in which the components are used remains tidy. The complete Hopsan model can be seen in figure 6.12.

6.1.1 Force generator

The force generator component represents the winding part of the linear motor. It calculates the force that would be exerted on the mover when an electric current is applied to it and sends it to the mover. It makes use of the mathematical model described in section 5.1 and calculates the total force with the expression from section 5.1.2. It also implements the mathematical model of the saturation presented in section 5.4.2. All relevant helper functions for saturation are present in the component and the final force calculation for each timestep is modified with the correction factor, $k_{cf}$.

$$F_{tot} = k_{cf}F(z)$$

where $F(z)$ is a function call to equation 5.7 and $z$ is the position of the mover. $k_{cf}$ is calculated by using equation 5.9 and a linear and a non-linear permeability. The non-linear permeability is calculated from a BH-curve in a subsystem and is explained in more detail in section 6.1.2.
6.1. Custom components

The force generator has two physical ports called ‘power ports’ in Hopsan. These can in the future be used with a more advanced current supply but in this thesis it is just treated as a pure signal component. The ports are for now just connected to two ground components. The force generator and all its ports can be viewed in figure 6.1. The letters in the figure are explained in the bullet list below:

- A: Input for single phase current.
- B: Force output which is fed to the mover via a force component from standard library of Hopsan as shown in fig 6.12.
- C: Output for magnetic field strength. Used to calculate the non-linear permeability. More about that in section 6.1.2.
- D: Inputs for the permeability of the mover and stator.
- E: Input for the relative position of the mover.
- F: Ground connections connected to the power ports.

![Figure 6.1: Force component](image)

The mathematical model assumes an infinitely long coil and that assumption is mathematically present in the force component as well. It is assumed that the mover always is covered by coil so the design can be thought of as having a coil that covers the entire moverlength + strokelength. A detailed design of the coil is not considered in this thesis. The conductor thickness is assumed to be 1 mm. Sabulsky et al. [42] show that using Bitter plates with 1 mm copper conductor thickness, it is possible to transmit approximately 500 Amperes. Using this assumption the number of conductors per pole are calculated as,

$$\text{Number of conductors} = \frac{\text{Pole pitch}}{0.001}$$

This modification allows the number of conductors that can be fit on the pole pitch of the TLPM to vary with the geometry and removes solutions where excessively large number of conductors are present on a small pole pitch.
6.1.2 Permeability subsystem

The saturation calculation in the force component requires a non-linear permeability value for the stator and mover core. The TLPM mathematical model assumes an infinitely permeable iron core and stator so the saturation model will correct that. The mover core material will therefore be changed to a test material provided by Epiroc that can be used as a percussion hammer. The same material will also be used as the stator material. To calculate the non-linear permeability, a subsystem was created which can be seen in figure 6.2. The magnetic field strength calculated by the force component is sent into the subsystem as input and a non-linear value for permeability is sent out. The permeability is then split into two when fed back into the force component, one for the stator and mover core respectively. In this concept they are assumed to be same but the option of having them as different exists.

Figure 6.2: The permeability subsystem component in Hopsan computes a non-linear permeability from a magnetic field strength, $H$.

The permeability calculation makes use of a standard library component called 1DLookUpTable. It is possible to manually write or load a .csv file into it with x and y values. It will then interpolate all the values between those into a graph. With this it is possible to feed in a x value and get back the corresponding y-value. This feature was utilised by creating a .csv file with a BH-curve. The BH-curve was provided by Epiroc and was obtained from experimentally testing a material, see figure 6.3 below.

Figure 6.3: BH-curve for the test material. The values were experimentally measured by Epiroc on a material sample.
The data of the BH-curve only existed in a PDF and had to be extracted with a digitising tool. The result is figure 6.4 below. The data in Excel was linearly interpolated until the B-value reached 1.8 T. It was saved in a .csv file and added to the LookupTable. Since the maximum value of the data is 1.8 T, it is also the maximum B-value that the LookupTable will have. It means that all H-values above 29 525 A/m will result in 1.8 T from the component.

![Figure 6.4: Interpolated BH-curve used in the LookUpTable component.](image)

The permeability from the BH-curve was found using the following expression:

$$\mu = \frac{B}{H}$$

If equation 6.1 is applied to the BH-curve in figure 6.4 it results in a permeability plot shown in figure 6.5 below. It is not smooth throughout and has some discrepant spikes. This can be explained by the rough plot in figure 6.3, but also the digitising which made the plot even less smooth. By applying equation 6.1 in the subsystem in figure 6.2, it takes in the H-field, extracts the B-field value and divides that by the H-field value. The permeability value then gets returned to the force component.
6.1 Custom components

6.1.3 Mover component

Stress waves are an essential part of rock drilling and the mover was therefore made as a separate component to accommodate them. The hydraulic rock drill uses a piston to hit against the shank and a variety of these pistons exist in Epirocs custom Hopsan component library. The pistons from Epiroc are divided into a number of elements depending on what is required. Figure 6.6 below shows an example of this.

![Piston component](image)

Figure 6.6: Piston component that shows the individual elements.

The code from one of these pistons was modified to become the mover. This was achieved by for-loops and each element is assigned a length and a diameter. The length and diameter assigned, is determined by whether it is a magnet or not. The final geometry will look similar to the image representing the component in figure 6.7. The left part of the piston facing the shank adapter has a uniform diameter. The size and length of the magnets will affect the rear part only. One assumption that is made, is that the magnet and steel core have the same density. This assumption simplifies the mass calculation since the densities does not differ considerably with about 7.4-7.7 and 7.75-8.05 g/cm$^3$ for neodymium and steel respectively [16].

![Mover component](image)

Figure 6.7: Mover component.

Figure 6.5: Permeability curve
6.1. Custom components

Below follows an explanation of the different ports labeled with letters in figure 6.7.

A: Input for the thrust force sent from the force component and acts as a connection to the casing.
B: Output connection to the shank.
C: Output for total mover length.
D: Output for total mover mass.
E: Output for largest diameter of mover.
F: Output for the cross section area of the mover front end facing the shank.
G: Output for the mean velocity of the mover.

6.1.4 Controller implementation for current

The percussion motion needs to be controlled and for this, a position and velocity based controller was implemented. It alters the current direction which in turn makes the force either positive or negative. For the purposes of this thesis the current supply was only modelled to behave like an electrical switch. As can be seen in figure 6.8, it is simply a switch between either positive or negative current. The switch component is a Hopsan standard component and it is being controlled by the controller subsystem.

The controller, seen in figure 6.9 below, is a logic based controller and uses four inputs. Two switching positions, one for the impact position and one for the return position, and two velocity conditions, one for positive and one for negative velocity. The two conditions that determine if the current should be positive or negative are:

1: Positive velocity AND reached impact position → switch to negative current.
2: Negative velocity AND reached return position → switch to positive current.
6.1. Custom components

An example on how the output control signal from the controller subsystem can look is shown in figure 6.10.

![Controller subsystem diagram](image)

The return switching position is, just as the name suggest, a position where the current is switched and the thrust force will switch direction to accelerate the mover for impact again. However, first it has to brake the mover. This will create a overshoot which depends on the inertia of the mover and the thrust force. This is illustrated in figure 6.11 below.

![Controller output signal](image)
6.2 Electromagnetic rock drill model

A simulation model of the electrified rock drill was created by connecting the custom components with components from the Hopsan standard library and from Epiroc in-house developed library, figure 6.12. Components are labeled with letters and the custom components mentioned before are the mover (B), the force component (I), controller subsystem (G), and permeability subsystem (H). The main components from the Hopsan and Epiroc library are shank (A) which gets impacted on by the mover and transfers the stresswave. A Translational mass component (C) which represents the casing of the rock drill. On the casing there is a feed force (D) pushing the rock drill forward into the rock model (E).

The Hopsan models implements two of the main principles of percussion rock drilling as explained in section 4.1. Percussion from the mover hitting on the shank and the feed force. The other two, that is rotation and flushing are not present in the model. Rotation is not considered since what is interesting in this initial study is the longitudinal waves and the impact energy. Furthermore, as mentioned in 1.1 rotation only induces strain in the rock and contributes to tightening of the steel, hence it was deemed not necessary to model for the simulation of percussion rock drilling. Flushing is not necessary to simulate since it does not affect the study.
As mentioned in previous sections, the TLPM has been separated into two parts. The force component requires the mover position to calculate the thrust force; therefore a position feedback is connected from the mover. To account for the feed force and that the rock drill is moving forward into the rock, the relative position between the mover and the casing is calculated and fed back to the force component.

The casing of the rock drill as mentioned previously, is represented by a component called *Translational mass*. The mass and viscous friction parameters of the component were set to represent an actual rock drill which weighs about 300 kg. The viscous friction were set to 10000 Ns/m to emulate the feed friction which the rock drill experiences from the feed beam on the drill rig. To connect the casing to the mover and the shank Epiroc has some special components (F in figure 6.12) that can connect multiple connections and keep track of gaps and positions of the components that are connected together. If it notices that two components are in contact with each other it will match the velocity of the two. In other words, transfer movement or impact.

The drill rod (A) is another component from the Epiroc component library. It has the function of transferring the stresswave from the impact of the mover into the rock. In between the drill rod and the mover there is a shank onto which the mover is hitting. The shank then transfers the stresswaves to the drill rod. In this model the drill rod is represented by two components so that the stress waves could be measured in the middle. This makes it easier to discern between an impact wave going towards the rock and a reflection wave that is going towards the rock drill.

As mentioned previously, Epiroc has a rock model in their standard library. This simulates actual rock which makes it possible to test the drilling performance. It also simulates reflections that get transmitted back against the rock drill. Since this rock drill concept does not have any damper system implemented, these reflections propagate back into the rock drill and create a oscillatory stress behaviour. This is illustrated in figure 6.13. The library also provides a reflex free rock model, which as the name suggests, do not send any reflections back into the rock drill. The stress waves from that is illustrated in 6.14. This makes it easier to only measure the impact stress wave without any noise or reflections which was important when optimisation was performed.

Figure 6.12: Hopsan model for the electromagnetic rock drill
Epiroc has developed some components to make the measuring and evaluation of the performance of rock drill models easier which also applies to the electromagnetic model. An example is a component which calculates the impact velocity, stroke length, impact frequency, and impact position. Another is a component which finds the stress peak of a stress wave. All this data makes it possible to, for example, calculate impact energy which was important to know in the optimisation.
6.3 Results from the Hopsan test model

This section will present and explain some plots and data. The rock drill configuration is not optimised and is chosen arbitrarily just to explain the different plots and phenomena. The thrust force acting on the hammer in hydraulic rock drill is very consistent. Comparatively, the thrust force from the electromagnetic concept is more inconsistent due to the single phase current. An example of the thrust force is shown in figure 6.15 below.

![Thrust force plot](image)

Figure 6.15: Thrust force and average thrust force in Hopsan over a short distance of an arbitrary value of $2\tau$ and a constant current of 200 A.

The force over the full stroke length is therefore not continuously applied which can be seen in figure 6.16. In this figure both the force and mover position have been plotted and the discontinuous force behaviour is clearly seen.

As mentioned in section 6.1.3, the mover component calculates a mean velocity and sends it out through an output port. This velocity had a lot of noise and would in some cases produce unreliable peak values, see figure 6.17. This behaviour is due to the characteristics of the piston component that the mover component is based on. Referring back to figure 6.7, the component consists of multiple individual elements which, depending on the configuration, can be very short in length. This means that the step time needs to be sufficiently small to be able to compute the stress waves throughout the length of the component. This had to be balanced against the total simulation time and was desirable to be kept at a minimum in an optimisation scenario.

The unreliable peak values of the mean velocity could result in unstable energy calculations since those peaks will be the impact velocity from which the impact energy is calculated. To achieve a more stable and reliable energy calculation, a first order low pass filter was applied to the mean velocity output before it was sent into the component which calculates the impact velocity. This meant that any noise would get filtered and the impact velocity would be more reliable. The result of the filtered mean velocity can be seen in figure 6.18.
6.3. Results from the Hopsan test model

Figure 6.16: Thrust force and mover position in Hopsan. Shows the oscillatory force behaviour.

Figure 6.17: Mean mover velocity of the mover.
To visualise the rock drilling figure 6.18 is used, which in this report will be called a drill scope. It shows the position of the mover and how it repeatedly strikes the shank in a percussive motion. The top line is the shank position and shows how far into the rock it has drilled. The bottom line is the position of the casing which should proportionally follow the shank position due to the applied feed force. The oscillating line is the position of the mover which is hammering against the shank.
6.3. Results from the Hopsan test model

As mentioned earlier, each impact from the mover onto the shank produces a stress wave which travels into the rock. The shape of this stress wave affects the rock drilling efficiency of the rock drill and it is therefore of interest how the plot looks. A plot of an impact stress wave for the reflex free rock model is presented in figure 6.24.

### 6.3.1 Bianchi model comparison

To confirm that the C++ conversion was successful and that the component was working as intended, the dimensions in table 5.2 was applied and simulated. Figure 6.20 below shows the force plotted over $2\tau = 48\text{ mm}$. The current control was removed to compare the sinusoidal behaviour to the plot from Mathematica in figure 5.6.
6.3. Results from the Hopsan test model

Figure 6.20: Force with the dimensions presented by Bianchi. Current control is removed to compare against Mathematica. A current of 1 A and 13 fourier terms was used.

6.3.2 Saturation

If the $k_{cf}$ presented in section 6.1.2 is applied to the thrust force it makes force non-linear and experience diminishing returns for an increase of current. Figure 6.21 below shows an example of how the thrust force is affected by the saturation. The current was ramped from 0-200 A in a fixed mover position.

Figure 6.21: Thrust force with and without saturation with a linear increase of current from 0-200 A. Mover position is constant.
Figure 6.22 shows the saturation from another perspective. In this plot it was the current that was kept constant at 200 A and the mover position was varied from 0 to $2\tau$ mm where $\tau$ is arbitrarily put as 45 mm. As can be seen, the force gets rounded and the peaks get halved.

To showcase the behaviour of the correction factor $k_{cf}$ it was plotted with the non-linear permeability against the current in figure 6.23.
6.3.3 COP 1838

The hydraulic rock drill this electromagnetic rock drill concept was compared against was the COP 1838 seen in figure 1.4. The specifications are presented below in table 6.1. The stresswave for COP 1838 is presented in figure 6.24 and has a peak of \( \sim 261 \) MPa.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Energy</td>
<td>300 J</td>
</tr>
<tr>
<td>Power</td>
<td>15 kW</td>
</tr>
</tbody>
</table>

Table 6.1: Specifications for the COP 1838 rock drill.

Figure 6.24: Stress wave of the COP 1838.
Model Investigation

In this chapter the results from experimentation on the model designed in chapter 6 are collected. A pattern has been identified in the nature of TLPM forces so that the range for selecting the parameters can be tweaked accordingly.

7.1 Influence of geometrical parameters on TLPM force

The geometrical parameters of the mover significantly influence the characteristics of the thrust force. For instance, it is seen that increasing the pole pitch increases the force but only up to a certain point. After that the force output is reduced (section 7.1.6). Thus based on the requirement these characteristics if tweaked can result into better performance. The influence of individual parameters is presented in the following sections.

7.1.1 Core thickness

The force output of the TLPM is restricted due to the saturation of the core which occurs as the magnetizing field strength increases. To counter this, the core thickness can be increased and thereby allowing more flux to pass through the mover. This however, also increases inertia and size of the TLPM.
7.1. Influence of geometrical parameters on TLPM force

Figure 7.1: Influence of increasing core thickness with an arbitrary base value.

7.1.2 Magnet axial thickness and radial thickness

For a high force output the magnet axial length should be rather small. This ensures that more number of magnets can be packed across the length of the mover. With more magnets the number of poles increases as well which leads to higher peak forces during the stroke of the mover. This, then results in higher accelerations and impact velocity.

Figure 7.2: Influence of magnet axial thickness with an arbitrary base value.

Radial thickness on the other hand can be increased and decreased without having large repercussions on force output. However, some of the delimitations like, magnetostriction can affect this parameter. The plot for force variation with increasing radial thickness of magnet is given below.
7.1. Influence of geometrical parameters on TLPM force

Figure 7.3: Influence of increasing radial thickness with an arbitrary base value.

7.1.3 Number of magnets

The force output of the mover is seen to be directly proportional to number of magnets on the length of the mover. A mover with more number of axially thin magnets is better than a lesser number of axially thick magnets. This is a logical conclusion as the number of magnets equal to number of poles. Thus there are more force peaks throughout the mover stroke.

Figure 7.4: Influence of number of magnets with an arbitrary base value.

7.1.4 Air gap

With increasing air gap it was seen that there was a reduction in force output of the TLPM. Owing to low permeability of air, the flux density in the TLPM is reduced if the air gap is
7.1. Influence of geometrical parameters on TLPM force

high. Hence, air gap is inversely proportional to force output. However, air gap can be used to regulate the energy and frequency of the TLPM during optimization since, unlike number of magnets the airgap need not to be an integer value.

Figure 7.5: Influence of increasing air gap with an arbitrary base value.

7.1.5 Hole diameter

The effect of a hole through the axis of the mover is twofold. The hole diameter, when increased, can result in reduced mass which helps in achieving higher frequency in the rock drill but it comes at a cost of reduced area for transmission of flux, thereby limiting the force due to saturation.

Figure 7.6: Influence of increasing hole diameter with an arbitrary base value.
7.1.6 Pole pitch

The nature of pole pitch is not linear and the limits up to which an increase is seen varies with the rest of the geometry. In figure 7.7, it can be seen that the effect of increasing pole pitch increases the force only up to a certain point after which, the magnets are spaced too far apart and there is no more increase in the force output. It is difficult to know at which point the value is maximum and hence optimization algorithms are best suited to find it.

![Figure 7.7: Influence of increasing pole pitch with an arbitrary base value.](image)

7.2 Time step

It was seen that in the electromagnetic rock drill model, (section 6.2) the minimum time step to get consistent result is observed to be at least $7 \cdot 10^{-7}$ seconds. Other time steps were studied to obtain the results for frequency and energy. However, $8.5 \cdot 10^{-7}$ was chosen because it provided consistent energy, albeit with a small deviation in frequency. In the interest of reducing optimization time, $8.5 \cdot 10^{-7}$ provides more incentive to be used.
Figure 7.8: Study of variation of energy and frequency with change in timestep
Once the Hopsan model for the electric rock drill was finished, the dimension inputs for the model can be optimised to meet certain target objectives. The target objectives were chosen such that the electrified rock drill would have a comparable performance to a COP 1838 rock drill. The list of objectives included a set range of impact energy, operating frequency and stress in the drill steel. The chosen ranges for these objectives are listed below:

- Impact energy: For impact energy the range was chosen as 280 J - 320 J. This value was selected based on the performance parameters of the COP 1838 and representative for blast holes for tunneling.

- Frequency: Frequency was chosen based on the existing specifications of the COP 1838. Therefore the target frequency was set to 50 Hz and above.

- Drill steel stress: Limit for drill steel stress was set as 280 MPa. This specification was set according to the material restrictions in the drill steel.

- Largest mover diameter: The largest diameter was preferred to be between 30 mm and 60mm so that the mover dimensions aligned closer to COP 1838 piston.

The objectives were then written as a list of target functions which would result in weight values for different values of frequency, energy, stress and diameter.

8.1 Optimization prerequisites

To run an optimization it was necessary to define an objective function, a parameter space and select an appropriate algorithm.

8.1.1 Defining target functions

The weight functions were modelled so that the return value would indicate the weight of the input parameter. For instance, the acceptable value of energy was between 280 - 320 J. Thus, the weight function was written as two different slopes, see figure 8.1.
8.1. Optimization prerequisites

The plot shows how the weight function for energy varies for different values of energy. The function yields a value of 1 between 280 J - 320 J while anywhere else, weight is less than one. The slopes are not steep to avoid numerical instabilities that might occur while running the optimization. Mathematically, the function is represented as,

\[ W_e(e_{\text{kin}}) = \max(0, \min(w_1(e_{\text{kin}}), \min(1, w_2(e_{\text{kin}})))) \]

where,

\[ w_1(e_{\text{kin}}) = \frac{e_{\text{kin}} - e_1}{e_2 - e_1} \]
\[ w_2(e_{\text{kin}}) = \frac{e_4 - e_{\text{kin}}}{e_4 - e_3} \]
\[ e_{\text{kin}} = m_{\text{piston}} \cdot \frac{v_{\text{imp}}^2}{2} \]

above \( e_1 = 1 \) J , \( e_2 = 280 \) J , \( e_3 = 320 \) J and \( e_4 = 599 \) J and \( m_{\text{piston}} \) is the mass of piston, \( v_{\text{imp}} \) is the impact velocity of piston.

The function takes the impact energy of the piston as an input and calculates the slopes with functions \( w_1 \) and \( w_2 \). It then compares \( w_2 \) against 1 and selects minimum from them. This is done to have a value which is always less than 1, being compared against \( w_1 \). Then, minimum value between \( w_1 \) and 1 is selected to be compared against 0. The maximum value between them is selected. The function is therefore designed to always keep the value of weight between 0 to 1. So, if all the weights are scaled between 0 to 1 then the optimization should aim to converge at a target value of 1.

Similarly, other weight functions have been designed to ensure that solver converges onto to the set of parameters which are closer to the reference rock drill COP 1838. These are frequency, drill steel stress limit and a mover outer diameter limit. They are defined in a way similar to energy and are graphically represented in figure 8.2.
8.1. Optimization prerequisites

The total objective function whose value would vary between 0 to 1 based on the geometry can be defined as the product of individual weight functions. For this work the weight for energy was prioritised over other weights to ensure that the energy delivered with every impact is about 300 J. This was achieved by squaring the weight of energy. Due to effect of squaring the solver has to achieve higher value of weight on energy to get as high value as possible on the total objective function. The total objective function was defined as,

$$\text{totalObj}(e_{\text{kin}}, \text{freq}, \text{stress}) = W_e(e_{\text{kin}})^2 \cdot W_f(\text{freq}) \cdot W_s(\text{stress}) \cdot W_d(\text{diameter}) \cdot (-1)$$

Hopsan optimisation finds the optimum by minimising the objective function, therefore -1 is multiplied to the whole expression which means that the most optimal solution will be -1.

8.1.2 Range selection for parameters

The mathematical formulation had the input system parameters defined as separate independent radii but to avoid non physical results from the solver, the dimensions of the mover had to be defined in relation to each other. For instance, $r_o$ or the core radius had to be defined as a sum of hole radius of the mover and core thickness. Now, hole radius and core thickness can be defined as separate optimization parameters with arbitrary limits as there cannot be a case where the hole radius could be bigger than the core radius. Similarly, $r_m$, or the outer radius of the PM, was defined in the same manner as $r_o$ but with added PM radial thickness. For length of the mover, an integer number of magnets were multiplied with the pole pitch. The number conductors per pole were made into a function of pole pitch over thickness of conductors, which was assumed to be 1 mm.

Figure 8.2: Weight functions for (a) frequency, (b) stress in the drill steel and (c) largest diameter of mover
8.1. Optimization prerequisites

The ranges of the parameters were selected such that combination was geometrically feasible
and the solver would still have enough room to vary the parameters. The optimum ranges
were figured out by running an initial optimization study using Complex-RF, see table 8.1.

Table 8.1: Parameters used for optimization

<table>
<thead>
<tr>
<th>Optimisation Parameter</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole radius (ri)</td>
<td>0 - 50</td>
<td>mm</td>
</tr>
<tr>
<td>Core thickness (corethk)</td>
<td>15 - 80</td>
<td>mm</td>
</tr>
<tr>
<td>PM radial thickness (dmag)</td>
<td>2 - 40</td>
<td>mm</td>
</tr>
<tr>
<td>Number of PMs</td>
<td>5 - 24</td>
<td>-</td>
</tr>
<tr>
<td>PM axial thickness (taum)</td>
<td>3 - 30</td>
<td>mm</td>
</tr>
<tr>
<td>Gap between PM (dTau)</td>
<td>4 - 50</td>
<td>mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1 - 9</td>
<td>mm</td>
</tr>
</tbody>
</table>

8.1.3 Optimization algorithm selection

Multiple algorithms are available in Hopsan optimization. The selection of an appropriate
algorithm is affected by multiple factors like number of cores available on the processor,
number of model parameters and simulation time per analysis to name a few. It was difficult
to predict from the beginning which solver could be appropriate, so it was chosen to start the
optimization with Complex-RF since this is commonly used by Epiroc.

For optimizing the geometry of mover in this work, Complex-RF algorithm was used ini-
tially to understand the convergence pattern the solver is going to follow using the parameters
as given in 8.1. Then the algorithm was changed to Particle Swarm since the computer had
enough cores to handle parallel computations.

It was seen that, although Complex-RF can find one optimum point faster it does not
always converge to the global optimum irrespective of increasing the number of evaluations.
Furthermore, Particle Swarm algorithm seemed to be slower due to large number of particles
to reach the optimum point but the converged values seemed to have reach the global optimum
as the difference between the objective function values amongst the models was negligible.
8.1.4 Parameters used for Particle Swarm optimization

The parameters that were modified in the Particle Swarm settings are listed in Table 8.2. All other parameters values were set to default.

**Table 8.2: Parameters for Particle Swarm optimization**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling</td>
<td>Latinhypercube</td>
<td>Two methods of sampling are available, latinhypercube and random. With random sampling the solver time was seen to be higher and unpredictable</td>
</tr>
<tr>
<td>Maximum evaluations</td>
<td>300</td>
<td>300 evaluations were chosen because it was observed that convergence in values would happen around 200 iterations but sometimes more was needed</td>
</tr>
<tr>
<td>npoints</td>
<td>22</td>
<td>Sufficiently large number of particles are needed to explore entire sample space. 22 was chosen as CPU had maximum 11 threads</td>
</tr>
<tr>
<td>nmodels</td>
<td>22</td>
<td>Number of models need to be equal to number of particles for optimization to run</td>
</tr>
<tr>
<td>nparams</td>
<td>7</td>
<td>Number of parameters is equal to optimization parameters. For switching case it was set to 8</td>
</tr>
</tbody>
</table>

8.1.5 Simulation time reduction and memory management

Longer model simulation time will result into longer optimization time, hence it is important to reduce the model simulation time as much as possible to have faster convergence. Furthermore, memory management is crucial as well. Hopsan by default logs all the signals which causes the optimization program to be less responsive after large number of evaluations. An easy fix for this was to use the function '\texttt{dlog *}' in the optimization script to disable all data logging and then use '\texttt{elog +}' where '+' were the signals required to be logged for calculation of objective function.

For reducing model simulation time, the time step and number of Fourier terms were tweaked to get faster model simulations.

8.2 Convergence check

After the optimization loop was completed, the optimization parameters were checked if convergence was achieved or not. On observing the target functions and the initial results from the Complex-RF, it is understood that mover must be longer in length and smaller in diameter. This footprint of the mover should yield the best value for the total objective
function as it is dependent on maximising impact velocity, minimising mass and maximising frequency. If the mover is shorter then the force generated would not be enough as the number of magnets that can be mounted onto the mover would reduce. Furthermore, the larger diameter, which although allows more flux to counter the effects of saturation, will also inadvertently increase inertia and thereby reducing the frequency of the rock drill. Thus, the optimized value should have an aspect ratio which results in longer length and smaller outer diameter.

The plot for fitness of solution obtained from the optimization using Particle Swarm indicate that convergence was achieved (figure 8.4). The optimization cycle was run for 250 evaluations utilising 22 models in parallel which resulted in 5508 function evaluations.

![Plot showing fitness values across evaluations using Particle Swarm](image)

In the plot it can be seen that the total objective function values with increasing evaluations become constant for the latest and the worst value and are almost equal to best value meaning the solver was not able to increase the value for objective function anymore. Thus it was considered that the convergence in the optimization analysis had been achieved.

**8.3 Optimisation results**

This section presents the results from the Particle swarm optimisations. They have been performed with both a fixed return switch position and as a parameter. For individual optimisations, both impact and return stroke uses the same amount of current. The rock model that was used throughout the optimisations was the reflex free rock model. All the resulting specifications are collected and shown below in table 8.3. A more detailed result for each optimisation is presented in the following sections.
8.3. Optimisation results

Table 8.3: A collective table displaying all the resulting specifications from the optimisations. SW-fix = Fixed return switching position. SW-var = Return switching position is an optimisation parameter.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>SW-fix, 200A</th>
<th>SW-var, 100A</th>
<th>SW-var, 200A</th>
<th>SW-fix, 585A</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mover outer diam.</td>
<td>59.4</td>
<td>59</td>
<td>43.9</td>
<td>50.0</td>
<td>mm</td>
</tr>
<tr>
<td>Mover length</td>
<td>740</td>
<td>690</td>
<td>1030</td>
<td>689</td>
<td>mm</td>
</tr>
<tr>
<td>Mover mass</td>
<td>13.7</td>
<td>12.8</td>
<td>10.2</td>
<td>8.1</td>
<td>kg</td>
</tr>
<tr>
<td>Tot. stroke length</td>
<td>142</td>
<td>226</td>
<td>170</td>
<td>96</td>
<td>mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>26.5</td>
<td>15.0</td>
<td>26.9</td>
<td>50.1</td>
<td>Hz</td>
</tr>
<tr>
<td>Impact energy</td>
<td>284</td>
<td>280</td>
<td>294</td>
<td>303</td>
<td>J</td>
</tr>
<tr>
<td>Power</td>
<td>7.5</td>
<td>4.2</td>
<td>7.9</td>
<td>15.2</td>
<td>kW</td>
</tr>
</tbody>
</table>

8.3.1 Return switch position as parameter, 100 A

In the first optimisation, the return switch position was included as a parameter with a range from 14 mm to 38 mm relative to the impact position.

Table 8.4: The return switch position as a optimisation parameter. The values are measured from the impact position.

<table>
<thead>
<tr>
<th>Optimisation Parameter</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return switch position</td>
<td>14 - 38</td>
<td>mm</td>
</tr>
</tbody>
</table>

The resulting optimisation parameters are shown in table 8.5 and the rock drill specifications are shown in table 8.6. The specifications were taken from component outputs after the optimised parameters were applied to the model and simulated. The drill scope is presented in figure 8.5.

Table 8.5: Parameter optimisation result, for optimisation at 100 A with return switch position as parameter.

<table>
<thead>
<tr>
<th>Optimisation Parameter</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole radius (ri)</td>
<td>0</td>
<td>nm</td>
</tr>
<tr>
<td>Core thickness (corethk)</td>
<td>27.5</td>
<td>nm</td>
</tr>
<tr>
<td>PM radial thickness (dmag)</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Number of PMs</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>PM axial thickness (taum)</td>
<td>3</td>
<td>mm</td>
</tr>
<tr>
<td>Gap between PM (dTau)</td>
<td>50</td>
<td>mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Return switch position</td>
<td>38</td>
<td>mm</td>
</tr>
<tr>
<td>Objective function</td>
<td>-0.64893729</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 8.6: Resulting geometry and specifications for optimisation at 100 A with return switch position as parameter.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mover outer diameter</td>
<td>59</td>
<td>mm</td>
</tr>
<tr>
<td>Mover length</td>
<td>690</td>
<td>mm</td>
</tr>
<tr>
<td>Mover mass</td>
<td>12.8</td>
<td>kg</td>
</tr>
<tr>
<td>Total stroke length</td>
<td>226</td>
<td>mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>15.0</td>
<td>Hz</td>
</tr>
<tr>
<td>Impact energy</td>
<td>280</td>
<td>J</td>
</tr>
<tr>
<td>Power</td>
<td>4.2</td>
<td>kW</td>
</tr>
</tbody>
</table>

Plotting the thrust force that acts on the mover shows that it peaks at $\sim 4$ kN (figure 8.6). The current and position are plotted in figure 8.7. It shows that it has an overshoot of 62 mm after the return switch position.
8.3. Optimisation results

Figure 8.6: Thrust force and mover position for optimisation at 100 A with return switch position as parameter.

Figure 8.7: Mover position and the input current to the force component for optimisation at 100 A with return switch position as parameter.
8.3. Optimisation results

A stresswave from the mover impact is shown in figure 8.8. The peak value is at 189 MPa.

Figure 8.8: A stresswave measured in the middle of the drill steel for optimisation at 100 A with return switch position as parameter.

8.3.2 Return switch position as parameter, 200 A

Similarly, this optimisation also includes the return switch position as a parameter shown in table 8.4. Running the optimisation with 200 A yields the following parameters presented in table 8.7. The resulting specifications, which were taken from component outputs after the optimised parameters were applied to the model and simulated, are shown in table 8.8.

<table>
<thead>
<tr>
<th>Optimisation Parameter</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole radius (ri)</td>
<td>0</td>
<td>mm</td>
</tr>
<tr>
<td>Core thickness (corethk)</td>
<td>20.0</td>
<td>mm</td>
</tr>
<tr>
<td>PM radial thickness (dmag)</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Number of PMs</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>PM axial thickness (taum)</td>
<td>15.1</td>
<td>mm</td>
</tr>
<tr>
<td>Gap between PM (dTau)</td>
<td>50</td>
<td>mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Return switch position</td>
<td>38</td>
<td>mm</td>
</tr>
<tr>
<td>Objective function</td>
<td>-0.76938709</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8.7: Parameter optimisation result for 200 A with switch position as parameter.
Table 8.8: Resulting geometry and specifications for 200 A with switch position as parameter.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mover outer diameter</td>
<td>43.9</td>
<td>mm</td>
</tr>
<tr>
<td>Mover length</td>
<td>1.03</td>
<td>mm</td>
</tr>
<tr>
<td>Mover mass</td>
<td>10.2</td>
<td>kg</td>
</tr>
<tr>
<td>Total stroke length</td>
<td>170</td>
<td>mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>26.9</td>
<td>Hz</td>
</tr>
<tr>
<td>Impact energy</td>
<td>294</td>
<td>J</td>
</tr>
<tr>
<td>Power</td>
<td>7.9</td>
<td>kW</td>
</tr>
</tbody>
</table>

The drill scope is presented in figure 8.9. The frequency is higher in this optimisation which can be visually observed on the mover position compared to figure 8.5.

Plotting the thrust force that is acting on the mover shows that it peaks at \( \sim 10 \) kN (figure 8.10). The current and position is plotted in 8.11 and shows that the overshoot of mover from the return switching position is 42 mm.
8.3. Optimisation results

Figure 8.10: Thrust force and mover position for optimisation at 200 A with return switch position as parameter.

Figure 8.11: Mover position and the input current to the force component for optimisation at 200 A with return switch position as parameter.
A stresswave from the mover impact is shown in figure 8.12. It peaks at 173 MPa.

**8.3.3 Fixed return switch position, 200 A**

In this optimisation, the switch position for the return stroke was fixed at 30 mm from the impact position and the current was set to 200 A. The most optimal parameters that were found are presented in table 8.9. The resulting specifications, which were taken from component outputs after the optimised parameters were applied to the model and simulated, are shown in table 8.10.

<table>
<thead>
<tr>
<th>Optimisation Parameter</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole radius (ri)</td>
<td>0</td>
<td>mm</td>
</tr>
<tr>
<td>Core thickness (corethk)</td>
<td>27.7</td>
<td>mm</td>
</tr>
<tr>
<td>PM radial thickness (dmag)</td>
<td>2.0</td>
<td>mm</td>
</tr>
<tr>
<td>Number of PMs</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>PM axial thickness (taum)</td>
<td>10.6</td>
<td>mm</td>
</tr>
<tr>
<td>Gap between PM (dTau)</td>
<td>42.8</td>
<td>mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1.45</td>
<td>mm</td>
</tr>
<tr>
<td>Objective function</td>
<td>-0.7647588</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 8.10: Resulting specifications for optimisation with 200 A with a fixed return switch position.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mover outer diameter</td>
<td>59.4</td>
<td>mm</td>
</tr>
<tr>
<td>Mover length</td>
<td>740</td>
<td>mm</td>
</tr>
<tr>
<td>Mover mass</td>
<td>13.7</td>
<td>kg</td>
</tr>
<tr>
<td>Total stroke length</td>
<td>142</td>
<td>mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>26.5</td>
<td>Hz</td>
</tr>
<tr>
<td>Impact energy</td>
<td>284</td>
<td>J</td>
</tr>
<tr>
<td>Power</td>
<td>7.5</td>
<td>kW</td>
</tr>
</tbody>
</table>

Figure 8.13 shows the drill scope. The frequency is almost the same as for the optimisation with the return switch position as parameter at 200 A, so visually it looks very similar to figure 8.9.

Figure 8.13: Electromagnetic drilling performance with a reflex free rock for optimisation with 200 A with a fixed return switch position.

Plotting the thrust force (figure 8.14) that is acting on the mover shows that it peaks at \(\sim 10\) kN. Figure 8.15 shows the input current and the mover position. Notice the overshoot which is about 35 mm measured from the return switch position.
8.3. Optimisation results

Figure 8.14: Thrust force and mover position for optimisation with 200 A with a fixed return switch position.

Figure 8.15: Mover position and the input current to the force component for optimisation with 200 A with a fixed return switch position.

A stresswave from the mover impact is shown in figure 8.16. Peak value is 183 MPa.
8.3 Optimisation results

8.3.4 Fixed return switch position, 585 A

To test if it was possible to reach the desired specifications that the COP 1838 has, an optimisation with higher current than the other tests was performed. The optimisation was performed with 550 A as current and a fixed return switch position at 30 mm from the impact position. The result from this did not reach the desired 50 Hz and therefore the current was increased until this was achieved. The final current was 585 A and the resulting parameters can be seen below in table 8.11. The rock drill specifications, which were taken from component outputs after the optimised parameters were applied to the model and simulated, are shown in table 8.10.

Table 8.11: Parameter optimisation result for optimisation with 585 A and a fixed return switch position.

<table>
<thead>
<tr>
<th>Optimisation Parameter</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole radius (ri)</td>
<td>8.0</td>
<td>mm</td>
</tr>
<tr>
<td>Core thickness (corethk)</td>
<td>15.0</td>
<td>mm</td>
</tr>
<tr>
<td>PM radial thickness (dmag)</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Number of PMs</td>
<td>9.0</td>
<td>-</td>
</tr>
<tr>
<td>PM axial thickness (taum)</td>
<td>30.0</td>
<td>mm</td>
</tr>
<tr>
<td>Gap between PM (dTau)</td>
<td>41.0</td>
<td>mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Objective function</td>
<td>-1</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 8.16: A stresswave measured on the middle of the drill steel for optimisation with 200 A with a fixed return switch position.
Table 8.12: Resulting specifications for the 585 A optimisation.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mover outer diameter</td>
<td>50.0</td>
<td>mm</td>
</tr>
<tr>
<td>Mover length</td>
<td>689</td>
<td>mm</td>
</tr>
<tr>
<td>Mover mass</td>
<td>8.1</td>
<td>kg</td>
</tr>
<tr>
<td>Total stroke length</td>
<td>96</td>
<td>mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Impact energy</td>
<td>303</td>
<td>J</td>
</tr>
<tr>
<td>Power</td>
<td>15.2</td>
<td>kW</td>
</tr>
</tbody>
</table>

The drill scope is shown in figure 8.17. Notice the difference in frequency for the mover position compared to the other optimisations.

![Graph](image)

**Figure 8.17:** Electromagnetic drilling performance with a reflex free rock for the 585 A optimisation.

Plotting the thrust force that is acting on the mover (figure 8.18) shows that it peaks at ~15 kN. Figure 8.15 shows the input current and the mover position. The overshoot from the return switch position is 16 mm.
8.3. Optimisation results

A stresswave from the mover impact is shown in figure 8.16. The peak value is 217 MPa.
8.3. Optimisation results

Figure 8.20: A stresswave measured on the middle of the drill steel for 585 A optimisation. Peak is at 217 MPa.
The parameters obtained from optimization have been used and then parameters such as current and TLPM parameters were varied to obtain the characteristic curves. By utilising an optimised geometry and varying one parameter at a time it was possible to plot the effect on performance. Resulting parameters from the optimization with fixed switching position and 200 A, presented in section 8.3.3, was used.

9.1 Effect of varying mass of the mover

To study the influence of mover mass on the performance, the density of the mover component was varied. With a correcting factor ranging from 0.5-1.5 multiplied by the steel density of 7.8 g/cm$^3$. This resulted in a maximum mass of 20.5 kg which was gradually decreased with steps of 2.8 kg until it reached 6.8 kg.

Fictitiously, if there existed a material with strength and magnetic properties similar to steel but less dense, then the performance of the rock drill is seen to benefit from it. This is mostly due to the fact that inertia of the mover is reduced and subsequently the TLPM thrust force are large enough to handle rapidly changing velocities of the mover.
9.2. Effect of varying current

To study the effect of current it was decreased from 280 A in steps of 20 A down to 20 A. The result is presented in figure 9.2 below. It can be seen that the power output is increasing with the current. For the optimised geometry at 200 A with a fixed switching position it is possible to increase the current input to 220 A and still be within the impact energy range of 280-320 J. This results in a frequency of 27.6 Hz and an impact energy of 309 J which yields an output power of 8.5 kW.
9.3 Effect of varying core diameter

The influence of the steel core was investigated by varying the diameter. Since all other radial parameters are defined in relation to the mover core, this value was the only one that would need to be varied for this test. It was decreased from 36 to 14 mm in steps of 2 mm. It is seen that increasing the core diameter also increases the output energy at the cost of a reduction in frequency. Below 16 mm the frequency drastically reduces and no longer follows the linear trend.

![Figure 9.3: Influence of mover core diameter.](image)

9.4 Effect of length

This analysis investigated the effect of length. The length is varied with the amount of PM, or more specifically, in multiples of \( \tau \) which kept constant at 53.4 mm. The analysis started with 18 PM (1.01 m in length) and then decreased with 2 PM (2\( \tau \)) until 4 PM (0.263 m).

Similarly to the influence of core diameter, there is a point where the linear trend does not continue anymore. In this case it is at about 6 PM or 0.4m. Above these values the result is very linear where the frequency remains unchanged but the impact energy increases with the length.
9.5 Effect of varying hole diameter

To test the influence of a hollow mover a hole diameter was set to 20 mm and then gradually reduced down to 0 mm in steps of 2 mm. The initial value of 20 mm was somewhat arbitrarily chosen so that the core still would have some thickness since the core diameter is 27.7 mm.
Drilling a hole along the axis, through the mover core reduces the weight of the mover but it also reduces the cross section area for the flux to travel through. Just removing mass increases the frequency which was shown in section 9.1, but removing mass at the cost of cross section area does not produce the same behaviour. It is seen that a larger hole diameter yields a lower frequency but increases energy. With this said, it is also apparent that the energy gained is displaying diminishing returns with an increase of hole diameter. The plot shows that increasing the airgap yields lower impact energy and frequency and therefore lower power.

9.6 Effect of varying airgap

The impact of performance due to the airgap between the outer diameter of the magnet and the coil was also investigated. The airgap was initially set to 9 mm and was then gradually reduced in steps of 1 mm until 1 mm. It is apparent that an increase in airgap comes with a decrease in power.

![Figure 9.6: Influence of airgap.](image-url)
The results obtained in chapter 9 follow an expected pattern. It was seen that while solving the optimization problem, the algorithm converged towards as large core diameter as possible to counter the effects of saturation in the core. When a penalty function was applied to the outermost core diameter, the algorithm had incentive to design a mover with smaller core but with increased length. This seemed in line with the logic as a certain amount of force from the TLPM is required to get the required striking energy and frequency.

A major challenge with electrical machines is the absence of damping from the viscosity of the hydraulic fluid. In the electromagnetic rock drill model, there is no provision of damping and hence the overshoot in the return stroke, after the piston impacts onto the shank, is higher which in a hydraulic system could be far smaller.

10.1 Effect of delimitations

In the section 1.6 the delimitations that had been considered in this work are discussed in brief. If the design is translated to reality, these delimitations will have some sort of effect on the performance of the percussion mechanism. A quantitative assessment has not been discussed but a qualitative study has been done on the following delimitations.

10.1.1 Hysteresis

Hysteresis in electromagnetism is a phenomenon which occurs when a ferromagnetic material gets magnetized or demagnetised. It is dependent on the material and cannot currently be changed by changing parameters in the system. From material test data, hysteresis in the piston material was observed to be rather small. Though it may cause some force reduction in the TLPM, hysteresis is presumed not to be a major problem due to good material properties.

10.1.2 Eddy currents

Eddy currents are induced currents that oppose the relative motion of magnets through a conductor. They can be visualized as an electromagnetic equivalence of fluid viscosity in the system. While, the eddy currents are expected to reduce the amount of peak force generated
in the system, they could potentially also increase damping in the system which may improve some system characteristics. One such characteristic might be the electromagnetic braking when the mover has reached the return switch position. Currently, it was difficult to turn around the piston but if eddy currents are considered in system analysis, it may help with slowing the piston down after impact.

10.1.3 Skin effect

Skin effect is a phenomenon observed when changing magnetic fields within a current carrying conductor affect the distribution of current due to the creation of internal eddy currents [30]. This forces the current to flow in a shallow band just underneath the surface of the conductor. This increases the apparent resistance of the conductor.

Skin effect is highly dependent on the frequency of the current [30]. In this work the frequency of strokes affects the frequency of current. So, if the frequency of percussion is increased the resistance of the conductor increases thereby limiting how much current can be delivered at increased frequency. However, skin effect is hardly noticeable at the frequencies which a rock drill usually operates at (40 - 110 Hz).

10.1.4 Demagnetization

Magnets lose their magnetization over time when exposed to higher magnetic fields for prolonged duration. Heat further aggravates this phenomenon. It was not known whether the stress waves propagating through the magnets will aggravate the demagnetization. Overall, the mechanism for demagnetization in this application was difficult to predict.

10.1.5 Temperature control

Since this work assumes the current supply to be hundred to several hundred Amperes, significant heat generation can be expected. This can potentially be detrimental to the longevity of the TLPM. Neodymium magnets get demagnetized when exposed to heat because heat randomizes the polarized nature of the magnetic poles in the magnets [34].

Furthermore, maintaining the structural integrity of the conductor will also be a concern and maintaining the temperature will be essential for continuous operations.

10.1.6 Magnetostriction

Magnetostriction is a material intrinsic property due to which it changes its shape when subjected to magnetic field [24]. This will have effects on the stress wave propagation since magnetostriction also imposes compressive stress into the material. It may add more nonlinearities into the Hopsan model. There are however ways to reduce magnetostriction in a component which need to be studied.

10.1.7 Current controller

In this work the switching position is controlled by a simple logic which assumes current to be similar to an electric switch. It is possible to implement a position controller with a reference for the mover to follow. Using a feedback and a PI-controller or similar could potentially reduce the current requirement, especially in the return strokes if the piston retains some inertia. It opens up additional possible adjustments in the system parameters to improve performance. The complexities with introducing a position control entails that the reference position must allow for a natural motion of the piston while braking during the return stroke.
This is complicated as the profile of the curve from the actual position of the piston is a n-degree curve as seen in figure 6.19.

### 10.1.8 Structural strength of PM

The mathematical TLPM model in this thesis uses surface mounted, radially magnetised magnets. This in itself is nothing out of the ordinary which was found in the literature study presented in chapter 2. However, since the mover of the electromagnetic rock drill also acts as the hammer, there is a potential issue of how the rock drill will sustain in a normal operational environment. The stress from each impact might eventually break the magnets. As mentioned in section 2.2.2, another way to utilise PMs in linear motors is by using axially magnetised PM, integrated into the mover. Axially magnetised and radially magnetised PM linear motors have a similar performance in terms of force per volume \[5\]. Integrating the PMs therefore has the potential to increase the structural strength without compromising on performance.

### 10.2 Effect of assumptions in modelling

A number of assumptions have been made throughout this work the effect of which is presented in the sections to follow. These assumptions had to be made due to the constraints of computational complexity and avoiding uncertainty.

#### 10.2.1 Restricting BH curve

The BH-curve obtained from Epiroc’s material data (figure 6.3) had data points restricted to 1.8 T. The behaviour of the material post this point was an unknown and hence the curve has not been extrapolated to keep the analysis closer to reality. However, there may be some performance gains if higher B-field is allowed.

#### 10.3 Inconsistent forces

It could be seen from figure 6.22 that the nature of forces due to the usage of single phase supply has peaks but at certain positions and at other positions there is zero force. If a multi phase supply, for instance a 3 phase supply, is used then the number of force peaks, albeit lower, could be more in number and therefore a potentially more uniform force application. Since saturation eliminates much of the highest forces, a lower, more evenly spaced force would potentially yield better performance.

### 10.4 Model performance: strengths and caveats

It was observed that increasing and decreasing time step did not have a linear effect on solver time. Since the model uses a number of calculations involving Fourier series the solution time is affected by the changing the number of Fourier terms.

#### 10.4.1 Maximum usable time step: Force component

The maximum usable time step with the force component (section 6.1.1) was found to be \(1 \cdot 10^{-3}\) s. However, the maximum usable time step is dependent on other components in the electromagnetic rock drill model. For instance, as mentioned in section 7.4, the minimum time step to get consistent result is \(7 \cdot 10^{-7}\) seconds. This is due to the stresswave propagation calculations being performed in the mover component (section 6.1.3). A small time step like \(7 \cdot 10^{-7}\) makes the model perform calculations, which are placed in a for-loop to sum the Fourier series terms, 13 times per calculation per iteration. In other words, if the H-field density was to be calculated at a given time step, the model would have to execute the for-loop 13 times to
10.4. Model performance: strengths and caveats

sum up all the Fourier terms in the equation for H-field. Compounding this with other B-field and current density calculations, it leads to excessively large number of computations for the Hopsan model. However, a time step of $8.5 \cdot 10^{-7}$ was chosen as the difference in frequency from $7 \cdot 10^{-7}$ was negligible while the energy was roughly the same. Hence, with $8.5 \cdot 10^{-7}$ we were able to reduce the time for optimization as opposed to what it would have been if $7 \cdot 10^{-7}$ was used.

Unfortunately, the total solver time cannot be reduced even more unless other components in the system are able to work with a larger time step. The effect of time step is demonstrated on individual component simulation time in figure 10.1 below.

![Figure 10.1: Timestep influence on individual component simulation time](image)

10.4.2 Time to acquire steady state

One of the major benefits of the Hopsan model is that it requires short times to reach steady a steady percussion behavior. A reason for this could be attributed to the force component using analytical method to calculate the output force of the TLPM. The major delay in achieving steady state then stems from having the stress wave propagation being realised using TLM method.

10.4.3 Remark on oscillations in piston velocity

It was seen that the piston mean velocity from the simulations was rather oscillative. These oscillations are unwanted as the result obtained from the component which calculates the impact velocity is rendered incorrect. Hence the low pass filter was used. It filters out the oscillations to allow for identification of true impact velocity peaks.

After some experimentation, it was found that the oscillations stemmed from using large number of elements in the mover component presented in section 6.1.3. The mover component was derived from Epiroc code and hence the reason for oscillations could not be identified. The speculated cause for it, seemed to be due to the nature of propagation of stress waves.
10.5 Trends seen in optimization

The differences in filtered signals with number of elements in the mover have been illustrated below.

![Figure 10.2: Oscillations in mean velocity of piston](image)

It can be observed that in Figure 10.2c, the peak for the mean velocity from the filtered signal is roughly about 0.2 m/s higher. This leads to a false optimum in the optimization and has to be accounted for. Unfortunately, the only way it could be accounted for was to run multiple optimisations and get a rough understanding of where the true optimum lies. Then it was possible to adjust the maximum magnet limit and the number of mover pieces according to a rough estimate on the maximum number of magnets the algorithm was allowed to use.

10.5 Trends seen in optimization

As mentioned in section 8.1.3, particle swarm was used as the optimization algorithm in this work. It was seen that when the limits of the parameter space or the number of parameters were increased it resulted in a subsequent need for increase in number of particles being used by the algorithm. The reason for this could be that an increase in sample space of the parameters increases the effect of luck on spawning the particles and the chances of converging onto a local optimum would be high.

10.6 Merits and demerits with using electromagnetism

Electromagnetism is a neat solution for generating periodic motion with high speed. Furthermore, they have fast response times and free of unwanted characteristics such as cavitation. This allows for implementation of sophisticated control strategies which can adapt with operational requirements.

However, electromagnetic systems are more challenging to design and analyse. They lack the power density possessed by hydraulic systems and require a separate heat dissipation system. To make their design more complicated, the losses due to eddy currents, hysteresis and saturation reduce the maximum force available. Adding to this is the fact that these
losses vary dynamically with the applied input power.

In spite of the shortcomings, an electric rock drill, if designed and optimized for better efficiency, has the potential to reduce energy losses compared to its hydraulic counterpart.

10.7 Input power

Since the design of coil was not a part of this work it was also not possible to calculate the reactance of the coil. Because of this, the current was not drawn from a source and rather supplied arbitrarily. Consequently, it was not known how much input power was being supplied to the rock drill and whether it was enough to reach the requirement of 300 J and 50 Hz, that is 15 kW. Unfortunately, to solve this in a meaningful way, the only option would be to design the coil and then model the reactance.
Conclusion

An initial investigation to identify whether a completely electric rock drill is feasible has been carried out using modelling, simulation and optimisation.

11.1 Research questions

*What is a suitable electromagnetic percussion concept?*

The quest for a suitable concept started with the question whether an EM linear motor or a rotary electric motor with a crank shaft could be the way forward. The investigation of an electromagnetic linear motor, more specifically a TLPM with radially magnetized PMs, has been shown as a potential candidate. The optimisation results and characteristic curves in section 8.3 and chapter 9 present initial evidence on the possibility of electrification of rock drills. Substituting a TLPM in place of a hydraulic piston can work, albeit with multiple challenges which would need further investigation.

*How does the electromagnetic concept compare to its conventional hydraulic equivalent in terms of performance?*

The performance of the EM rock drill concept is dependent on several factors but as has been shown in this report, current is one parameter that has a great impact. After parameter optimization, the rock drill model will in theory reach the same performance as a COP 1838 if supplied with 585 A. As discussed in section 10.4, the required input power is unknown and it is therefore a possibility that 585 A is too little, or even too much.

*What is the characteristic behaviour of the electromagnetic percussion concept?*

When it comes to controlling the piston motion, having a TLPM is more beneficial than a hydraulic cylinder. It also eliminates certain drawbacks that are associated with the hydraulic counterpart such as cavitation, compressibility and other phenomena related to hydraulic oil.
11.2 Concluding remarks on electrified percussion mechanism

From this work certain conclusions can be drawn on the behaviour of electrified percussion mechanism in rock drills.

- Strokes are longer compared to hydraulic counterparts of similar size with lower input current.
- Energy and frequency are inversely proportional when using lower currents. There is a trade off as to what energy one wants with corresponding frequency.
- There is a compromise between use of lower currents and dimensions of the mover. A mover needs to be longer if less current is applied for the same diameter to achieve the required energy.
- There can be virtually non existent switching delay between polarities of the current.
- Electrified percussion can offer much more finer control over piston position and frequency than in the hydraulic counterpart provided high enough current is applied.

11.3 Future work

“All models are wrong, but some are useful” - George E.P. Box

This thesis work serves as a great platform for a multitude of possible improvements.

11.3.1 Closed loop position and frequency control

In this work a simple controller with a switching position is used to commence the impact or return stroke after the piston has reached a certain position.

An improvement over this controller could be controlling the position of the piston to follow a certain trajectory for optimum utilisation of energy along with controlling frequency of percussion. This could potentially make it possible to have variable percussion depending on the stiffness of the rock. If the rock stiffness changes during the drilling process, then a closed loop control can adjust the amount of current applied to the percussion mechanism.

11.3.2 Coil design

A coil has not been designed in this work. All the calculations involving current use number of conductors and current as an input without considering the dimensions of the coil which will required to power the TLPM. Coil design could involve designing a Bitter plate magnet which could then be cooled by deionised distilled water.

Furthermore, designing the coil gives the opportunity to calculate reactance. Using reactance current rather being supplied arbitrarily as a signal could be drawn from a voltage source which in turn allows for calculation of input power and from it the efficiency of the electrified rock drill.

11.3.3 Eddy current effects modelling

An analytical model of eddy current’s effect on the piston movement inside the coil could be made. Eddy currents could aid the damping of the system as they tend to oppose the motion of a magnet inside a conducting material.
11.3.4 Hysteresis modelling

Hysteresis losses could affect the maximum value of forces. A study could be made on influence of different materials and their effects on forces considering hysteresis.

11.3.5 Condition monitoring and fault study

Since TLPM is an electrical machine it will have electrical signals such as Back EMF emanating from it in response to motion of the piston inside the coil. These signals could be studied for data collection on condition of the rock drill and rock characteristics.

Furthermore, in relation to section 11.3.1, the data from rock characteristics can be used for dynamic tuning of the PI controller gains. Perhaps, fuzzy logic can be utilised for this.

11.3.6 Integration with hydraulic system

As mentioned before, electric machines tend to have poor power density. To compensate for this a TLPM could be used in conjunction with a hydraulic cylinder and pump. This also provides opportunity for potential recuperation in the system during the return stroke if the piston were to bounce.

11.3.7 Structural strength investigation

As mentioned in chapter 2, PM linear motors have higher performance than an equivalent linear motor without. If the mover with PM can be proven to structurally work in a rock drill environment, this increases the possibility of replacing the hydraulic rock drill with an electromagnetic.

11.3.8 Other magnet configurations

As mentioned in section 2.2.5, there are many different magnet array configurations and making a comparison between them and investigating how they perform in a rock drill could be useful.

11.3.9 Rotary motor with crankshaft

As mentioned in section 1.3, one more concept which could be investigated in detail is having a rotary motor with a crankshaft to create percussion. This may require a design of a stroke adjuster.


