



Self-sustaining Power Supply For a Low-power Sea Buoy

by

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Abstract

With the ever-expanding electricity usage of mankind, we lean further towards green reusable energy sources such as hydro, solar, and wind power. Another less known method of generating reusable energy is harnessing the immense potential of our oceans. Under the sea lie strong currents flowing endlessly and on the surface powerful waves swoop across the sea with immense forces. Few power companies around the world have already begun to explore the potential of the sea for large-scale power plants but the opportunities do not end there. These oceanic forces can also be used for smaller-scale projects and could prove extremely valuable for projects based on smaller electronics. Sea buoys are used for all manner of oceanic research and often use low-powered electronics to achieve their tasks. This thesis focuses on the creation of a self-sustaining power supply for such a buoy and looks into the viability of such a device. Different methods of power generation are explored ranging from undersea currents to oceanic waves and all aspects of the design are looked into in detail. The outcome should yield a self-sustaining power system for an oceanic device that could be left out at sea for long periods without having to worry about its internal battery running out. With fine-tuning of parts for the device and the correct design parameters, it will be shown how this is viable and how it can be used for future low-powered projects stationed at sea.

Sjálfbær spennugjafi fyrir sjó bauju með litla afl notkun

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June 2021

Útdráttur

Með sívaxandi raforkunotkun mannkynsins höllumst við ferkar að grænum endurnýtanlegum orkugjöfum eins og vatnsorka, sólarorka og vindorka. Önnur minna þekkt aðferð til að framleiða endurnýtanlega orku er að nýta gífurlega möguleika hafsins okkar. Undir sjónum liggja sterkir neðansjávar straumar um allt hafið og á yfirborðinu sveiflast kraftmiklar öldur yfir hafið. Nokkur orkufyrirtæki eru farin að kanna möguleika þess að virkja úti á sjó með stóriðju í huga en möguleikarnir enda ekki þar. Þessa krafta sem hafið býr yfir er einnig hægt að nota í smærri verkefni og gætu reynst afar dýrmætir til notkunnar með minni raftækjum. Sjóbaujur eru notaðar við alls kyns hafrannsóknir víða um heim og nota oft rafbúnað sem notar lítið afl til að framfleyta verkefnum sínum. Þessi ritgerð fjallar um gerð á sjálfbærum aflgjafa fyrir slíka bauju og skoðar möguleika slíks tækis. Kannaðar eru mismunandi aðferði við orkuframleiðslu eins og notkun á neðansjáfarstraumum og sjávaröldum og allir þættir hönnunarinnar eru skoðaðir ítarlega. Loka útkoman ætti að vera sjálfbært orkuframleiðslu kerfi sem hannað er fyrir úthafs aðstæður sem gæti verið skilið eftir úti á sjó í langann tíma án þess að þurfa að hafa áhyggjur af því hvort að innri rafhlaðan renni út. Með fínstillingu á hlutum tækisins og réttum hönnunarskilyrðum verður sýnt fram á hvernig þetta er mögulegt og hvernig hægt er að nota það í öðrum framtíðarverkefnum sem krefjast lítils afls úti á sjó.

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List of Abbreviations

GWh	Gigawatt hours
OWC	Oscillating Water Column
AC	Alternating Current
DC	Direct Current
emf	Electromotive force
AlNiCo	Aluminum, nickel and cobalt blend
RPM	Rounds per minute

List of Symbols

Symbol	Description	Value/Units	Unit Name
E	Energy	J	Joule
f	Frequency	Hz	Hertz
T	period	s	Seconds
x	distance	m	Meter
ω	Angular Velocity	s^{-1}	Radians per second
A	Area	m^2	Square meter
a	Acceleration	m/s^2	Meter per second squared
H	Height	m	Meter
B	Magnetic field	T	Tesla
B_r	Magnetic remanence	T	Tesla
L	Length	m	Meter
r	Radius	m	Meter
M	Mass	Kg	Kilogram
Φ	Magnetic flux	W	Weber
d	Diameter	m	Meter
k	Spring Constant	Constant	Constant
F	Force	N	Newton
g	Gravity	g	m/s^2
v	Velocity	m/s	Meters per second
R	Electrical Resistance	Ω	Ohm
I	Electric Current	A	Ampere
W	Power	W	Watts
I	Moment of inertia	$Kg\ m^2$	kilogram meter squared
α	Angular acceleration	rad/s^2	radians per second squared

Part I

The First Part

Chapter 1

Introduction

The Ocean possesses immense potential in the field of renewable energy, ranging from The strong winds out at sea, the potential energy of oceanic waves, and the kinetic energy from strong underwater currents, known as marine currents, waiting to be harnessed. Wind energy has been utilized quite a bit in recent years with new wind farms opening up both off-shore and on land in multiple areas around the world with great success.

Although wind energy is one of the leading renewable energy sources used today [1], the marine current and wave energy have yet to show their full potential. The idea to use the currents and waves to generate electricity is fairly young and has not been developed yet to the standards we see other power generation technologies at. It is expensive to invest in new technologies that have yet to be refined to their fullest potential so companies and individuals looking into power generation at sea go with things that have already been tested and proved efficient like the offshore wind farms.

Looking away from the large power generation and down to smaller scale, these power generation methods become more viable to look into with limited resources. Generation for low-power applications at sea is important for devices that require a stable source of electricity for long periods without maintenance and without using an oversized battery in the design of the product. Using the energy available at sea for these low power applications instead of large power generation becomes easier to test without a large amount of infrastructure and resources and could be developed to prove invaluable for all kinds of naval equipment.

This thesis looks into the possibility of harnessing the oceanic waves to generate low-power electricity for a sea buoy using the resources available at sea to make the electrical components more or less self-sustaining. The sea buoy is a buoy that will be used to listen for whales at frequencies of around 1Hz - 100kHz while logging the data from a hydrophone and transmitting the data from the buoy to shore where the data could be used for further research, tourist attraction, or other studies into the behavior of whales. While this buoy would be quite a large-scale project, this thesis will only cover the power generation part of the buoy. The ideal outcome would be that the buoy could be placed out at sea and left there for long periods without having to worry about the battery running out. Another feature that will be focused on is to make the buoy as light and easy to handle as possible, ideally so that a single person

1.1 Background

For such a small-scale project, wind power is not exactly viable. Wind power would require a turbine mounted to the buoy with large wind blades to capture the force of the wind which

would mean that the buoy would be a lot larger than the ideal size. The buoy would also likely need a counterweight to prevent it from tipping in strong winds which would further increase its size. The other two options of either using oceanic waves or marine currents are more likely to be viable for a buoy that needs to be quite easy to handle and reasonably small in size.

1.1.1 Marine currents

Marine Currents are mostly caused by the gravitational relations between the earth, moon, and sun which cause the rise and falls of the tides. This causes the sea to flow around and generate these currents. Other factors such as temperature, salinity, regional differences, and the Coriolis effect are also major factors in generating these currents.[2]

The look into using these marine currents as a potential power source began to expand after the oil price crash back in 1973 [3]. After a considerable increase in oil prices around the world, the power industry looked into other viable options for power generation and renewable alternatives to burning fossil fuel. One of the ideas was to look into the vast underwater currents around the world and use their kinetic energy to generate electricity. Just like the wind is used to turn a wind turbine, these currents could also be used. A hydro turbine would be placed in the path of these currents and secured in place where the current would turn the turbine and generate electricity. Since the fundamentals of operation of wind turbines and marine current turbines are quite similar, many factors can be transferred from a typical wind turbine design to a marine current design [4]. They both operate by having matter, in these cases, air or seawater, with a certain speed hit the turbine blades thus transforming a portion of that energy into rotational energy which is used to generate electricity.

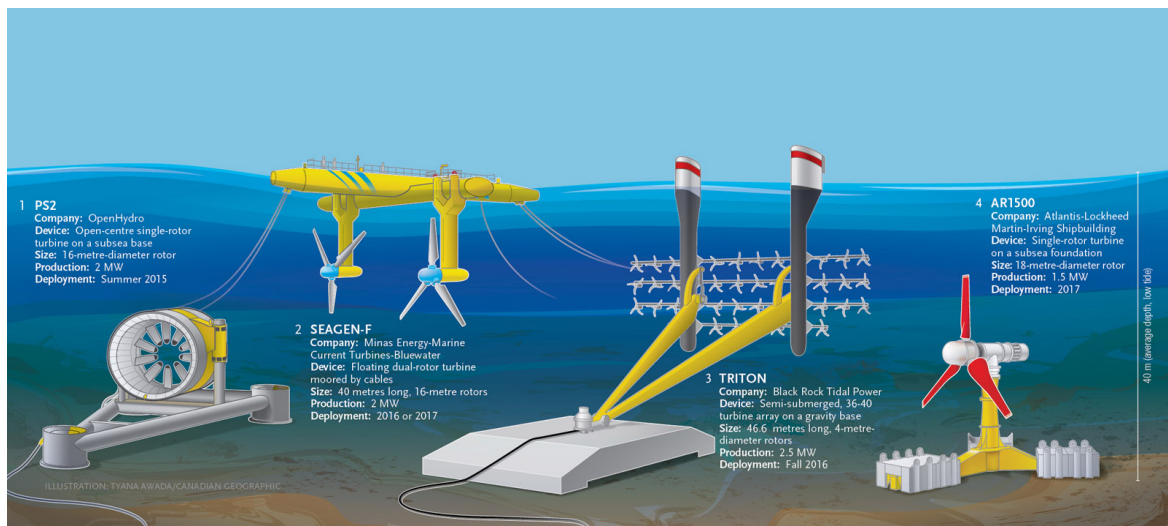


Figure 1.1: Different turbines used for power generation using marine currents [5]

The main concerns for using Marine currents as a power source for the whale listening buoy are both that the buoy would need to be completely secured in the sea to get the most efficient power generation and it would have to be quite large for the turbine to yield any usable power. The buoy would need to be secured so it wouldn't drift away in the strong currents and preferably have it completely stationary which would be extremely difficult without using direct connection to the seabed. Both these factors would increase the total weight and size of the buoy by margins that would defeat one of the main design points of the

buoy, to keep it light and easy to handle. *Figure 1.1* shows a few different types of industrial turbines used for power generation in marine currents. as can be seen, these turbines are quite bulky and require infrastructure around the turbines to function. On a smaller scale, this might be a viable option for the buoy but the size of all required parts needs for a small-scale marine current turbine needs to be looked at beforehand.

1.1.2 Oceanic waves

The idea to harness the power of waves on the ocean surface is not a new one. the first patent in France dates back to Girard & Son back in 1799 and the history of patents related to oceanic wave harnessing was well documented in Britain with over 300 patents in the years 1855 to 1973 [6]. Research into wave energy in Europe took a leap in the year 1973, as the research into marine currents, after the crash of the oil market. In recent years there have not been any large breakthroughs in the field. For large-scale power generation, technology and implementation of wave energy plants have not reached the point where it can keep up with other renewable energy sources such as hydropower or wind power. The research into it continues though with new ideas and implementations showing up every year.

Wavestar energy, a company located in Denmark, is one of the companies working on development in this field. Their goal is to make a viable regular energy output from oceanic waves with a period of around 5-10 seconds. The approach they use is to have a large offshore platform with a row of floats that rise and fall with the movement of the waves. the floats are attached with arms to the main platform where the motion is transferred with hydraulics to spin a generator, producing electricity. They have shown that a 20-float demonstration machine with 6 meter floats off the coast of Belgium could initially produce 1.4 GWh per year and with further optimization and improvements it could be increased up to 3.1 GWh per year in the near future [7]. The theory that is used to convert the vertical movement of the waves to rotational energy to turn a generator could be used scaled down for smaller scenarios such as the whale listening buoy, although the mechanics would have to be modified since the buoy is floating on top of the waves, but not stationary on a platform out at sea.

Other methods to use oceanic waves have been well documented and tested in the past years. The oceanic attenuator is a worm-like device that floats on the top of the ocean. A representation of it can be seen in *Figure 1.2*. The body of the device is segmented into multiple parts with joints and uses the movement changes between parts of its body to generate electricity. This can either be done by converting the flexing motion from the segments into rotational energy or using the motion to drive a hydraulic pump.

An Oscillating water column, or an OWC, is a structure or a device that uses air pressure changes from waves coming in and going out to turn an impulse turbine [9]. A representation of an OWC can be seen in *Figure 1.3*. Each wave coming into the structure pushes up into an air-filled chamber, creating pressure and pushing the air out through a turbine. When the wave goes back down the air is sucked back into the chamber through the turbine.

An overtopping device is a device that sits half-submerged on top of the ocean. A representation of an overtopping device can be seen in *Figure 1.4*. Incoming waves flood over the ramps and into a reservoir where it can be pushed down through a turbine using the small head that it gets from the water that flows in. Specialized turbines that are designed to work with a very low head are required for these devices to work.

Yet another method to harness the oceanic waves is the use of a point absorber. A representation of a point absorber can be seen in *Figure 1.5*. These devices are often buoys that are tethered to the ocean floor. The vertical movement of the waves is used to move parts of the buoy vertically along another stationary part. These movement differentials can

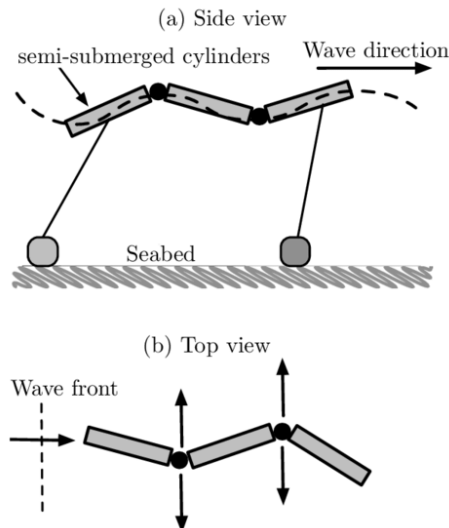


Figure 1.2: Representation of a oceanic attenuator [8]

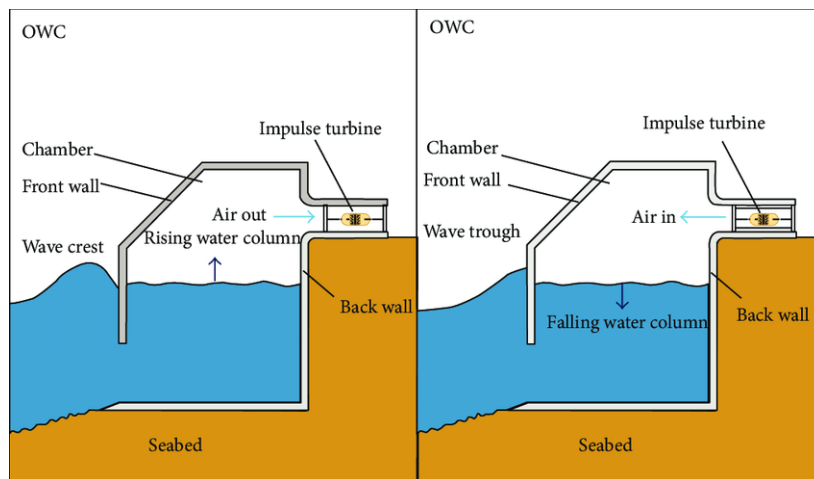


Figure 1.3: Representation of an Oscillating water column[10]

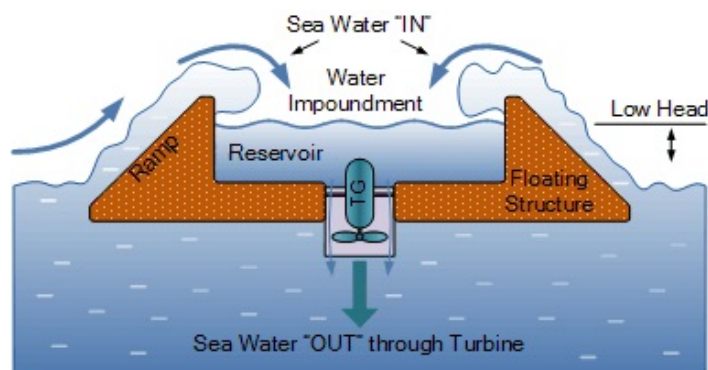


Figure 1.4: Representation of an overtopping device [11]

be used in different ways to generate power that can either be used for the buoy or transferred to land with cables leading down the tether of the buoy.

This buoy has been an ongoing project for a few years and previous students have given their ideas to design and implement it. Back in 2015, Hjalti Freyr Guðmundsson went with

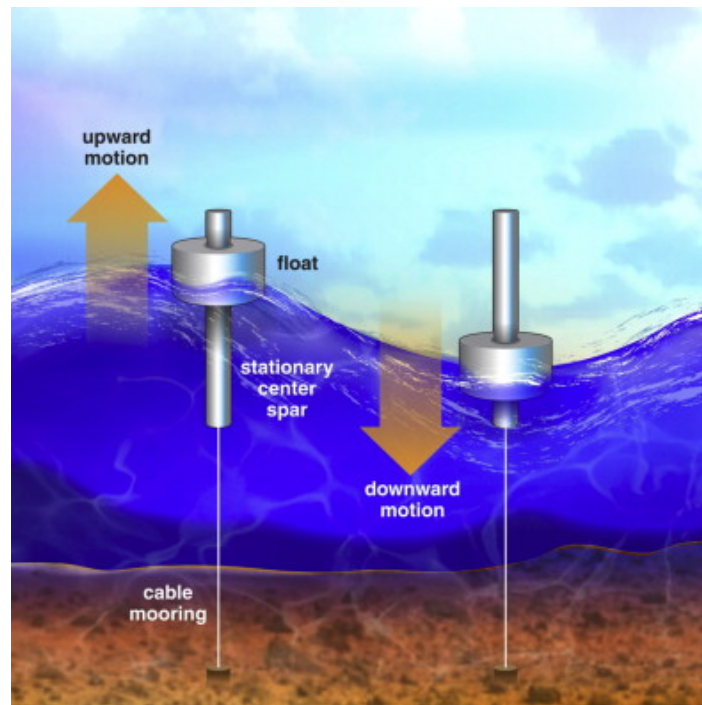


Figure 1.5: Representation of a point absorber [12]

a design similar to a point absorber where a magnet is secured to the top with springs inside a cylinder [13]. The magnet moves vertically up and down past a stationary coil as can be seen in *Figure 1.6* inducing emf in the coil. This method proved viable and could be further explored and improved upon.

The possibilities when it comes to renewable energy from the ocean are vast. Finding the ideal design for a small-scale buoy will prove vital for the success of this project and could prove valuable in future endeavors. Many of these power conversion methods are relatively young and have not been fully explored, especially when it comes to low-power generation so all factors need to be looked into when the final decision is made on the method to use.

1.1.3 Power supply circuitry

When it comes to transforming voltage from AC to DC, multiple options are available. Two of these methods are the Diode bridge rectifier and a MOSFET bridge rectifier. These two circuits are similar in their operations while converting AC signals to DC. A third converter circuit that can be looked at is the boost converter which is quite different from the other two in its operations.

Multiple different rectifiers will be looked into and a choice will be made for which to use for the voltage transformation. Additionally, to these rectifier circuits, a filter stage and signal smoothing circuitry are required to get the DC result that is required for the electronics of this project.

The first rectifier method is a Diode bridge rectifier. It uses four diodes working in two pairs to transform the input voltage. With this circuit, the negative portion of the input signal can be transformed into a positive signal resulting in a variable signal ranging from 0 to the amplitude of the input signal as can be seen in *Figure 1.9*. These types of transformers are called full-bridge rectifiers. The main benefit of using a diode bridge rectifier is that the circuit is simple and durable. The circuit will be placed inside a moving buoy out at sea so

	Pros	Cons
Oceanic Attenuator	* Low maintenance * High usability both in deep and shallow water * Modular, can be designed according to power needs	* Requires large parts depending on the wave size * Requires anchoring to sea floor * visual pollution over a large area of sea
Oscillating water column	* Impulse turbines are very efficient * Adjustable depending on the predicted waves	* Only viable in shallow water or on shore * Spacious. Requires large air pocket and structure around it
Overtopping device	* Hydro turbines are very efficient * High usability both in deep and shallow waters	* Require a structure for the water head * Need to be sitting stable and semi submerged * Handles change in wave heights poorly
Point absorber	* Low space requirements * Can work both anchored and as a floating point * Work well both in large and small scale	* Hard to implement in deep waters * Not as efficient as other methods
Underwater current turbine	* No visual pollution over sea * High power generation in specific areas	* limited usability, only viable in strong oceanic currents * High maintenance on underwater turbines * Requires anchoring to the sea floor * Require weight ballast to keep from tipping

Table 1.1: Summary of the different methods of power generation



Figure 1.6: Previous design by Hjalti Freyr Guðmundsson [13]

the circuit needs to handle vibration, rotation, and all kinds of movement without it affecting the operations. Another beneficial factor of using a diode bridge rectifier is that they are cheap and easy to make. The downsides however of the diode bridge rectifiers are that there is a voltage drop over each of the two diodes working at each time meaning that the voltage drop at any given time is twice the voltage drop over a diode. This could prove problematic while working with low-powered devices and needs to be addressed while deciding which transformation method should be used since the voltage drop of a regular silicon diode is around $0.6 - 0.7V$ [14].

Instead of the normal diodes, Schottky diodes could be used. Schottky diodes are metal-semiconductor junction diodes that have less forward voltage drop than the normal diodes [15]. The average voltage drop over a Schottky diode is $0.2 - 0.3V$ which is less than half of what the voltage drop over a normal diode is. The average Schottky diode can handle up to $50V$ and handles low currents easily but at higher currents and higher temperature, the reverse leakage current increases and the voltage rating goes below the rated value. Since this project is not working with high currents or any voltages above $50V$ these diodes could prove valuable for the design of this project.

The other AC to DC rectifier method is built similar to the diode bridge where MOSFETs are used instead of the diodes as shown in *Figure 1.8*. This circuit is more complex than the previous circuit where the MOSFETs conduct both ways and they need to figure out which two MOSFETs should be open at each time. The MOSFETs use the current direction to decide which two should open at any time. This is the main concern with this method, It's

not as stable as the previous method and more prone to failure in harsh environments and could short circuit the transformer circuit. The important part that makes this circuit viable for this project is that the voltage drop over the circuit is significantly less compared to the diode bridge circuit [16]. The output of the MOSFET rectifier would be similar to the the output by the diode bridge and can be seen in *Figure 1.9*

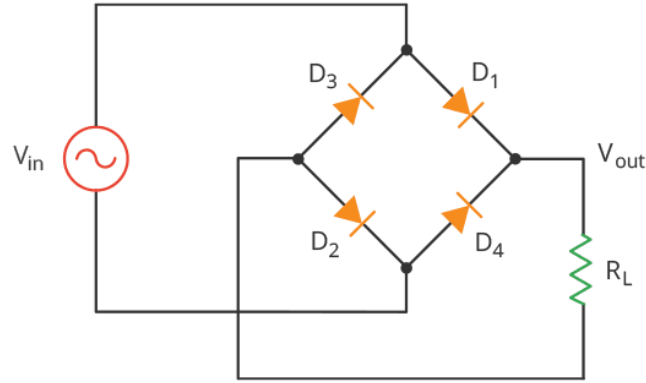


Figure 1.7: Diode bridge rectifier circuit [17]

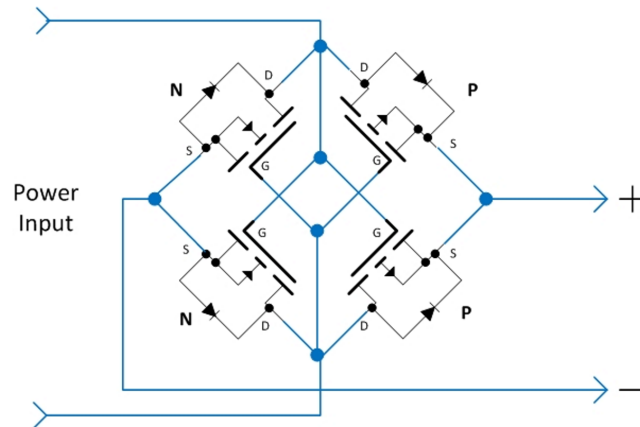


Figure 1.8: Mosfet rectifier circuit [18]

The boost converter is a simple type of switch-mode converter. It takes an input voltage and boosts or increases it using an inductor to store energy for conversion, a semiconductor switch like a MOSFET, a diode to make sure the current goes the right way, and a capacitor that stores the output voltage.[19]. When the MOSFET switch is open the output capacitor is charged until it reaches the input voltage minus the voltage drop of the single diode. When the MOSFET closes, all the current is diverted through it and the inductor While this is happening the output capacitor stays charged since it can't discharge through the diode. When the MOSFET switches back to being open the current through the inductor is stopped and the inductor tries to maintain a smooth current flow by generating a large amount of voltage with the opposite polarity of the voltage originally supplied. The inductor can now

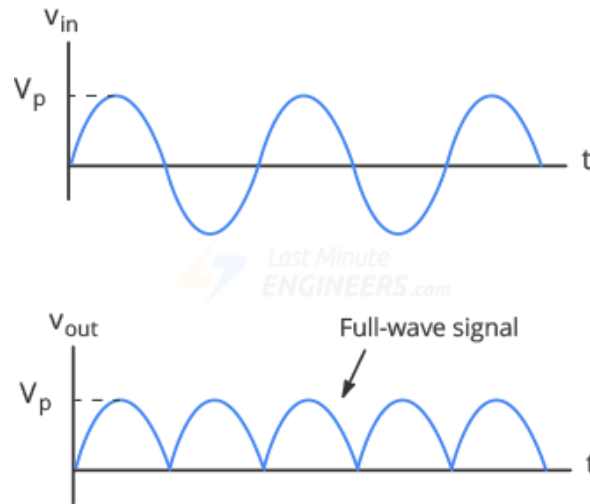


Figure 1.9: Transformation of signal using a rectifier circuit [17]

be thought of as a short-term voltage source in series with the input signal. This happens rapidly while the MOSFET switches from being open to being closed. The output capacitor charges to a higher voltage than before because of this which means that the output signal has been boosted up from its original signal. A circuit diagram for a typical boost converter can be seen in *Figure 1.10*. This circuit sacrifices current to increase the output voltage so it needs to be addressed that using this circuit will affect the usable output current and will require a decent amount of input current to work. This circuit does not rectify the signal so a rectification stage, as was discussed before, would be required for this circuit to operate

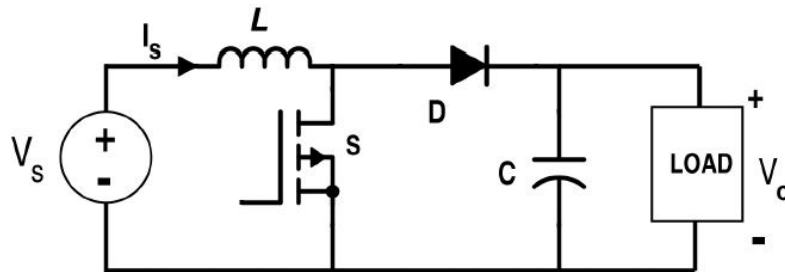


Figure 1.10: Boost converter circuit [19]

The next step of the power supply circuit, after the rectifier, would be to get the signal from a fluctuating positive signal to a semi-stable usable DC voltage with the use of a smoothing capacitor. A smoothing capacitor is a large capacitor used to smooth out a signal. When the voltage rises, the capacitor is charged. When the voltage lowers the capacitor discharges and tries to keep the voltage up as can be seen in *Figure 1.11*

After this stage of the power supply, the signal will be a fluctuating DC signal with varying amplitude. The final stage uses this input to deliver a stable voltage of 5V to be used by the electronics of the buoy. This stage involves a voltage regulator, for example, an LM7805[21]. A voltage regulator is an integrated circuit that provides a constant preset voltage output regardless of a change in the load or input voltage [22]. To finish the circuit of small capacitors can be added to the regulator circuit as shown in *Figure 1.12* to filter out the noise and make the signal as smooth as possible.

These three steps of the circuit will be looked into and configured to find an ideal circuit setup for this power supply. Efficiency will be the main factor to consider for this project

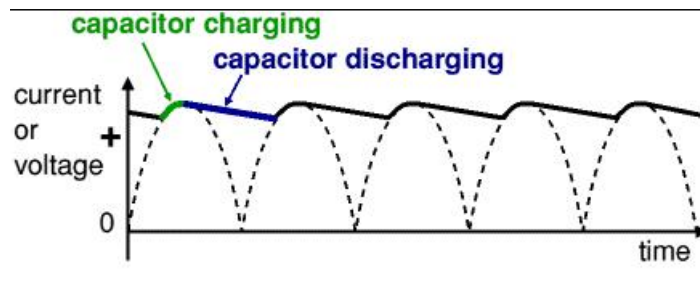


Figure 1.11: Effects of a smoothing capacitor [20]

since the buoy will be working on low power generation. The durability also needs to be good and withstand the harsh environment that the buoy faces out at sea.

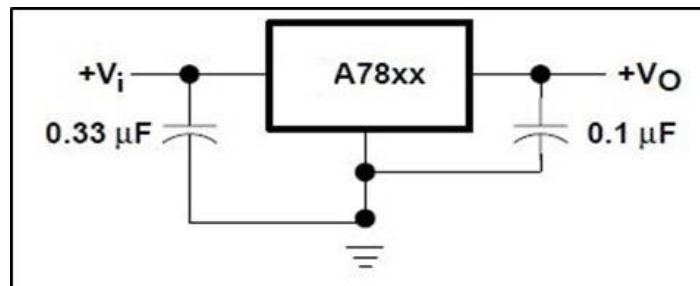


Figure 1.12: Sample LM7805 regulator circuit [23]

Chapter 2

Methods

2.1 Approach

Moving forward with the project, a decision needed to be made regarding which approach to power generation was used. Many of the methods talked about in the background chapter are still in early development and are of considerable size. Scaling them down would be a hard task requiring a lot of research and development into the field and a large budget to work on. Having the power generation portion of the buoy too large would break the design parameters of the build. An OWC would not work for this project the structure of the device needs to be quite large compared to the wave height. the cylinder or structure that would generate the pressure to spin the turbine needs to be higher than the waves. This would also not work well with a buoy that sits on the surface of the ocean. An overtopping device would not work either on a small scale since the reservoir would be so small that the waves would overlap it entirely and the head pressure would barely move any type of turbine. The oceanic current methods require specific locations where oceanic currents are strong and require quite the infrastructure around the build. This method could be viable if the project were larger scale, but for low power generation, the oceanic current method is too cumbersome and would break the design parameters for the buoy.

The methods that use the vertical movement of the oceans like the point absorber or similar technologies where the buoy floats on the oceanic waves which cause movement between two individual parts of it are the most viable for this build. They can easily be scaled down and don't require a large infrastructure of machinery and technology around them for power generation. Looking at the previous design by Hjalti [13], the main concern is the efficiency since the magnet is only passing by the coil on a small portion of its travel. A large portion of the total kinetic energy isn't being used to generate emf in the coil which could be improved with a different design of the moving parts.

The approach that was decided upon was to use a type of a point absorber, where the vertical movement would be converted into rotational movement of an axle. This would be done by using two small wheels on the axles, one connected to a hanging weight. When the buoy moves up in the waves, the hanging weight would try to remain in position, thus pulling a fly-wheel and in turn, spinning the axle. on another fly-wheel wheel, a wired spring would be connected with string. These fly-wheels would have to be made out of strong materials since a large load would be pulling on them. Iron and aluminum will be looked at in regards to their material.

When the weight turns the axle clockwise, the tension on the spring would increase until it passes the equilibrium point and pulls the weight back, and turns the axle counter-clockwise.

This would in theory create a rotational wave pattern with oscillating peaks when the waves pass the buoy. The axle would then be connected to a disk-shaped wheel where multiple magnets would be indented into the sides. Around the magnet disk, multiple copper coils could be placed around it, stationary to the disk. When the magnet disk spins, the magnets move past the solenoid inducing emf in them.

The main improvement of this design is that it limits downtime and increases the efficiency of the converter. The change in the magnetic field passing through each solenoid is more rapid. The solenoids are substantially smaller in size than the solenoids used in the previous design by Hjalti since the speed of the magnetic field change is higher and more solenoids are present in the system. With the old design, there would only be one cycle of the magnet passing by the solenoid for each wave which leaves large amounts of the period where no electricity is being generated. An early sketch of the mechanism can be seen in *Figure 2.1*

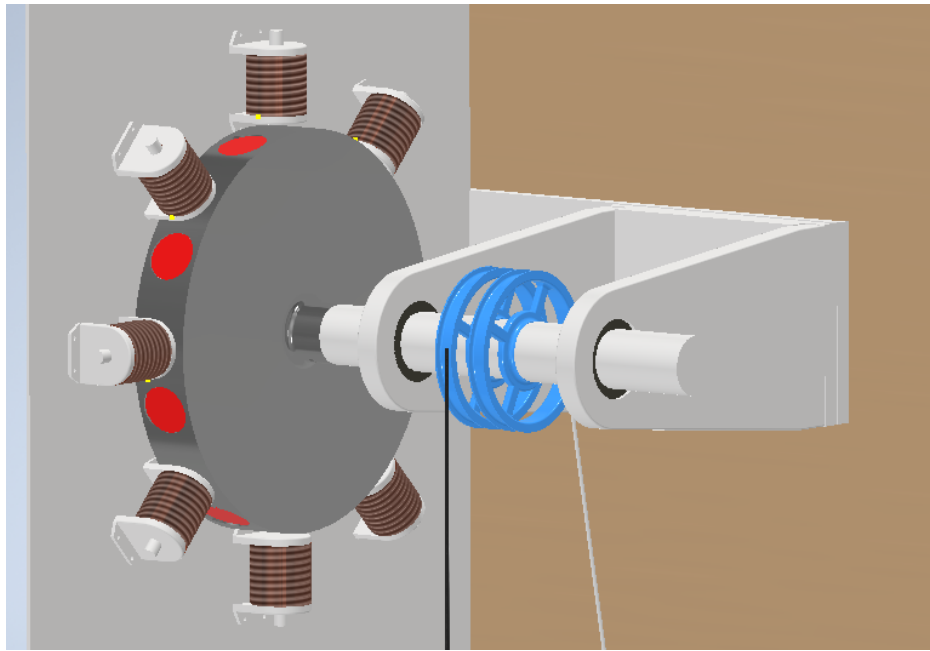


Figure 2.1: 3D drawing of the mechanism

The solenoids are wired together into a voltage converter to convert the raw AC voltage coming from the solenoids to a usable DC voltage which can be filtered and stabilized. This stabilized voltage signal can then be used by the electronics of the buoy.

2.2 Wave analysis

For early testing the wave patterns need to be looked at around Iceland to find ideal locations close to the coast for testing and find out what the limitations of the oceanic waves are to give a solid foundation to base the energy converter on. The data used is oceanic data from four different sea buoys around the coast of Iceland shown in *Figure 2.2* provided by Vegagerðin [24]. The data used was from both 2018 and 2020. The average data from four of these weather buoys can be seen in *Table 2.1* and it shows that the average wave height was $2.08 - 2.76m$ and the average period was $6.96 - 8.21s$.

The main concern working with the wave data is the irregularity of the waves. Looking closer into the data it is shown in *Figure 2.3* that the waves are quite erratic. Although the average height of the waves is $2.44m$, the standard deviation of $\pm 1.5m$ needs to be addressed.



Figure 2.2: Map showing the location of the four buoys used for data

	Latitude	Longitude	Average wave height	STD of wave height	Average period	STD of period
Buoy 1	63.5	-18	2.08	± 1.21	8.21	± 1.75
Buoy 2	64.5	-23.5	2.44	± 1.50	8.21	± 1.95
Buoy 3	65.5	-12.5	2.76	± 1.43	8.00	± 1.58
Buoy 4	66.5	18.5	2.12	± 1.47	6.96	± 1.81

Table 2.1: Wave height and periods around the coast of Iceland

This is due to the drastic differences in wind heights between the seasons. It can be seen both in the data from 2018 and 2020 that during the summer months the average wave height drops substantially and then picks back up around August. During the winter months, we see large spikes on some days where the wave heights go above $8m$ and that is needed to be taken into account when designing the energy converter, how it will react in high wave heights, and if it will manage to sustain itself in low wave heights.

To calculate the force that the waves exert on the buoy, the vertical acceleration of the wave needs to be calculated according to *Equation 2.1* where A is the amplitude of the wave in meters and ω is the angular velocity of the wave measured in radians per second.

$$a(t) = \frac{\partial v}{\partial t} = -A\omega^2 \cos(\omega t) \quad (2.1)$$

For use with the data from Vedurstofan, the equation can be adjusted as such to take the raw height and period data directly:

$$a(t) = -\frac{H}{2} \left(\frac{2\pi}{T} \right)^2 \quad (2.2)$$

Now the vertical acceleration of the wave can be calculated for each measurement point of the data by inputting the values from the data set directly into *Equation 2.2* where T is the period of the wave in seconds and H is the amplitude of the wave in meters.

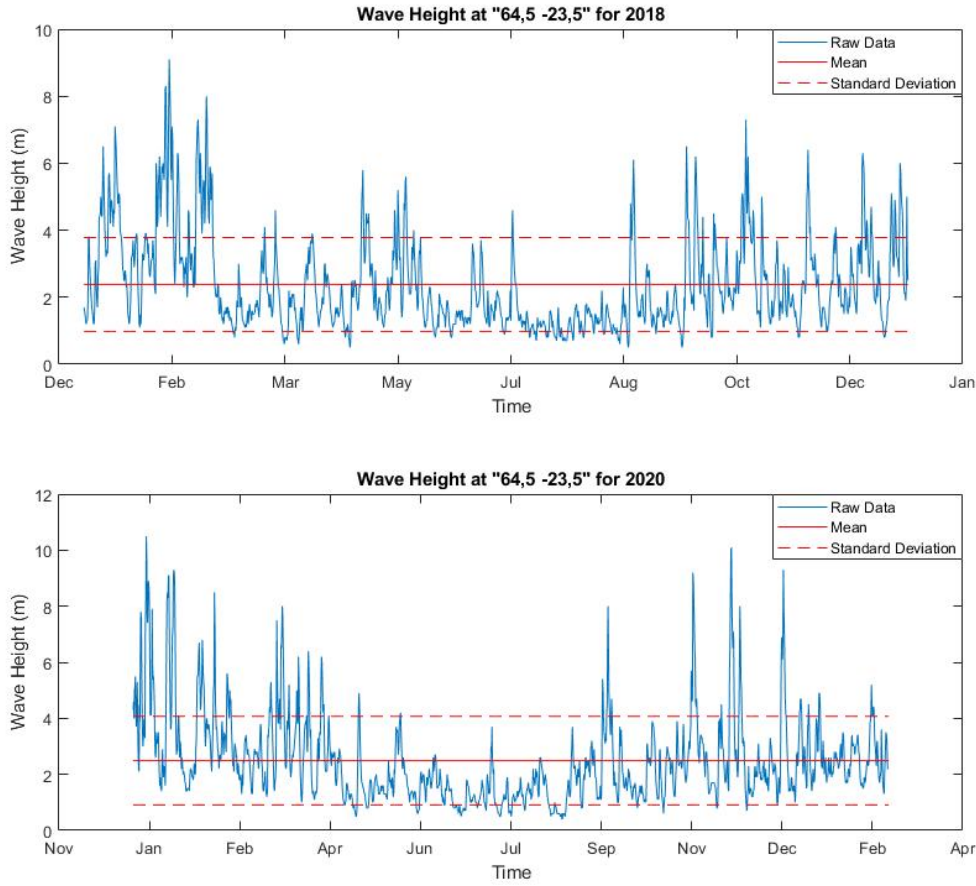


Figure 2.3: Analysis of wave height in 2018 and 2020 of buoy 2

2.2.1 Magnetic field calculations

For simple shaped permanent magnets, such as a solid cylinder, the magnetic field can be approximated by using Biot-Savart law [25].

$$B(x) = \frac{B_r}{2} \left(\frac{L+x}{\sqrt{r^2 + (L+x)^2}} - \frac{x}{\sqrt{r^2 + x^2}} \right) \quad (2.3)$$

The approximation for a cylindrical permanent magnet can be seen in *equation 2.3* where $B(x)$ is the strength of the magnetic field, measured in Teslas, B_r is the residual magnetism of the magnet or Remanence of the magnet, L is the length of the cylindrical magnet and r is the radius of the cylinder. x determines the length away from the magnet shown in *Figure 2.4*.

The Remanence is the magnetization remaining in a ferromagnetic material after an external magnetic field is removed [27]. This value differs between different types of magnets and is hard to approximate accurately. *Table 2.2* shows the remanence values of a few different types of magnets which could be used in this project.

These Remanence ranges can be used for the materials to make an approximation of the magnetic field strength at certain distances from the magnet according to *Equation 2.3*. The resulting approximation for Neodymium magnets can be seen in *Figure 2.5*

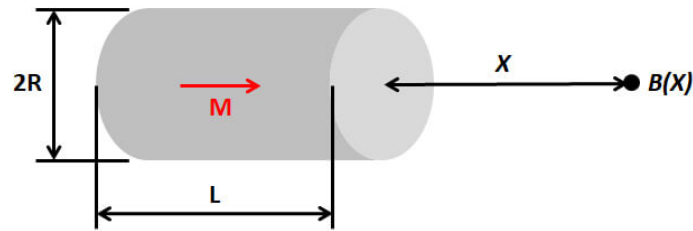


Figure 2.4: Descriptive image of magnet showing measurements [26]

Material	Remanence
Ferrite magnet	$\sim 0.35\text{T}$ / $\sim 3500\text{G}$
Samarium-cobalt magnet	$0.82 - 1.16\text{ T}$ / $8200 - 11600\text{G}$
AlNiCo 5	$\sim 1.28\text{ T}$ / 12800G
Neodymium magnet	$1 - 1.3\text{T}$ / $10000 - 13000\text{G}$
Steels	$0.9 - 1.4\text{T}$ / $9000 - 14000\text{G}$

Table 2.2: Remanence approximations of different types of magnets

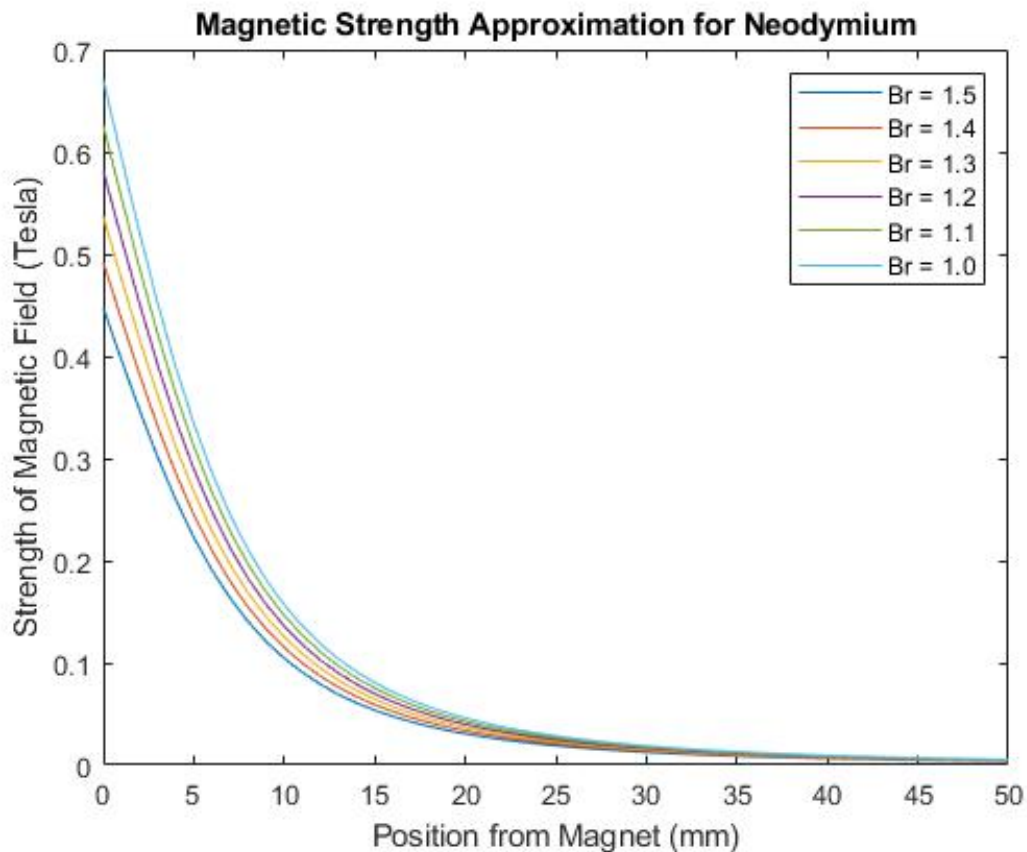


Figure 2.5: Magnetic field strength along the center of a cylindrical Neodymium magnet

2.2.2 Coil calculation

Faraday's law states that any change in the magnetic field around a coil of wire will cause an electromotive force to be induced in the coil. electromotive force or emf is an induced voltage in the coil and will be generated no matter how the change in the magnetic field

occurs. For example, this can occur when either the coil moves through a magnetic field or a magnetic field passes by the coil [28].

$$emf = -N \frac{\partial \Phi}{\partial t} = -N \frac{\partial (BA)}{\partial t} \quad (2.4)$$

Equation 2.4 shows how the emf generated is calculated by multiplying the change in magnetic flux (Φ) over time by the number of loops of the coil (N). Magnetic flux is the total magnetic field that passes through a given area. The negative symbol of the equation comes from Lenz's Law.

Lenz's law states when emf is generated by the change in an external magnetic field, the polarity of the magnetic field created by the induced current opposes the original magnetic field [29]. The induced magnetic field inside a loop of wire will always try to keep the magnetic flux in the loop constant [30]. The representation of this can be seen in Figure 2.6 where the different movements of a permanent magnet change the direction of induced current in the coil and induced magnetic field from it.

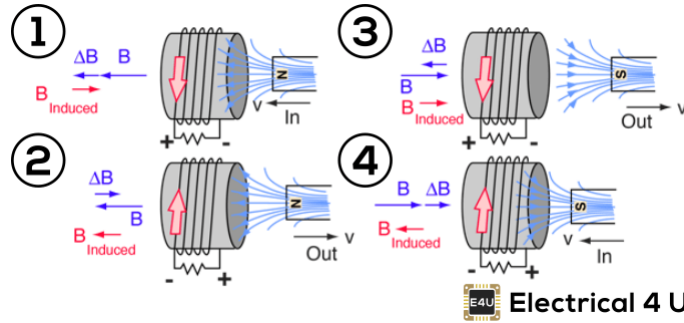


Figure 2.6: Representation of induced magnetic field according to Lenz's law[30]

A rough approximation of the windings of the coil can be made from Figure 2.7. The figure shows how the wire layering is approximated to a uniform pattern around the coil base. With this approximation calculations of the wire needed to wind the coil becomes easy to maintain and a rough estimate of the copper wire needed can be found.

$$N = \frac{A}{d_{wire}^2} \quad (2.5)$$

Assuming that the wire lies uniform on the coil base, the Number of windings can be estimated according to Equation 2.5 where N is the number of windings, A is the cross-sectional area of the coil and d is the diameter of the wire. The total length of wire required can also be calculated using this approximation.

$$L_{wire} = \sum_{k=0}^{\frac{B_{coil}}{d_{wire}}} 2\pi \frac{L_{coil}}{d_{wire}} (B_{coil} + \frac{d_{wire}}{2} + kd_{wire}) \quad (2.6)$$

Assuming uniform layering of the wire of the coil Equation 2.6 can be used to calculate the length of copper wire needed for all windings. This equation calculates the circumference of each turn of wire, the number of turns per winding, and the number of total windings per coil taking into account the change in diameter per winding.

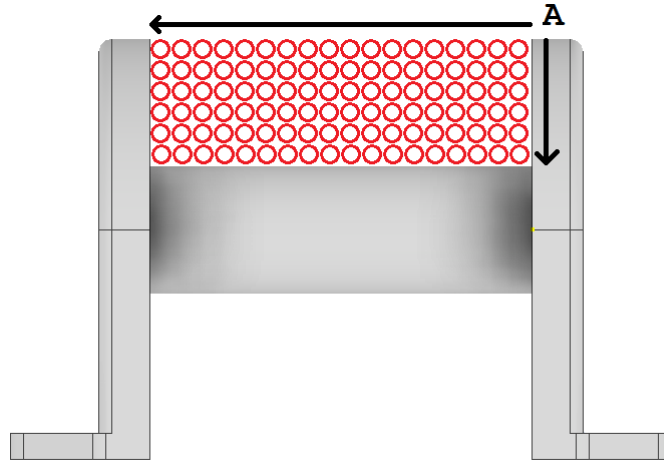


Figure 2.7: Rough demonstration showing uniform wire windings of the coil

2.2.3 Mechanical system calculation

Hooke's law states that the force required to extend or compress a spring by a distance x , which is relatively small compared to the size of the spring, scales linearly to that distance. Under these conditions, the spring returns to its original shape upon removal of the force [31]. Equation 2.7 Shows this relation.

$$F = -kx \quad (2.7)$$

Selecting the correct spring is vital for the converter to work correctly. The weight of the mass and its acceleration while in the motions of the waves needs to be taken into consideration to maximize the movement of the disk from each wave. The Spring needs to have a stiffness constant that allows it to extend easily, but not so easily that it interferes with the fly-wheel mechanic on the axle. The force pulling on the mass while the system is stopped would just simply be gravity, but when the system is in motion the acceleration of the waves need to be taken into the equation and added or subtracted from the initial gravity force on the mass, depending on where in the wave the mass is.

To test the springs a simple spring testing environment can be set up. Have the spring connected to an elevated bar and measure the starting point of the spring. After a starting point has been marked down, a mass with a known weight can be hooked to the lower end of the spring and a measurement of the change in the vertical position from the starting point can be noted down. This change in position can be used to calculate the stiffness constant for the spring and thus used in the calculations needed for the entire system to function correctly.

$$F = am \quad (2.8)$$

$$a_{max} = g + a_{wave} \quad (2.9)$$

$$a_{min} = g - a_{wave} \quad (2.10)$$

$$\Delta F = F_{max} - F_{min} \quad (2.11)$$

To calculate the total movement of the magnet disk and how many rotations can be achieved per period of the wave, a free body diagram of the spring and mass system was set

up and can be seen in *Figure 2.8*. Using the figure and *Equations 2.8 - 2.11* the force that the mass is pulling on the spring with can be calculated both when traveling up and down the waves and in turn the difference between the maximum and minimum forces asserted to the system from the mass.

With the difference in forces calculated, the total displacement of the spring can be calculated by using Hooke's law shown in *Equation 2.7*. The displacement for the spring at the minimum and maximum forces need to be noted down as well since that will determine how long the spring will be at its longest and shortest which will need to be addressed in the design of the device.

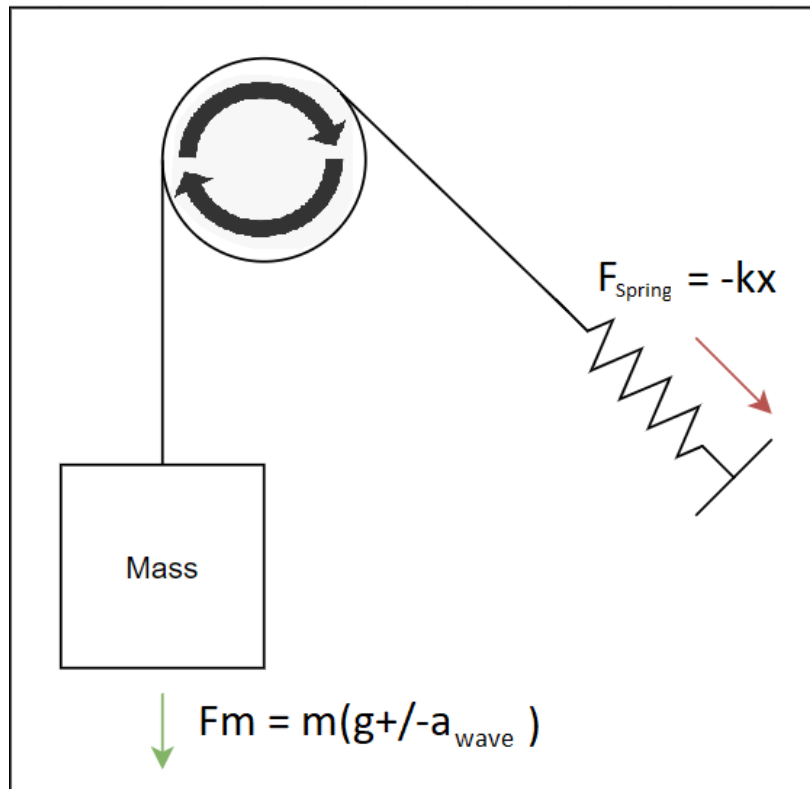


Figure 2.8: FBD of the mass and spring system

The axle of the system can not be simply thought of like a pulley connecting the mass and spring. Instead, the moment of inertia needs to be looked at for the entirety of the axle, including both fly-wheels, the axle itself, and the magnet disk. The bearings holding the axle also need to be taken into account when designing the system so that the predictions made will be as close as real-world scenarios. Since the axle unit is not a simple shape, calculating the moment of inertia could prove hard and would require the combination of many simpler shapes to get a relatively right approximation. A simulation from a 3D design program, like Inventor or Solidworks, may prove more reliable for this if the calculations become too complex.

The axle assembly is kept quite small so it can fit inside the buoy to keep it safe from the outside elements of the sea. corrosion and moving parts don't go well together so keeping the mechanical parts of the assembly inside and as dry as possible is important for this project to work. The mass could either be inside the buoy or hanging down from under it. If the mass would be inside the buoy, a large space for it would have to be accounted for when designing the buoy making it harder to handle and heavier but would protect the mass as well from the outside forces of the sea. Having the mass hanging outside of the buoy would make it

easier to handle and the buoy housing itself could be designed smaller. The main concern with this approach would be the corrosion of the mass and the effects of long-term exposure to the harsh environments out at sea. This would also require the rope or string holding the mass to move freely between the outside and inside of the buoy without leakage into the buoy which could prove hard but could be achieved with the right sealing method. The sealing between the outside and the inside of the buoy would be a weak point though and with time and constant motion through it, it would wear out and start leaking causing problems long term and increasing maintenance for the buoy.

Part II

The Second Part

Chapter 3

Results

3.1 Measurements of magnetic field

Two different magnets were originally considered, firstly a solid $27 \times 25 \text{ mm}$ cylindrical Al-NiCo magnet (product number: GAGN52.3-AN-27-25 from Ganternorm) comprised of aluminum, nickel, and cobalt and secondly multiple $3 \times 18 \text{ mm}$ neodymium magnet disks (product number: 5410329453954 from Velleman) which could be stacked together forming a solid cylinder. For preliminary testing, the AlNiCo magnet and six of the neodymium magnets stacked together were measured independently with a Model GM-2 Gauss meter from Alphalab Inc. The magnetic field was measured as close as possible to the magnets to compare their best results. The stacked neodymium magnets proved to be quite stronger with a magnetic flux density of around 4600 G , which translates to 0.46 T , while the AlNiCo magnet only measured at around 1800 G or 0.18 T .

The design was continued with the neodymium magnets and further measurements were done on the magnet. The magnetic flux density was measured at different lengths from the magnet, multiple times to get an accurate representation of the magnetic field that will be used for emf generation. The results from these measurements can be seen in *Figure 3.1*. Keeping in mind the conversion of Gauss to tesla is $10000 : 1$ this fits into the range originally approximated in *Figure 2.5* and shows that the magnets I'm testing out with lie in the lower ranges of that approximation and that the remanence of the magnets is around 1.0 .

This result also shows that to induce any usable emf in the coils, the coils have to be quite large and have to lie as close as possible to the magnet disk to utilize the strongest parts of the magnetic field.

3.2 Measurements of Spring Stiffness

The spring stiffness constant was estimated with a simple test. The spring was suspended a meter from the ground with one end connected to a stable surface. measurement was taken at the lowest end of the spring to get a base reading. A mass of known weight, 1 kg , was connected to the other end which was facing down. another measurement was taken when the mass was pulling the spring apart and the difference between the measurement points was noted down. Using the known mass, gravity, and the elongation of the spring was used in *Equation 2.7* to determine the spring stiffness. The masses vertical displacement was 0.49 m which yielded a stiffness of 200 N/m for the spring.

Distance from Magnet [mm]	Measurements in Gauss [G]						STD
	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Average Magnetic field strength	
0	4627	4545	4640	4580	4613	4601	±34.4
2.5	3301	3403	3332	3248	3324	3321.6	±50.2
5	2333	2324	2225	2265	2374	2304.2	±52.7
7.5	1500	1504	1499	1522	1561	1517.2	±23.4
10	1067	1154	1090	1077	1097	1097	±30.3
12.5	750	825	790	767	805	787.4	±26.6
15	550	575	576	562	577	568	±10.5
17.5	412	420	429	430	430	424.2	±7.2
20	312	320	325	327	322	321.2	±5.2
22.5	248	260	258	260	252	255.6	±4.8
25	200	208	204	203	203	203.6	±2.6
27.5	159	168	165	163	166	164.2	±3.1
30	128	136	135	136	138	134.6	±3.4
32.5	114	114	113	112	115	113.6	±1.0
35	94	96	97	96	97	96	±1.1
37.5	80	83	80	83	82	81.6	±1.4
40	66	66	68	67	68	67	±0.9
42.5	57	58	59	59	59	58.4	±0.8
45	50	50	50	51	51	50.4	±0.5
47.5	43	42	44	45	44	43.6	±1.0
50	38	38	38	38	38	38	0.0

Table 3.1: Raw Data from magnetic field measurements

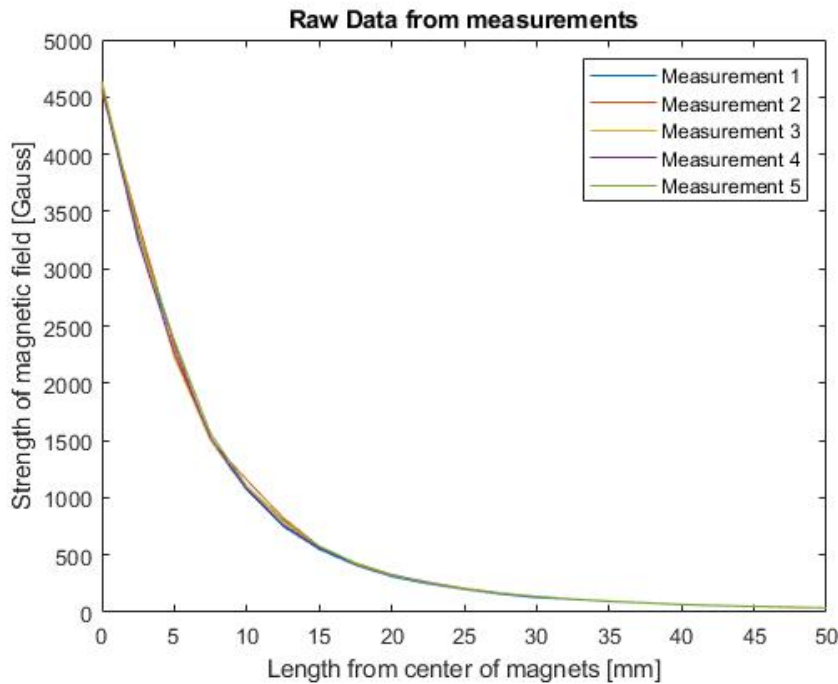


Figure 3.1: Measurements of the magnetic field relative to distance from the magnet

3.3 Calculations for mechanical assembly

The next problem that was faced was To figure out how much the mass in the system would move vertically in average-sized waves and in turn how much it would turn the magnet disk. To do this, *Equation 2.2* was used in conjunction with the data from Veðurstofan to figure out the maximum and minimum acceleration of the mass. This was calculated to be $a_{min} = 9.09m/s^2$ and $a_{max} = 10.52m/s^2$ downward acceleration.

With a mass of 10kg , the resulting forces according to *Equations 2.8 and 2.11*. This yielded results of $F_{min} = 90.9\text{N}$ and $F_{max} = 105.2\text{N}$.

To find the displacement of the spring, *Equation 2.7* was used. The spring stiffness used for the preliminary calculations was 60. Calculating the displacement for both F_{min} and F_{max} yielded a difference of around 238mm . The reason for the spring stiffness to be decided as such was to get the displacement of the spring approximately the same as the circumference of the flywheel being pulled by the mass. This means with this setup, every half period the magnet disk will approximately move one circle which will simplify further approximations. With the magnet disk having a radius of 100mm This means a single magnet on the disk will travel approximately 628mm before reaching a whole circle.

3.4 calculation for coils

Using the approximation method shown in *Figure 2.7* a preliminary calculation can be made of the size, area, and the number of windings for a test coil. The coil base chosen for this test can be seen in *Figure 3.2*. The wire chosen for the test coil was $\varnothing 0.4\text{mm}$ copper wire. using the data gathered and the approximation, the number of windings per row can be calculated by dividing the length of the coil base with the diameter of the wire, yielding 75 turns per row. The number of rows of windings can be calculated by dividing the thickness of the coil by the diameter of the wire, yielding 25 turns to reach the edge of the coil base. Multiplying these results gives a total winding of 1875 turns per coil. Since the copper coils will never be completely uniform as demonstrated in the approximation, the number of turns used for preliminary calculations was increased to 2000 for simplification. On this coil base, the thickness of the facade covering the coil ends is 4mm . This means a good estimation of the closest viable point from the coil to the magnet disk would be around 5mm before things would start rubbing together and cause problems.

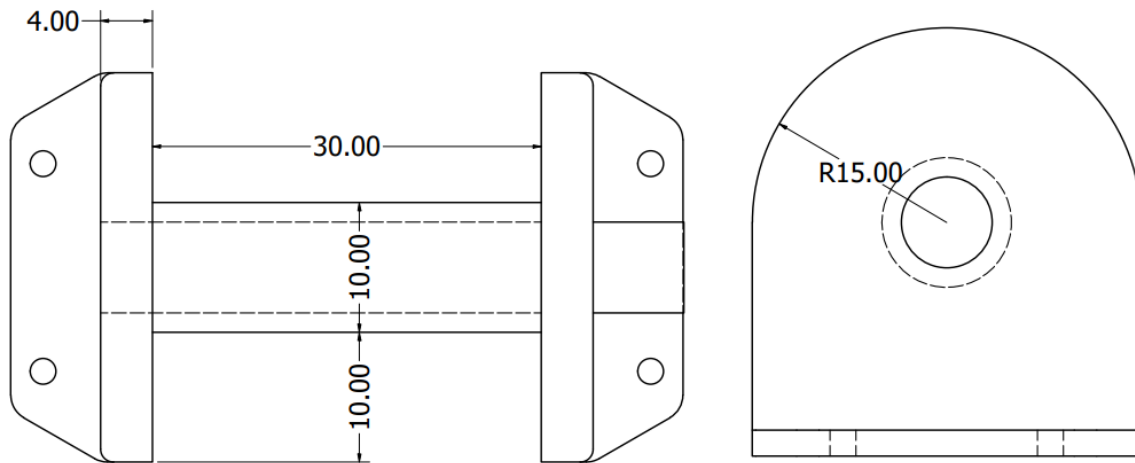


Figure 3.2: Dimensions of Preliminary coil (mm)

3.5 Calculations for induced emf

To calculate the expected induced emf in the coil, many approximations and assumptions need to be stated to keep the calculations from going overboard. The main factor that needs

to be looked at is how the area of a single winding of the coil is represented and how the area affected by the magnetic field is represented.

The first assumption is that the magnetic field that the coil experiences is uniform, meaning that the magnetic field going through the entire coil is the same. The average magnetic field of the coil was determined from *Figure 3.1* and assumed to be around $0.12T$. The next assumption is that the movement of the magnet disk and in turn the magnet itself passing by the coil can be represented as a linear movement along a line with a constant velocity. This assumption will be used for early tests and further development will include the change in velocity from the acceleration of the wave. The third assumption is that the average winding radius is $20mm$ since the maximum outer radius of the coil is $30mm$ and the inner core of the coil is $10mm$.

For this test a magnet disk of radius $100mm$ was used and a fly-wheel with a radius of $37.5mm$. These values were used to keep the magnet wheel small to fit easily in tight areas such as the buoy but still yielding a decent gear ratio between the fly-wheel and the magnet disk to increase the point velocity of the magnet disk. A mass of $10kg$ and a spring with stiffness of 200 was used.

Previous approximations from the mechanical assembly section are used here assuming that the magnet disk moves one circle per half the period. This makes preliminary calculations simpler and easier to get a clear idea of how well the mechanism works. All simulations and calculations for this experiment were done in Matlab and the code for emf calculations can be seen in *Appendix A.3* and the calculations for average distance traveled by the mass can be seen in *Appendix A.2*.

$$f(x) = \sqrt{r^2 - (x - L)^2} \quad (3.1)$$

To approximate the change in the area of the coil affected by the magnetic field, an integral over a shifted half-circle function shown in *Equation 3.1* is used where r is the radius of the circle and L is the shift coefficient. This can be seen as the blue function shown in *Figure 3.3*. The equation is used eight times and inverted to get the full representation of all eight magnets passing the coil. The figure shows how eight points spaced evenly on the outside of the magnet wheel would encounter the area of the coils.

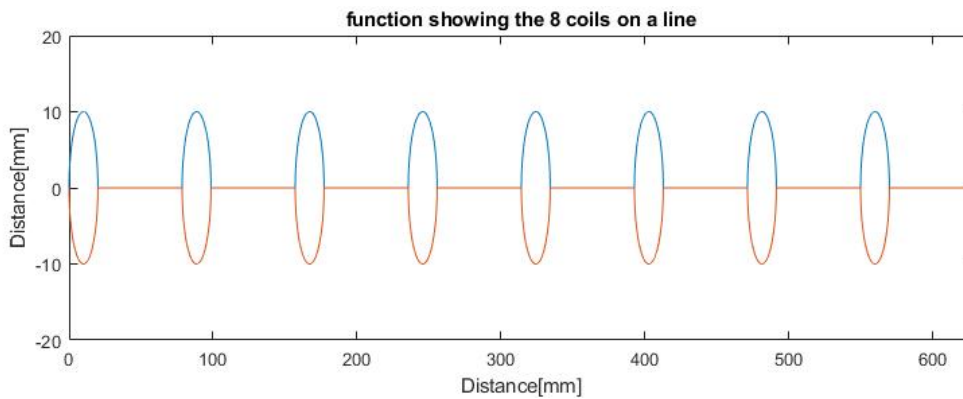


Figure 3.3: representation of coil density and area

With all the data ready, the emf can finally be approximated by looking at the change of the area of the coil passing into the magnetic field over time according to *Equation 2.4*. This approximation yields the results that can be seen in *Figure 3.4*. approximating the voltage output per cycle for eight coils is now easy since the angle between each magnet and the coil is the same, meaning each magnet passes each coil at the same time. This means that to get

a final result per cycle for the full system the amplitude of the emf can be multiplied by eight as represented in *Figure 3.5*.

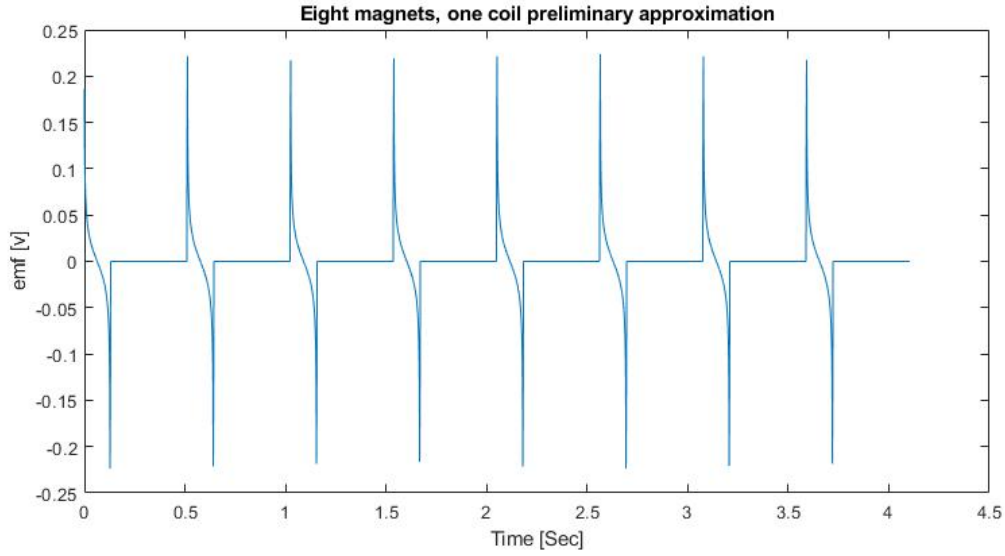


Figure 3.4: Induced emf in one coil with eight magnets

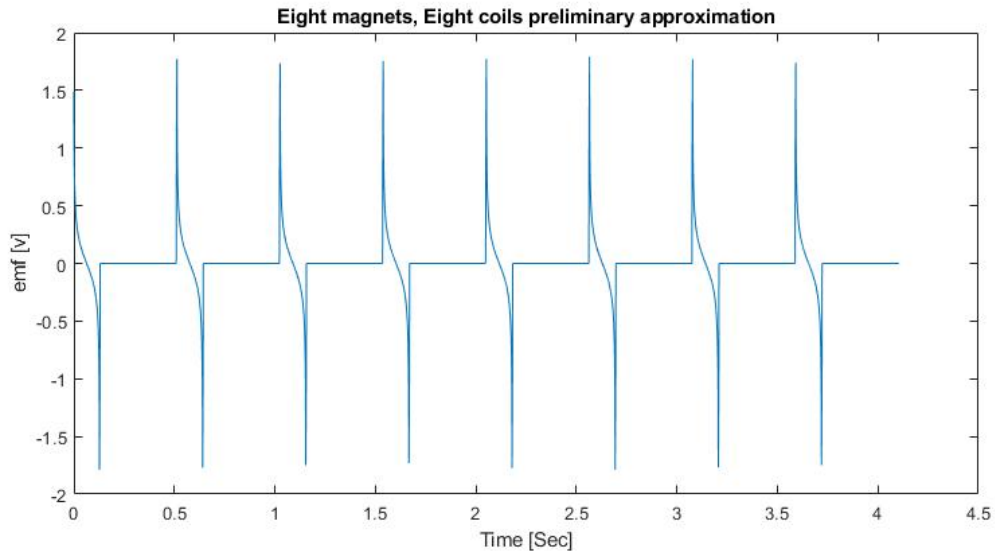


Figure 3.5: Induced emf in eight coils with eight magnets

For the next test, the acceleration of the wave was taken into account. Initially this was simulated with a 10kg mass and a spring with a stiffness of 200 but the resulting vertical movement of the mass only showed tiny movements of 70mm . Changes to the simulations were made so that the weight pulling the spring was increased to 40kg and the spring stiffness dropped down to 60. The magnetic field was set to 0.4T . These changes were made to see how the system would act with better conditions and in a more realistic environment.

The acceleration of the wave was calculated according to *Equation 2.2*. To find the force that the mass exerts on the system the acceleration of the wave and gravity acting on the mass was used. The acceleration pattern of the wave was approximated as a sine wave using the maximum acceleration as the amplitude and the period used was the average period from

the data gathered by Vegagerðin. An equation was approximated to fit the wave parameters which can be seen in *Equation 3.2* The acceleration pattern can be seen in *Figure 3.6*. From the acceleration pattern

$$a = 0.5\sin\left(\frac{9.7}{4\pi}x + 4.6\right) + 10 \quad (3.2)$$

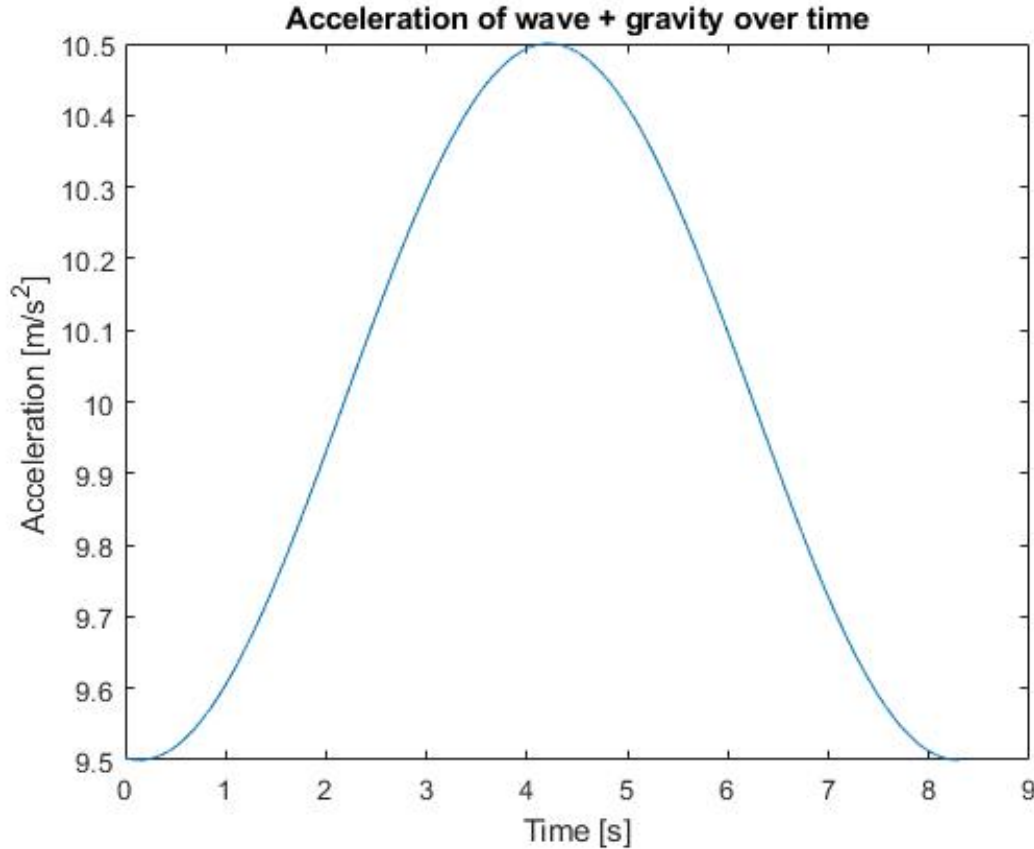


Figure 3.6: Acceleration acting on mass through the wave

From the acceleration pattern, Hooke's law can be used to calculate the elongation of the spring between the highest and lowest points of acceleration. This yields a positional curve shown in *Figure 3.7*. These calculations show that the mass will travel approximately $0.66m$ while moving either up or down the wave.

With the distance traveled of the mass, the turn that the small flywheel will take can be calculated using the circumference of the wheel. Using a flywheel with a radius of $37.5mm$ yields a total turn of approximately 2.8. The number of turns can then be used to calculate the total distance traveled by the magnet wheel. The magnet wheel has a radius of $100mm$ which yields a total distance traveled of approximately $1.77m$.

Using the same method as in the first test, the area of the magnets can be found by integration over a pattern representing the magnets. With the change in the area, change in time, magnetic field, and the number of turns of the coil, this could all be inserted into *equation 2.4* to find the emf generated by this specific setup. The results with one coil can be seen in *Figure 3.8* and using all eight coils the results can be seen in *Figure 3.9*.

These results yield significantly better results and are still using small coils for the emf generation. The peak voltages are around $8.8V$ at the highest speed and at the lowest speed, it yields $6.5V$. The rotational speed is still quite low or approximately $20rpm$ so improvements

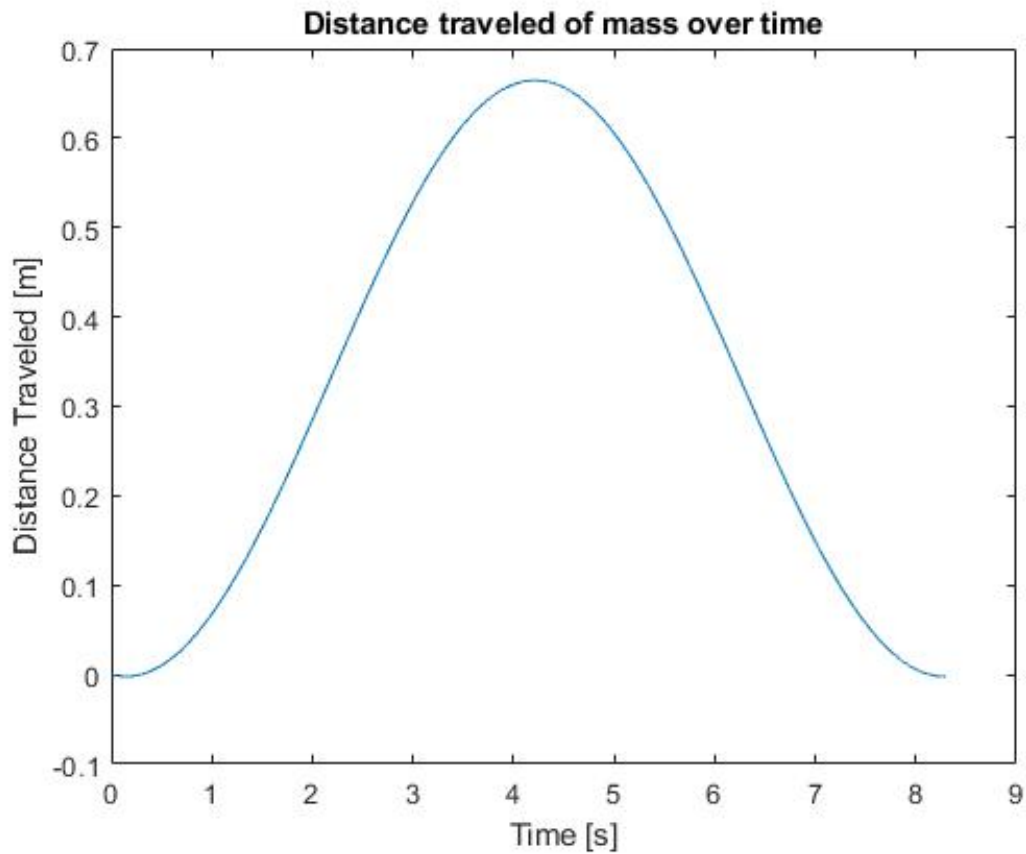


Figure 3.7: Displacement of spring

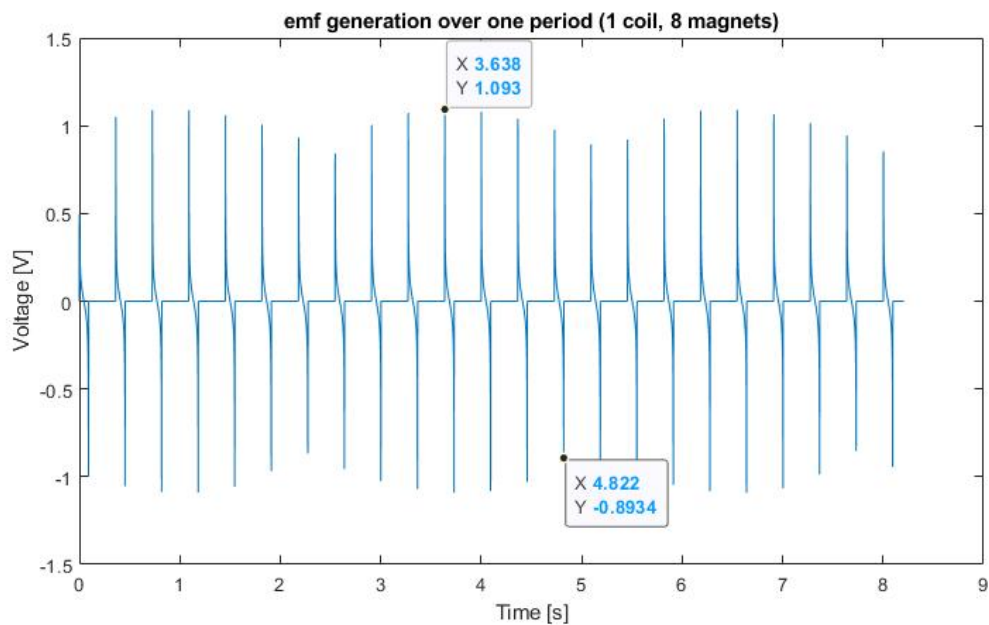


Figure 3.8: emf generated over one period with 1 coil

could be made there in order to get even better results. more rotational speed on the disk results in more emf generation. With more speed, the time between voltage peaks also

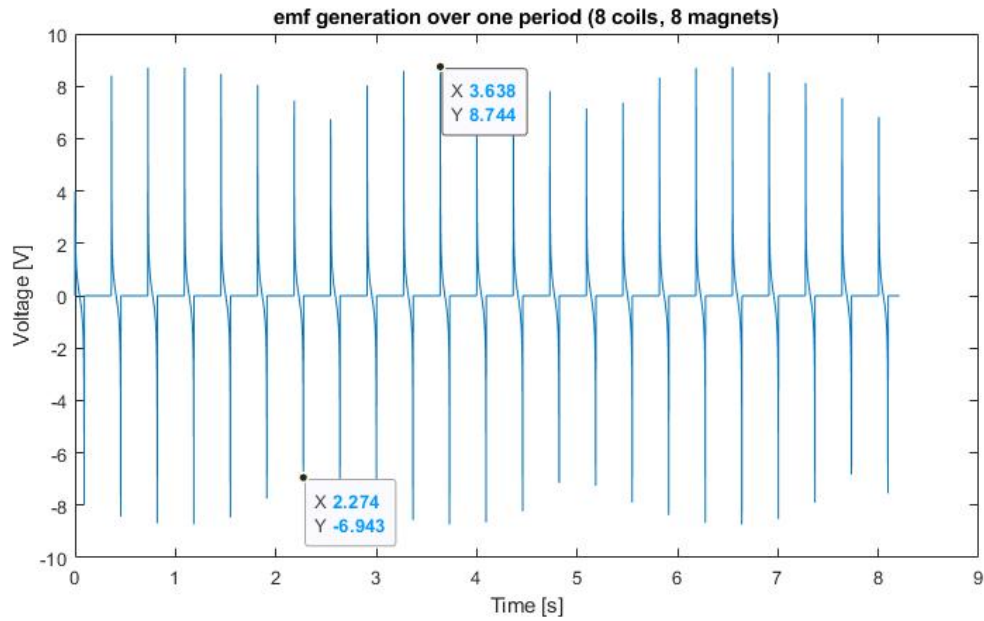


Figure 3.9: emf generated over one period with 8 coils

decreases and in turn helps with getting a stable and usable voltage signal that can then be rectified and equalized to a usable DC voltage signal.

3.6 Physical Testing

To design a testing platform, the theory of operation of the device needs to be looked at. The device consists of a mass connected to a fly-wheel on the main axle that is stationary inside the buoy. Another flywheel on the same axle would be connected to a spring that is grounded to the buoy on one end. The mass would pull and cause a torque on the axle while the buoy moves up the wave, elongating the spring. once the buoy reaches the top of the wave and starts to descend the wave the spring would pull the mass back up and cause the axle to rotate back around. On the end of the axle, the magnet disk would be attached. This disk would have eight magnets indented into the edges of it. around the disk on a stationary platform would be eight copper coils. When the magnets on the disk pass by the coil the magnetic field that the copper coil is under changes thus generating emf.

The decision on eight magnets and eight coils was made to leave room between each magnet so that the magnetic field between them would be minimal and the magnetic field change would be maximized. If more magnets would be used, the residual magnetic field from the adjacent magnets would affect the coils and in turn, reduce the emf generated. leaving too much gap between magnets would cause the disk to have a large downtime of no changes in the magnetic field asserted on the copper coil which would also reduce the frequency of emf generation.

The magnet disk was designed with a 100mm radius so that it would not take up too much space inside the buoy. The designed wheel can be seen in *Figure 3.10*. The fly-wheels connecting the mass and the spring to the axle were designed with a smaller radius of 37.5mm. The reason for this was to increase the linear speed at the edge of the magnetic disk. To calculate the linear speed at the edge of the wheel *Equation 3.3* was used. This equation can then be used to calculate the ratio between linear speeds of each of the wheels by expanding it as shown in *Equation 3.4*.

$$v = r\omega \quad (3.3)$$

$$v_1 = \frac{r_1}{r_2} v_2 \quad (3.4)$$

For testing purposes, a simple testing bench was made to test the emf generation of the device. The testing bench used a KH56KM2 stepper motor to spin the magnetic disk and simulate the rotation caused by the movement of the buoy in waves. The stepper motor driven with a Easy Driver from Sparkfun and an Arduino Uno controlling the motor driver. For testing the emf generation only one magnet indent was used to simplify the build and get a better reading on how each magnet would perform with the copper coils. For this test, a testing segment of the wheel was made and can be seen in *Figure 3.11*. This segment had the capacity to turn one 18x18 cylindrical magnet at the same radius of the magnetic wheel.

Three different coils were wound to be tested to see how different materials would react on the testing platform. The first one was wound with 0.224mm copper wire. The coil was 20mm in diameter with a plastic core of 10mm diameter. Using the estimations of turns per coil from *Figure 2.7* and assuming that the winding is not perfect, the total number of windings was around 5000.

The second coil used copper wire with a diameter of 0.7mm with a coil diameter of 30mm and the same coil base yielding approximately 600 windings on the coil using the same estimations as in the first one.

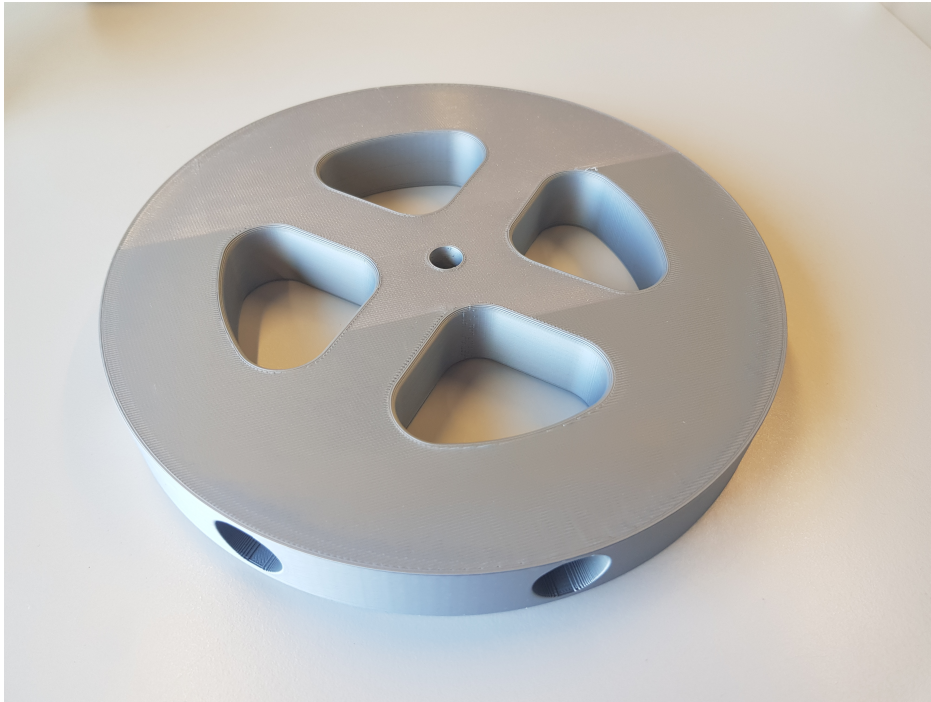


Figure 3.10: The Magnetic wheel for the system

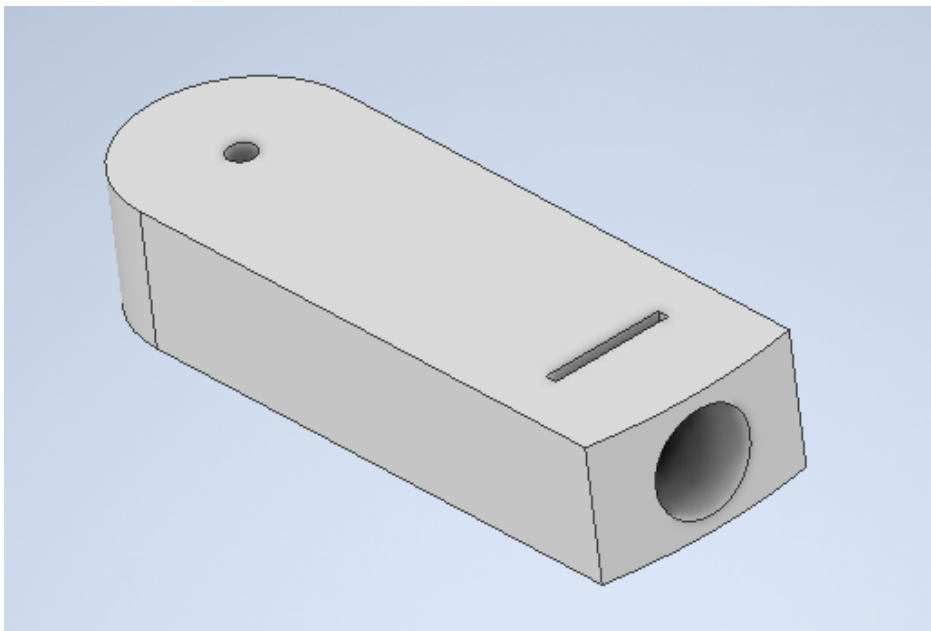


Figure 3.11: Testing segment of the magnetic wheel

The third coil was the same as the second coil but had a solid cylindrical steel core with a diameter of 6mm inside it. The core could be taken out to test the coil both with and without it to see how the core interacted with the coil. The wound coils can be seen in *Figure 3.12*

These parts were installed on the testing bench shown in *Figure 3.13* to be tested regarding the emf generation of the different coils and different setups. The segment of the magnetic wheel had a slit on the top of it to insert a u-iron piece around both the magnets and the coil as can be seen in *Figure 3.14*. This was an idea to test out since air has marginally lower magnetic susceptibility than iron does [32]. Using the U iron the path traveled through air

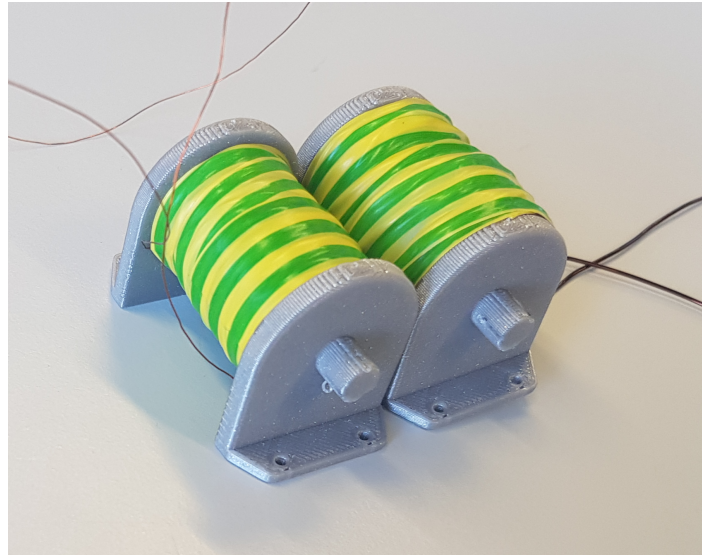


Figure 3.12: Wound copper coils used for testing

would be minimized and the magnetic field would travel through the iron instead of the air around the magnet.

Another idea that was looked into was adding a small magnet on the end of the u iron on the opposite end of the main magnet as can be seen in *Figure 3.15* as well to focus the magnetic field through the coil.

For testing the emf generation the stepper motor was set to a constant rotational speed of $150rpm$ to observe better how the emf was reacting to the movement of the magnets.



Figure 3.13: Testing bench setup



Figure 3.14: Implementation of U-iron in the design



Figure 3.15: Magnet added to the U iron

3.6.1 Test 1: small coil

The first test was done on the smaller coil wound with the 0.224mm diameter copper wire and an outer coil diameter of 20mm . The coil did not have a metallic core inside it. The measured resistance of the coil was 101Ω . The voltage pulses were measured without a load with an oscilloscope. three different tests were done. With the bare minimum setup, with the U-iron added and with the extra magnet added at the end of the U-iron. The results can be seen in *Figures 3.16 - 3.18*. With the bare minimum setup, the voltage peaks reach around 2.5V . Adding the U-iron has some effect, increasing the peaks to approximately 3V . The big change comes when adding the additional magnet to the other side of the U-iron. The voltage peaks go up to around 4.5V with the magnet added. Testing it out with an extra magnet added to the main magnet stack did not result in such a drastic change and only yielded around 3.3V .

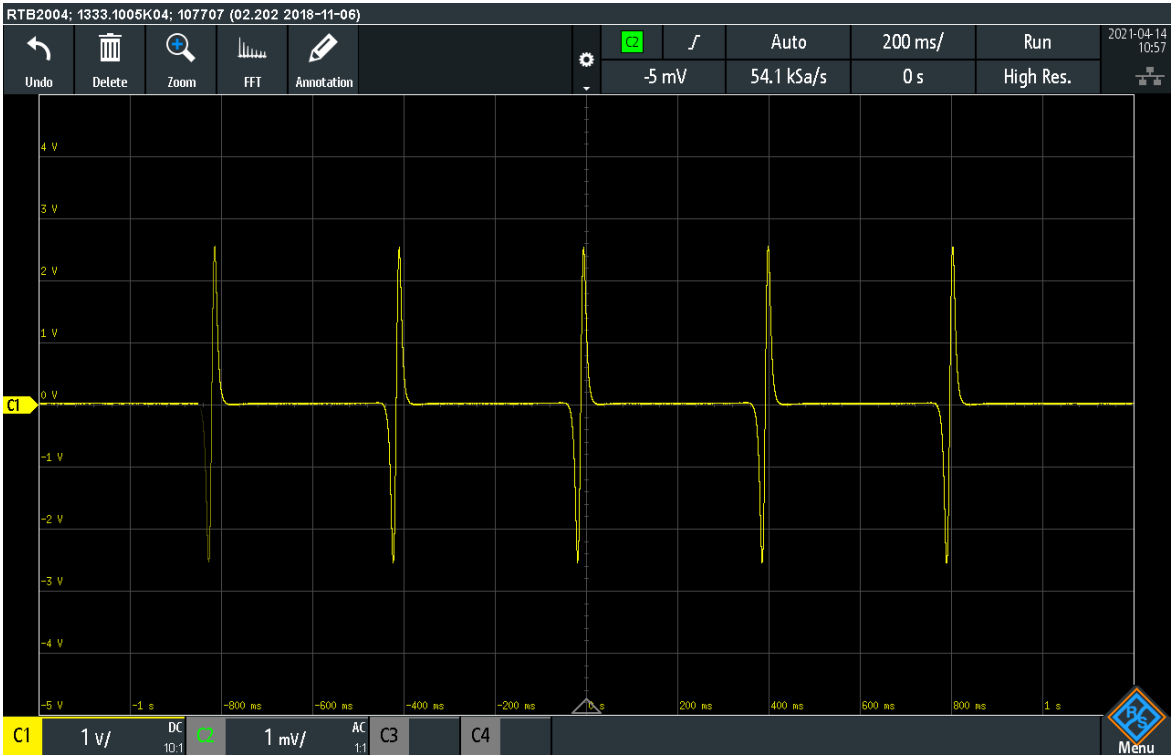


Figure 3.16: Results from small coil with no U-iron

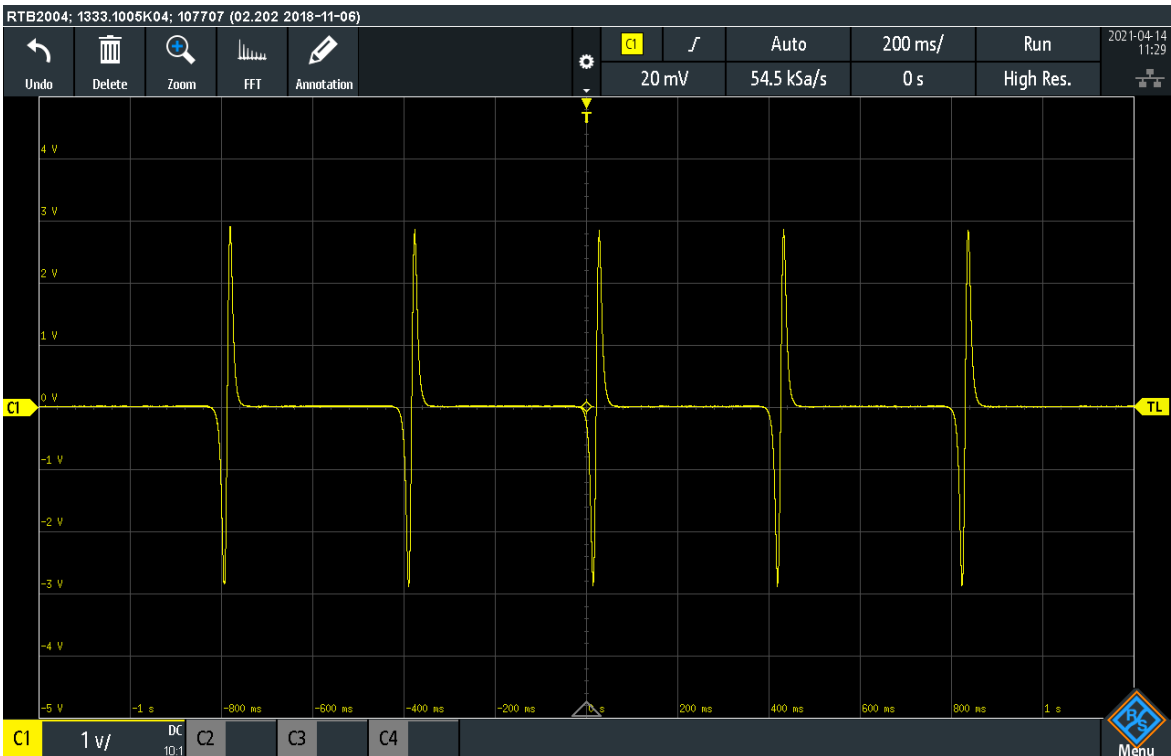


Figure 3.17: Results from small coil with U-iron

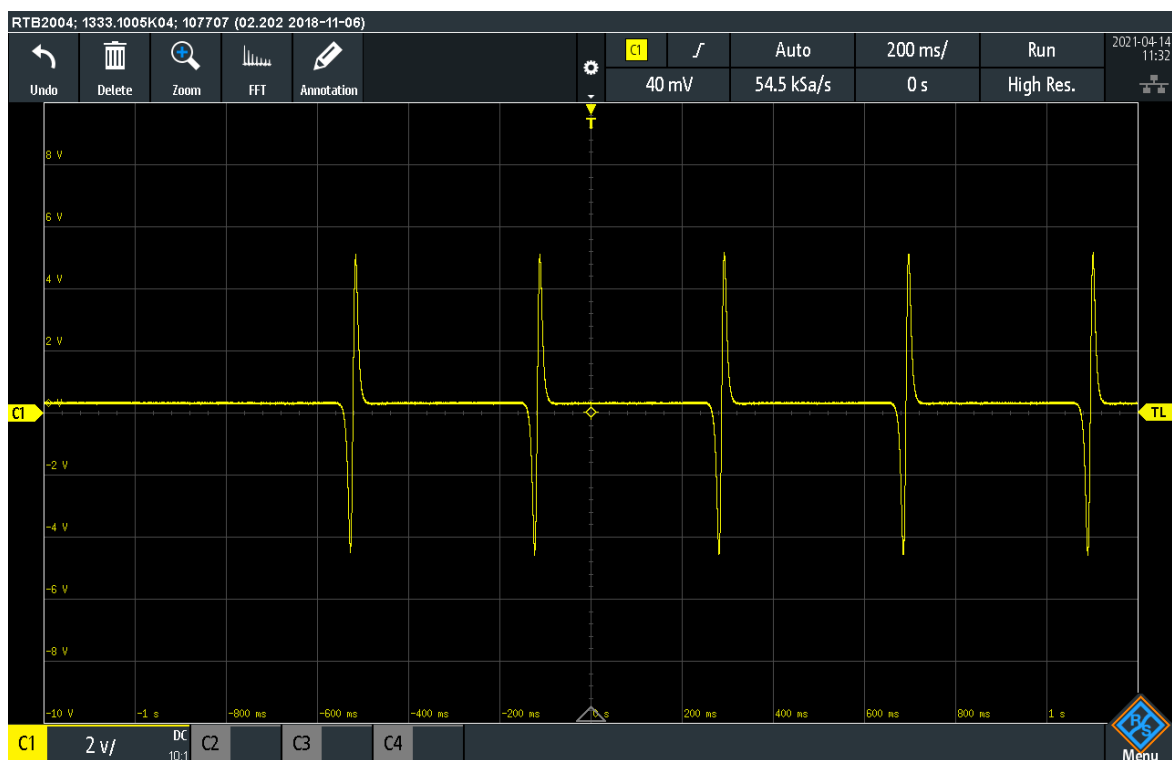


Figure 3.18: Results from small coil with U-iron and added magnet

3.6.2 Test 2: Large coil, No core

The same method for testing was used for the larger coil without a core. The coil was wound with a 0.7mm diameter copper wire with a coil outer diameter of 30mm . The measured resistance of the coil was 0.9Ω . The results from this test can be seen in *Figures 3.19 - 3.21* and show voltage peaks without a load on the bare minimum setup at 350mV . Adding the U-iron to the system shows a small increase to 390mV . With the magnet on the opposite side of the U-iron, there is a large change in the results yielding voltage spikes of 650mV .



Figure 3.19: Results from large coil with no U-iron



Figure 3.20: Results from large coil with U-iron



Figure 3.21: Results from large coil with U-iron and added magnet

3.6.3 Test 3: Large coil with steel core

The third test was done with a copper coil of the same type as in the second test except for a steel cylindrical coil of 6mm was added to the coil. Testing was done similarly to previous tests, firstly seeing a baseline for the coil with a steel core. After that adding the U-iron and finally adding the magnet on the end of the U-iron. The test was performed with no load attached to the coil. The results shown in *Figures 3.22 - 3.24* show how voltage peaks increase for everything added to the testing platform. Results from this test and the previous test done with an identical coil with no core were compared and the changes in voltage peaks between the different setups of the test bench can be seen in *Table 3.2*.

	No Core [mV]	With Core [mV]
Base result	363	854
With U-iron	397	902
With U-iron magnet	651	1955

Table 3.2: Change in emf generation depending on adjustments to the testing bench

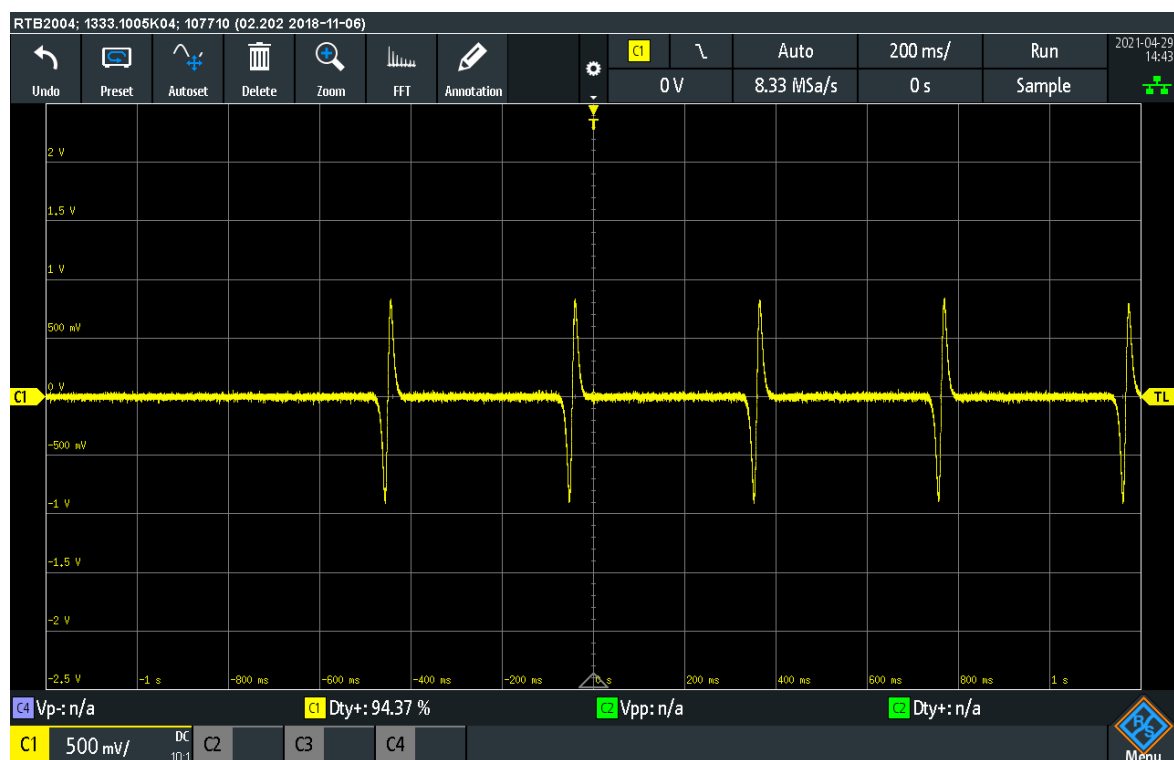


Figure 3.22: Base result from large coil, No U-iron with steel core

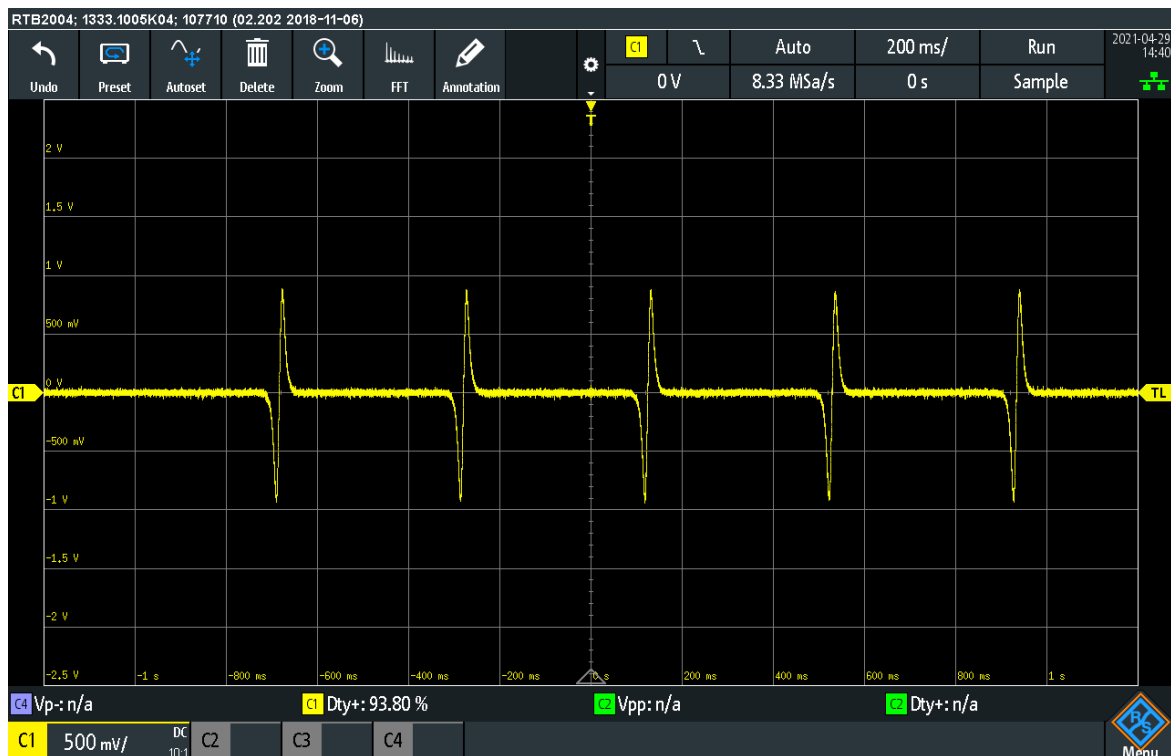


Figure 3.23: Result from large coil With U-iron and steel core

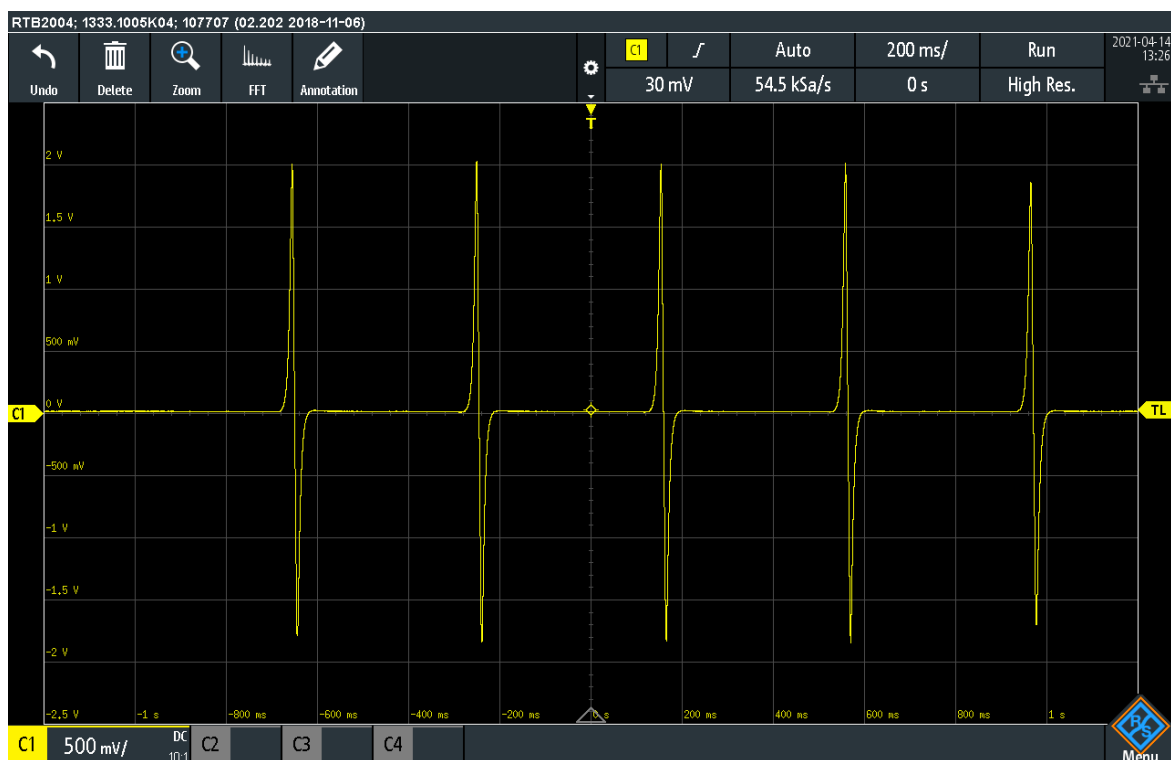


Figure 3.24: Results from large coil with steel core, U-iron and U-iron magnet

Comparing these results to the calculated results shown in *Figure 3.8*, The pulses from the test bench show have almost twice the expected voltage peaks from the approximation. This is understandable since the speed that the stepper motor was turning at was higher than the expected rotational speed from the calculations making the change in the magnetic field happen quicker and thus generating more emf. These tests and approximations give a relatively good view of how the emf generation behaves regarding the change in the environment of the system.

3.6.4 Coil testing with load

To test the coil under load the best outcome from the previous tests was used. For this experiment, the coil wound with the thicker wire and a core was used since the coil with the finer copper wire had too high internal resistance of about 101Ω and it could prove troublesome to get any usable current out of it. The Thicker coil was used and a 100Ω variable resistor was attached to the ends of the coil. The load resistance was decremented slowly starting at 100Ω down to 1Ω and the voltage peaks noted down at each decrement. The results from this test can be seen in *Table 3.3*. These measurements were also confirmed with a current monitor where $1A$ is translated to a $100mV$ measurement on the oscilloscope. The peak measured was $84.1mV$ as can be seen in *Figure 3.25* which translate to $841mA$. The average power from one coil would be around $280mW$ and if all eight coils were used the average power generated would be around $2.3W$.

Resistance [Ω]	Voltage Peak [v]	V/Ω [mA]	Power [W]
100	1.85	19	0.03
90	1.85	21	0.04
80	1.83	23	0.04
70	1.82	26	0.05
60	1.81	30	0.05
50	1.8	36	0.06
40	1.8	45	0.08
30	1.77	59	0.10
20	1.76	88	0.15
10	1.64	164	0.27
8	1.6	200	0.32
6	1.54	257	0.40
4	1.4	350	0.49
2	1.2	600	0.72
1	0.82	821	0.67

Table 3.3: Voltage peak measurements with load



Figure 3.25: Current measurements from the current monitor

3.7 Diode rectifier test

A test was conducted on two different rectifiers, one using normal 1N006 diodes and another with Schottky diodes. The voltage drop over the 1N006 was measured at 670mV while the voltage drop over the Schottky diodes was well lower and measured at 210mV . The test was done with the larger coil with a steel core with an input signal into the rectifier similar to the one that can be seen in *Figure 3.24* from previous tests. The output signals of the two rectifiers can be seen in *Figures 3.26 - 3.27*. Looking at the results from the tests done on the 1N006 diodes it's hard to see any pulses because of the high voltage drop over the diodes. There are always two diodes in series working together to rectify the signal meaning that the total voltage drop of the input signal would be expected to be around 1.34V meaning the majority of the signal is lost during the rectification. The Schottky diodes have a way lower voltage drop over each diode and yield a much better result showing rectified pulses with peak voltages at around 1.7V .

If the entire assembly was tested with all eight magnets and eight coils connected in series, the expected voltage pulses would reach eight times higher or up to 16V in this test. The normal diodes could work with that setup but reduce the peaks by more than 10% of their amplitude which is a large loss for rectification while using Schottky diodes would only consume about 3% making them the better choice.

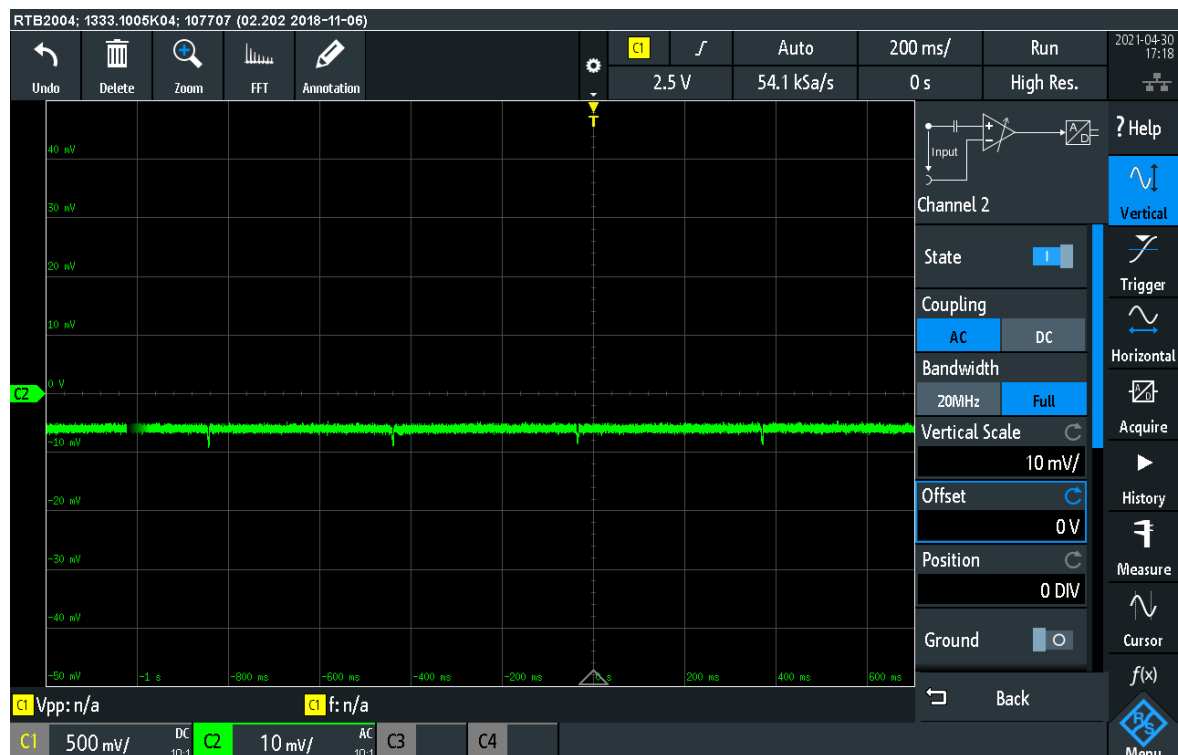


Figure 3.26: Results from normal diode bridge

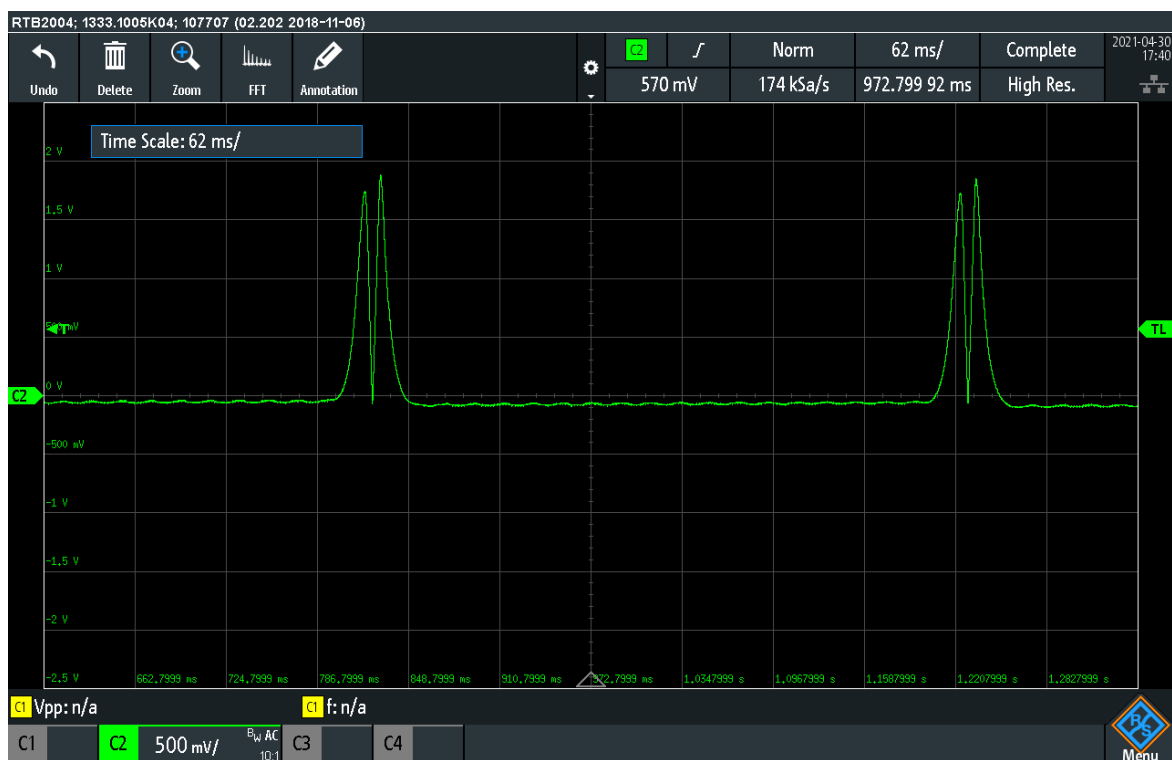


Figure 3.27: Results from Schottky diode bridge

3.8 Power generation over long period

Using the same methods as before to calculate the emf generation and the current measurements from the previous test a rough estimate of power production over long periods can be made. This was done by using the raw data from Vegagerðin as an input into the calculations done in the previous test for emf only changing the coil diameter and wire thickness to the same as was tested in the physical tests. The wire used had a diameter of 0.7mm and the diameter of the coil was 30mm . The data used for this test was from the buoy positioned at latitude 64.5, longitude -23.5 over the entire year of 2018. The results for the voltage peaks can be seen in *Figure 3.28* both for one coil and eight coils.

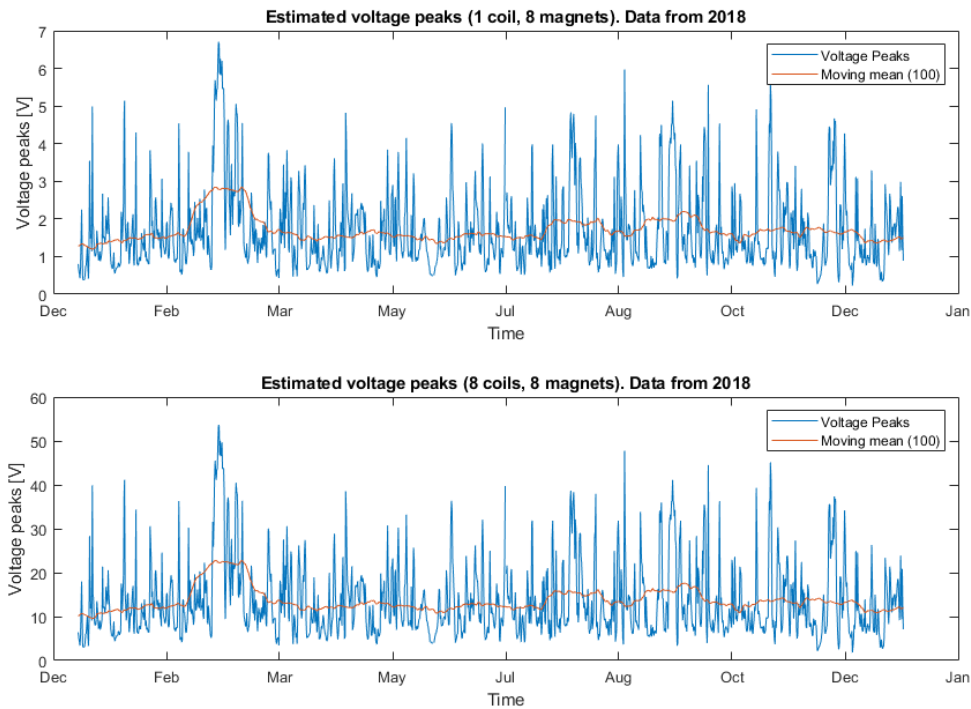


Figure 3.28: Voltage estimations over long periods of time

Since the data shows the voltage peaks and not the downtime between peaks a rough estimation was made from the number of pulses per time unit. The current limitations found in previous tests were used with the voltage graphs to generate a power curve over the period. To find the actual power generated over time an integral estimation using the trapezoidal method was used over the absolute curve of the power curve to find the area under the curve. The area represents the joules generated over the period and can be divided by the period of the wave to find the actual power generated by the system. This yields the results that can be seen in *Figure 3.29*. The results show a power curve with the power generation ranging from $0.4 - 4.46\text{W}$ With the highest average power generation around February and the lowest average around the summertime months from May to July. Using a running average over the past 100 entries an accurate average over the period can be made showing the power ranging from $1.7 - 2.9\text{W}$ on average throughout the year using the system with eight coils and eight magnets. A Thing to note here is that when current starts flowing, the coils might work as breaks for the current and will reduce the overall power generation.

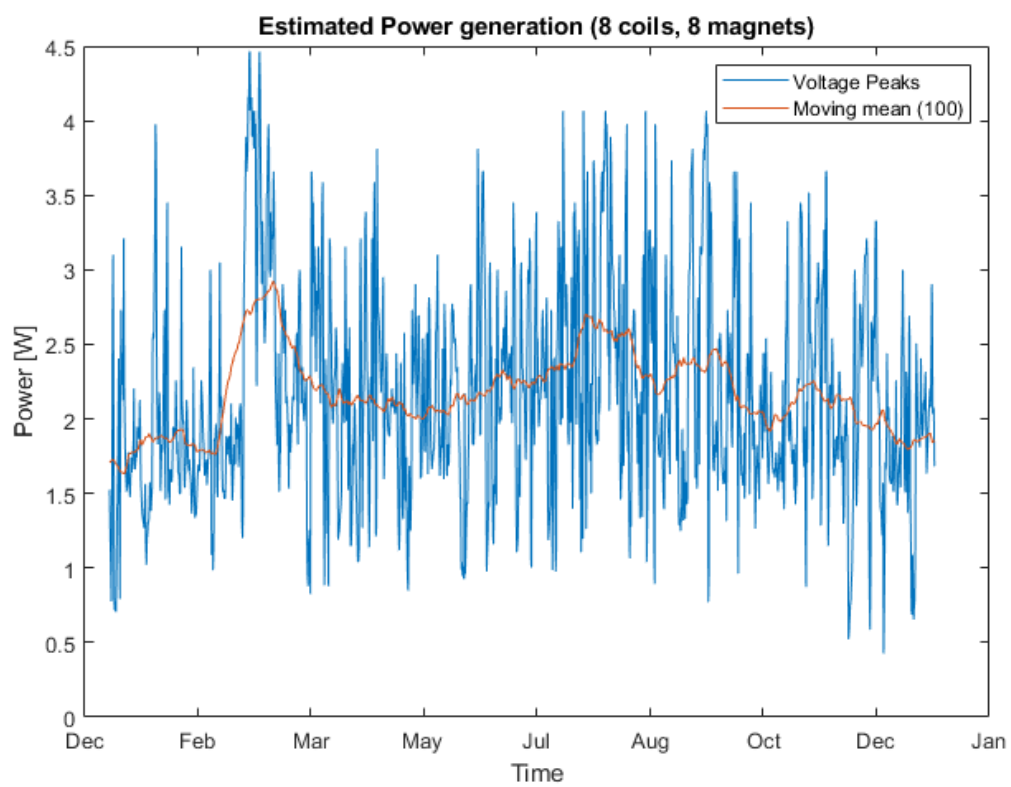


Figure 3.29: Power estimations over long periods of time

3.9 Moment of inertia calculations

Moment of inertia shows the difficulty to rotate an object from a stationary position [33]. To find the moment of inertia for the whole axle assembly the parts of the axle need to be broken down into individual smaller parts that have a moment of inertia that can be easily calculated by using *Table 3.4*.

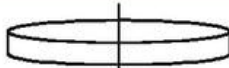
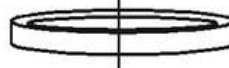
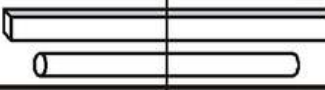
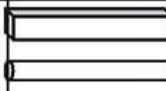
<i>Object</i>	<i>Drawing</i>	<i>Moment of Inertia</i>
Disk (rotated about center)		$\frac{1}{2}MR^2$
Ring (rotated about center)		MR^2
Rod or plank (rotated about center)		$\frac{1}{12}ML^2$
Rod or plank (rotated about end)		$\frac{1}{3}ML^2$
Sphere		$\frac{2}{5}MR^2$
Satellite		MR^2

Table 3.4: Moment of inertia of different shapes [33]

The axle assembly can be split into five different parts.

- The magnet disk
- The two fly-wheels
- The axle itself
- The magnets at the edge of the magnet disk.

The magnet disk, fly-wheels and axle can all be thought of as pure disks rotating around their center. The magnets are a little harder since their offset cylindrical masses at the edge of the magnet disk. To approximate this the magnets can be thought of as point masses with their center of mass in the middle. The radius used for the magnets would then be the distance from the center of the disk to the center of mass of the magnets which is 91mm . The moment of inertia of a single magnet is then multiplied by eight to account for all eight magnets. The resulting moment of inertia for each component and the total moment of inertia for the entire axle can be seen in *Table 3.5*. The calculations for moment of inertia were done in Matlab and the code can be seen in *Appendix A.4*

Using the F_{min} and F_{max} values found in *Section 3.3* We know the force acting on the mass in the waves is between 90.9N and 105.2N . The force is pulling downwards on the fly-wheel which has a 37.5mm radius. This yields a torque on the axle of approximately $3.4 - 4.0\text{Nm}$.

Part	Mass [g]	Radius [mm]	Number of Parts	Moment of Inertia [Kg m^2]
Magnet wheel	155.5	100	1	0.00078
Fly-wheel	333.9	37.5	2	0.00016 / 0.00047*
Axle	278.3	5	1	0.0054 / 0.00157*
Magnets	41.7	91	8	0.0028
U-Iron	49.5	114.5	8	0.0052
U-Iron Magnet	6.0	142	8	0.00097
Total				0.0152 / 0.0258*

* Showing difference between using aluminum / iron for the axle and flywheel

Table 3.5: Moment of Inertia results for axle assembly

$$\tau = I\alpha \quad (3.5)$$

Using the moment of inertia for the entire axle assembly listed in 3.4 with the angular acceleration of the axle, *Equation 3.5* can be used to calculate the torque for the moment of inertia. The angular acceleration can be found by dividing the change in linear acceleration of the wheel by its radius. This yields a result of 38.1 rad/s^2 . Multiplying the angular velocity with the moment of inertia yields 0.58 Nm torque with the axle and fly-wheel made out of aluminum and 0.98 Nm using iron. With this setup the disk should easily spin under these conditions.

Chapter 4

Discussion

4.1 Summary

This thesis set out to look into the possibility of creating a power source for a self-sustaining low-powered sea buoy. Different methods of power generations were explored and a decision was made on a modified version of a floating point absorber with vertical to rotational conversion built into it as the most efficient way to do this on small scale. The conversion from vertical movement to rotational is achieved by using a hanging mass connected to a fly-wheel on an axle with another fly-wheel connected to a spring. The mass, spring, and the movement of the oceanic waves work together as an oscillator turning the axle front and back. On the end of the axle, a disk with indented magnets on its sides was placed which would act as a magnetic rotor for power generation. Around the magnet disk, copper coils would be placed stationary to the wheel. When the disk would travel in circles, the magnets would move past the coils causing a change in the magnetic flux of the coils generating emf.

Multiple tests were done on each of the parts of the design, starting with the magnetic field of different magnets and how it would dissipate over distance. The strongest small magnets that could be found locally were neodymium magnets. These magnets were used for further testing of the device.

Measurements of spring constants on different springs found in the lab were tested to see if any of them could be used for this project. In the end, a suitable spring could not be found for the design.

The predicted vertical movement of the mass pulling on the axle was calculated to see how much the magnet disk would turn each wave period. This was done with the average wave height and period, to begin with, to get a base reading of the movement.

A simple approximation was set up for the copper coils to find the number of windings per coil according to the size and shape of the coil base.

A simulation of the induced emf of the coil was set up by using the integral of the area of the coils and tested out with both constant turning speed of the axle and then with the acceleration of the waves taken into account to both see the difference and to get a more realistic result.

A testing bench was set up to test the real emf generation of the coils using one magnet and one coil. The test bench used a stepper motor with a constant speed to get a better idea of both the induced emf and the current capabilities. Different variations of the coils were tested with copper wires found in the lab. Multiple tests were conducted on the coils with the basic setup of one magnet and the copper coil that yielded the best results was used for further testing. Further tests involved adding a U-iron to the magnetic disk making it easier

for the magnetic field to travel through the space around the coil. A magnet was added to the other end of the U-iron as well to see how it would change the outcome. Finally, the coil was tested with a steel core to see how adding a core to the coil would change the results.

The results from the spring test and the first were quite worrying showing with the change in force acting on the mass the system would require quite a large mass for a small vertical oscillating movement and with a 10kg mass and spring with a stiffness of 200, the change in vertical position was only 70mm . This meant that to get a decent vertical movement on the mass the weight of it would have to be increased and the spring stiffness would have to be lowered. This was tested with a mass of 40kg and spring stiffness of 60 and the distance traveled became something usable or 628mm . This creates another problem though where the resting elongation of the spring would be more than 6m . Fitting such a large spring straight into the buoy is impossible so clever routing or other methods would be needed to get this to work or change the spring out for a strong elastic rope with the same properties as the spring.

The initial simulation was done with a magnetic field of 0.12T , a mass of 10kg , and a spring with a stiffness of 200 showed very low voltage peaks. Changing the mass out for a higher weight and changing the spring out for a looser spring helped get the required vertical movement for the second simulation. The average magnetic field was also increased for the second test simulating how an iron core would affect the average magnetic field inside the coil. The results were promising with voltage peaks reaching 1.0V per coil which was a huge improvement from the first simulation which only got peaks of around 0.22V .

The physical testing results showed what setup would yield the best results. Even though the first coil tested with the thinner copper wire yielded more than twice the voltage peak amplitude compared to the second coil, the resistance of the coil was simply too high. The resistance of the first coil is almost a hundred times higher than the second coil so using the finer coil would yield very limited current. I found it strange when testing the second coil how little effect the U-iron actually made on the emf generation. Since the magnetic susceptibility of iron is higher than that of the air I assumed adding it would create an easier loop for the magnetic field to travel through and in turn making the magnetic field that affects the coil stronger. The extra magnet added to the end of the U-iron showed great results doubling the voltage peaks and showing that placements of the magnets have a large say in the results of this project.

The rectification circuit looked promising when using the Schottky diodes. Even using only one coil and one magnet the rectification circuit works with low voltage drops. Using it with the full system would prove even more efficient. I would have wanted to test out the MOSFET rectifier to compare the results from it to the other rectifiers but Since the correct MOSFETS were not available this will have to be left for another time.

The Power generation approximation for the data from 2018 from Veðurstoðan showed promising results with the average power production over the year at around 2W . This is still quite away from the desired $5 - 10\text{W}$ but for preliminary tests, this shows that the project is on the right track.

The moment of inertia calculations shows decent results where it won't interfere with the rotational force caused by the mass on any large scale. This also shows that there is a lot of potentials to increase the rotational ratio for the axle by, for example, adding gearing for longer movements of the magnetic disk.

4.2 Conclusion

Currently, the device has not been built but all aspects of it have been tested individually and proven to work in theory with minor adjustments.

The main concern with this project is the spring. With the parameters required, the minimum displacement of the spring is $6.3m$ and the maximum displacement is $7.0m$. This means that in a resting position the spring needs more than $6m$ that are not used at all and would need to be implemented somehow into the buoy which would require some clever routing and pulleys since having a straight $6m$ spring is not optional inside the buoy. A design parameter of the buoy is to have it as compact as possible so this puts a dent into that. This could be solved by dividing the spring into multiple smaller ones working together in a "zig-zag" pattern with pulleys or changing the spring out for an elastic rope with similar properties. Another method that could be tested is using a torsion bar. It would be interesting to see how a torsion bar would compare to the spring system and how viable its use would be.

From testing, we can see that there is a clear correlation between the weight of the mass and how much distance it travels and how many turns we get on the magnet disk. Having a mass that weighs too little, like was tested originally with a mass of $10kg$, yields too little change in the distance traveled for the system but having the mass too large results in the resting position of the elongation of the spring to be way too long. Finding the ideal size of mass for this system that yields a decent travel distance while not being too heavy is critical for future improvements of the project.

The results from the induced emf were a little lacking but they could be improved. The original hopes were to get around $5 - 10W$ of power generation from the device, but with the current configurations tested the results were a power generation ranging from $0.4 - 4.6$ with a running average of $1.7 - 2.9W$ using the setup of U-iron and a magnet on the other end of the U-iron as well. Looking back at these tests, when testing the system with only the U-iron, there was a small air gap between the coil and the U-iron on the outer end where the second magnet was added. This air gap could have worked as a weak point in the design limiting the flow of the magnetic field drastically and could explain why the U-iron did not perform better. This needs to be looked into moving forward with the project and all unnecessary air gaps need to be eliminated for the best results.

The power generation could be improved by increasing the gear ratio between the magnetic disc and the fly-wheel pulling on the axle. The gear ratio could be increased slightly by making the fly-wheel smaller or if space allows it, make the magnet disk larger. To get a more drastic change, a gearbox could be added to the system with a decent gear ratio. Since the mass pulling on the system is high, there is a large amount of torque that could be used to turn the axle at higher speeds. With proper gearing, the results could easily match the design parameters and reach the preferred $5 - 10W$ power generation. The current break that occurs when the current starts flowing through the circuit is something that needs to be looked into moving forward with the project to see if how harshly it will affect the output current and the power generation of the system.

The magnets could also be changed out for stronger industrial magnets and the coils made larger to get even more emf generation. An Idea that could also work is to make the magnets go through the entire disk having the north and south ends on the opposite ends of the disk. This would require some clever positioning of the magnets and a solid iron core in the middle of the wheel to account for the differently oriented magnets. This proved to be too hard to make with the resources available by hand but would be an interesting test comparison to the other methods.

With additional gearing, the movement of the mass can also be decreased and the spring can be adjusted for the new distance traveled. This is vital for the success of the project since the current requirements of the spring are just too ridiculous. With proper gearing, the spring could be changed for a reasonable spring and the whole problem of the long spring can be avoided.

Another concern when testing out the coils in the physical tests was when the coil was tested with the steel core, the wheel would magnetically lock in place in line with the coil requiring a force of around $5N$ applied at the end of the magnetic wheel to start moving again. In theory, when using eight coils and eight magnets to overcome this it would take a torque of around $4Nm$. This could prove problematic and maybe skipping the core altogether would yield a better result. This needs to be addressed moving forward with this project.

Regarding the rectifier and regulation circuit, there are a few things that need to be discussed. The rectification of the signal was tested out with a full bridge diode rectifier made with four 1N4006 diodes on one coil and as assumed the voltage drop over the diodes completely killed any voltage peaks that the copper coils induced. Using eight coils and eight magnets the voltage peaks most of the time would be around $10 - 20V$ according to *Figure 3.28*. That means on average $6 - 12\%$ of the voltage peaks would be lost to the rectifier assuming that the voltage drop over each diode is $0.6V$. The Schottky show a much more promising result when testing on one coil and show that the voltage drop over the rectifier is around $400mV$. The average Schottky diode can handle up to $50V$ and there is one month shown in *Figure 3.28* exceeds this limit which could prove problematic but Schottky diodes can be found with higher voltage limitations ranging up to $200V$. Since the current that is being used in this project isn't that high, Schottky diodes for rectification are viable for this project as a rectification method.

The correct MOSFETS could not be found to conduct tests on the MOSFET rectifier but in theory, the MOSFET rectifier method would prove better in this case but special caution needs to be taken to make sure that the circuit stays safe from the harsh environments it would experience at sea. The capacitor to stabilize the voltage peaks would need to be able to survive voltage of around $60V$ since the peaks around February when the waves are at their strongest would generate high voltage peaks. The frequency of the peaks is quite high as can be seen in *Figure 3.23*. With one magnet the pulses are coming in at every $400ms$. Using eight magnets would mean that the time between pulses would be approximately $50ms$.

Looking at the boost converter it has its downsides. There will always be a loss in power. The boost converter sacrifices current for higher voltages and is not 100% efficient. Using the circuit would not affect the power generation of the system positively. Since the circuit has around 90% efficiency the power output would most likely be affected negatively. To use the boost converter a rectifier would also be required for it to operate correctly meaning this circuit would not help at increasing the power generation of the system.

In closing, this project showed that this technology is possible and with minor tweaks, this buoy could become a reality. It shows how many opportunities the ocean has for future technologies both on a large scale and small scale. The potential power to do incredible things is just sitting there out at sea waiting to be harnessed by mankind. But like with every new technology the proper funding for research into them is required and hopefully, with time the oceanic waves will help improve our world and lead us to a cleaner future.

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Appendix A

Code

Listing A.1: WaveData.m: Importing wave data from Veðurstofan and plotting

```
1 close all
  clear all
3 clc
  %% IMPORT WAVE DATA AND FIND AVERAGES
5 %Dufl 1: 63,5 –18
  load('dufl_1.mat')
7 time1 = table2array(dufl_1(:,1));
  dufl1_waveHeight = dufl_1(:,2);
9 dufl1_waveHeight = table2array(dufl1_waveHeight);
  dufl1_period = dufl_1(:,3);
11 dufl1_period = table2array(dufl1_period);

13 Dufl1_avgPeriod = nanmean(dufl1_period)
  Dufl1_avgWaveHeight = nanmean(dufl1_waveHeight)
15 dufl_1_stdPeriod = nanstd(dufl1_period)
  dufl_1_stdWaveHeight = nanstd(dufl1_waveHeight)
17

19
  %Dufl 2: 64,5 –23,5
21 load('dufl_2.mat')
  time2 = table2array(dufl_2(:,1));
23 dufl2_waveHeight = dufl_2(:,2);
  dufl2_waveHeight = table2array(dufl2_waveHeight);
25 dufl2_period = dufl_2(:,3);
  dufl2_period = table2array(dufl2_period);
27
  Dufl2_avgPeriod = nanmean(dufl2_period)
29 Dufl2_avgWaveHeight = nanmean(dufl2_waveHeight)
  dufl_2_stdPeriod = nanstd(dufl2_period)
31 dufl_2_stdWaveHeight = nanstd(dufl2_waveHeight)
```

```

35 %Dufl 3: 65,5 -12,5
    load('dufl_3.mat')
37 time3 = table2array(dufl_3(:,1));
    dufl3_waveHeight = dufl_3(:,2);
39 dufl3_waveHeight = table2array(dufl3_waveHeight);
    dufl3_period = dufl_3(:,3);
41 dufl3_period = table2array(dufl3_period);

43 Dufl3_avgPeriod = nanmean(dufl3_period)
    Dufl3_avgWaveHeight = nanmean(dufl3_waveHeight)
45 dufl_3_stdPeriod = nanstd(dufl3_period)
    dufl_3_stdWaveHeight = nanstd(dufl3_waveHeight)
47
    %Dufl 4: 66,5 18,5
49 load('dufl_4.mat')
    time4 = table2array(dufl_4(:,1));
51 dufl4_waveHeight = dufl_4(:,2);
    dufl4_waveHeight = table2array(dufl4_waveHeight);
53 dufl4_period = dufl_4(:,3);
    dufl4_period = table2array(dufl4_period);
55
    Dufl4_avgPeriod = nanmean(dufl4_period)
57 Dufl4_avgWaveHeight = nanmean(dufl4_waveHeight)
    dufl_4_stdPeriod = nanstd(dufl4_period)
59 dufl_4_stdWaveHeight = nanstd(dufl4_waveHeight)

61 %% ***** PLOTS AND FIGURES
    % bouy 1
63 figure()
    subplot(2,1,1)
65
    x = datenum(time1);
67 x1 = x(1:1450);
    x2 = x(1451:length(x));
69 y1 = dufl1_waveHeight(1:1450);
    y2 = dufl1_waveHeight(1451:length(dufl1_waveHeight));
71 y1(623) = 1.1;
    y1(751) = 1.3;
73 y2(1) = 4.3;
    y2(3) = 4.0;
75 M1 = mean(y1).* ones(length(y1),1);
    STD1 = std(y1);
77 STD1_upper = M1 + STD1;
    STD1_lower = M1 - STD1;
79 M2 = mean(y2).*ones(length(y2),1);
    STD2 = std(y2);
81 STD2_upper = M2 + STD2;
    STD2_lower = M2 - STD2;
83 plot(x1,y1)

```

```

hold on
85 plot(x1,M1,'r')
87 plot(x1,STD1_lower,'r--')
   plot(x1,STD1_upper,'r--')
89 title('Wave_Height_at_"63,5"-18" for_2018')
   ylabel('Wave_Height_(m)')
91 xlabel('Time')
   datetick('x','mmm','keepticks')
93 legend('Raw_Data','Mean','Standard_Deviation');

95
subplot(2,1,2)
97 plot(x2,y2)
   hold on
99 plot(x2,M2,'r')
   plot(x2,STD2_lower,'r--')
101 plot(x2,STD2_upper,'r--')
   title('Wave_Height_at_"63,5"-18" for_2020')
103 ylabel('Wave_Height_(m)')
   xlabel('Time')
105 datetick('x','mmm','keepticks')
   legend('Raw_Data','Mean','Standard_Deviation');
107
   %%
109 % bouy 2
   figure()
111 subplot(2,1,1)

113 x = datenum(time2);
   x1 = x(1:1450);
115 x2 = x(1451:length(x));
   y1 = dufl2_waveHeight(1:1450);
117 y2 = dufl2_waveHeight(1451:length(dufl2_waveHeight));
   y1(623) = 1.1;
119 y1(751) = 1.3;
   y2(1) = 4.3;
121 y2(3) = 4.0;
   M1 = mean(y1).* ones(length(y1),1);
123 STD1 = std(y1);
   STD1_upper = M1 + STD1;
125 STD1_lower = M1 - STD1;
   M2 = mean(y2).*ones(length(y2),1);
127 STD2 = std(y2);
   STD2_upper = M2 + STD2;
129 STD2_lower = M2 - STD2;
   plot(x1,y1)
131 hold on

```

```

133 plot(x1,M1,'r')
    plot(x1,STD1_lower,'r--')
135 plot(x1,STD1_upper,'r--')
    title('Wave_Height_at_64,5-23,5"for_2018')
137 ylabel('Wave_Height(m)')
    xlabel('Time')
139 datetick('x','mmm','kepticks')
    legend('Raw_Data','Mean','Standard_Deviation');
141

143 subplot(2,1,2)
    plot(x2,y2)
145 hold on
    plot(x2,M2,'r')
147 plot(x2,STD2_lower,'r--')
    plot(x2,STD2_upper,'r--')
149 title('Wave_Height_at_64,5-23,5"for_2020')
    ylabel('Wave_Height(m)')
151 xlabel('Time')
    datetick('x','mmm','kepticks')
153 legend('Raw_Data','Mean','Standard_Deviation');

```

Listing A.2: distanceTest.m: Calculating the distance traveled of the mass

```

1 vir = 0.0004;
  lengd = 0.03;
3 breidd = 0.02;
  thykt_kjarna = 0.01
5 numberOfWindings = breidd/vir
  %hringur: 2piR
7 ummal = 2*pi*(thykt_kjarna+(vir/2))
  winding = (lengd/vir)*ummal
9
  % approximation for length of wire needed
11 syms k
  lengthOfWire = symsum(((lengd/vir)*2*pi*(thykt_kjarna+(vir/2)+(k*vir))),k,0,25)
13
  %%
15 close all
  clear all
17 clc

19 H = 2.44; % Wave Height
  T = 8.21; % Wave period
21 k = 60; % Spring stiffness
  M = 40; % Mass
23 N = 1000; % Number of turns

25 a = (H/2)*(2*pi/T)^2; %Wave acceleration equation
  amax = 9.81+a;
27 amin = 9.81-a;
  Fmin = amin*M;
29 Fmax = amax*M;

31 xmin = Fmin/k;
  xmax = Fmax/k;
33 deltaX = xmax-xmin

35 r1 = 0.0375;
  u = 2*pi*r1
37 r2 = 0.1;
  B = 2.5; %From measured values at 5mm
39
  T2 = T/2; %Half period
41
  %Average speed:
43 AvgSpeedSmallWheel = deltaX/T2;
  AvgAngularSpeed = AvgSpeedSmallWheel/r1;
45 AvgSpeedLargeWheel = AvgAngularSpeed*r2;

47 %Area of coil from middle

```

```

A_spola = 0.02^2*pi; %m^2
49
    %Assuming the magnetic field in the area of the magnet is the same at 5mm
51 %for the entire magnet coil and the coil is approximatedd to a square:

53 ummal2 = 2*r2*pi;
    x = -ummal2:0.001:ummal2;
55 rSpola = 0.15;
    deltaT = T2/1257;

```

Listing A.3: emfCalc.m: Calculations for emf generation

```

1 close all
2 clear all
  clc
4
  syms f(x)
6 R = 100; %mm
  U_stor = 2*R*pi; %Assuming the circular disk is a long strip:
8 % Testing with different functions
  f(x) = (sqrt(100-(x-10)^2)) + (sqrt(100-(x-10 - U_stor/8)^2)) + (sqrt(100-(x-10 - ↵
    ↵ 2* U_stor/8)^2)) + (sqrt(100-(x-10 - 3* U_stor/8)^2)) + (sqrt(100-(x-10 - 4*↵
    ↵ U_stor/8)^2)) + (sqrt(100-(x-10 - 5* U_stor/8)^2)) + (sqrt(100-(x-10 - 6*↵
    ↵ U_stor/8)^2)) + (sqrt(100-(x-10 - 7* U_stor/8)^2)); %Average loop radius = ↵
    ↵ 10mm
10
  fun = @(x) (sqrt(100-(x-10).^2)) + (sqrt(100-(x-10 - U_stor/8).^2)) + (sqrt(100-(x↵
    ↵ -10 - 2* U_stor/8).^2)) + (sqrt(100-(x-10 - 3* U_stor/8).^2)) + (sqrt(100-(x↵
    ↵ -10 - 4* U_stor/8).^2)) + (sqrt(100-(x-10 - 5* U_stor/8).^2)) + (sqrt(100-(x↵
    ↵ -10 - 6* U_stor/8).^2)) + (sqrt(100-(x-10 - 7* U_stor/8).^2));
12 q = integral(fun,0,20);
  AreaOfCoil = 2*q;
14
  %ploting representation of coils
16 x = 0:0.05:U_stor; %mm
  y = f(x);
18 y2 = -y;
  plot(x,y)
20 hold on
  plot(x,y2)
22 axis([0 628.3 -20 20])
  title('function showing the 8 coils on a line')
24 xlabel('Distance[mm]')
  ylabel('Distance[mm]')
26
28 integralArray = zeros(1,length(x));
  diffArray = zeros(1,length(x));
30 counter = 1;
32 % Integral over the area of coils
  for i=0:0.05:U_stor
34
    integralArray(counter) = real(2*integral(fun,i,i+0.5));
36
    counter = counter + 1;
38 end
  %difference in area between runs
40 for i = 1:1:length(x)-1

```



```

        diffArray(i) = integralArray(i) - integralArray(i+1);
42 end
    diffArray(length(x)) = 0;
44
    %emf generation
46 N = 2000;
    B = 0.12;
48 testT = 0:4.105/length(x):4.1047;
    deltaT = 4.105/length(x);
50 diffArray = diffArray*(10−6); %convert area to m^2
    emf = −N * (B*diffArray)/deltaT;
52
    %emf plotting for 1 and 8 coils
54 emf8Coil = 8*emf;
    figure()
56 plot(testT,emf)
    title('Eight_magnets,one_coil_preliminary_approximation')
58 xlabel('Time_[Sec]')
    ylabel('emf_[V]')
60
    figure()
62 plot(testT,emf8Coil)
    title('Eight_magnets,Eight_coils_preliminary_approximation')
64 xlabel('Time_[Sec]')
    ylabel('emf_[V]')
66
    %ploting rectified emf
68 figure()
    plot(x,abs(emf8Coil))
70
    %%
72
    close all
74 %clear all
    clc
76
    m = 40;
78 k = 60;
    rSeglaHjol = 0.1;
80 rTogHjol = 0.0375;

82 % function representing the acceleration of the wave.
    fun = @(x) 0.5*sin((9.7/(4*pi))*x + 4.6) + 10;
84
    x = 0:0.001:8.3;
86 y = fun(x);
    figure()
88 plot(x,y)
    title('Acceleration_of_wave+_gravity_over_time')

```

```

90 xlabel('Time_[s]')
   ylabel('Acceleration_[m/s^2]')
92 T = 8.21;
   amax = 10.5246;
94 amin = 9.0954;

96 %distance traveled array
   f = m*y;
98 dist = f/k;
   %%
100 %plot for distance traveled
   dist = dist - dist(1); %to get change in distance
102 figure()
   plot(x,dist)
104 title('Distance_traveled_of_mass_over_time')
   xlabel('Time_[s]')
106 ylabel('Distance_Traveled_[m]')
   uSeglaHjol = 2*pi*rSeglaHjol;
108 uTogHjol = 2*pi*rTogHjol;
   numberOfTurns = max(dist)/uTogHjol;
110 distSegla = numberOfTurns*uSeglaHjol;
   DistanceBetweenMagnets = uSeglaHjol/8;
112

114 %% **** RUNNING ON ENTIRE WAVE DATA WARNING THIS TAKES TIME
   % APPROXIMATED RUN TIME ~5 HOURS
116
   finalArray = zeros(length(dufl2_waveHeight));
118 for j = 1:length(dufl2_waveHeight)

120 %same approach as above for each iteration
   rSeglaHjol = 100;
122 rLitlaHjol = 37.5;
   U_stor = 2*pi*rSeglaHjol;
124 k = 60;
   M = 40;
126
   T = dufl2_period(j);
128 H = dufl2_waveHeight(j);
   counter = 1;
130
   a = (H/2)*(2*pi/T)^2;
132 amax = 9.81+a;
   amin = 9.81-a;
134 Fmin = amin*M;
   Fmax = amax*M;
136
   xmin = Fmin/k;
138 xmax = Fmax/k;

```

```

    deltaX = xmax-xmin;
140 distSegla = deltaX*(rSeglaHjol/rLitlaHjol);

142
    syms f(x)
144 syms k
    x2 = 0:0.2135:distSegla*1000; %mm
146 %function from above simplified
    fun2 = matlabFunction(symsum(sqrt(100-(x-10 - k.*U_stor/8).^2),k,0,24));
148 y2 = fun2(x2);

150
    diffArray = zeros(1,length(x2));
152 integralArray = zeros(1,length(x2));
    for i=0:0.2135:distSegla*1000
154
        integralArray(counter) = real(2*integral(fun2,i,i+0.2135));
156
        counter = counter +1;
158 end

160 for i =1:1:length(x2)-1
    diffArray(i) = integralArray(i) - integralArray(i+1);
162 end
    diffArray(length(x)) = 0;
164
    N = 4000;
166 B = 0.4;

168 testT = 0:T/length(x2):T - T/length(x2);
    deltaT = T/length(x2);
170 diffArray = diffArray*(10^(-6)); %convert area to m^2
    emf = -N * (B*diffArray)/deltaT;
172
    % Stores the voltage peaks from each iteration
174 maxEmf = max(emf)
    finalArray(j) = maxEmf;
176

178 end
    %% ***** PLOTTING FOR LONG PERIOD OF TIME
180
    x = datenum(time2);
182 x1 = x(1:1450);
    x2 = x(1451:length(x));
184
    y1 = finalArray(1:1450);
186 y2 = finalArray(1451:length(finalArray));

```

```

188 movAverageVolt = movmean(y1,100,'omitnan');
    figure()
190 subplot(2,1,1)
    plot(x1,y1)
192 hold on
    plot(x1,movAverageVolt);
194 title('Estimated_voltage_peaks_(1_coil,_8_magnets).Data_from_2018')
    ylabel('Voltage_peaks_[V]')
196 xlabel('Time')
    datetick('x','mmm','kepticks')
198 legend('Voltage_Peaks','Moving_mean_(100)')

200 subplot(2,1,2)
    plot(x1,8*y1)
202 hold on
    plot(x1,8*movAverageVolt);
204 title('Estimated_voltage_peaks_(8_coils,_8_magnets).Data_from_2018')
    ylabel('Voltage_peaks_[V]')
206 xlabel('Time')
    datetick('x','mmm','kepticks')
208 legend('Voltage_Peaks','Moving_mean_(100)')

210 %%

212 figure()
    TestVolt = 0.25*8*y1;
214 TestCurr = 0.841;
    TestPower = TestVolt*TestCurr
216 movAveragePower = movmean(TestPower,100,'omitnan');
    plot(x1,TestPower)
218 hold on
    plot(x1,movAveragePower)
220 title('Estimated_Power_generation._25%_efficiency_of_peaks')
    ylabel('Power_[W]')
222 xlabel('Time')
    datetick('x','mmm','kepticks')
224 legend('Voltage_Peaks','Moving_mean_(100)')
    %%

226
    hold on
228 plot(x2,M2,'r')
    plot(x2,STD2_lower,'r--')
230 plot(x2,STD2_upper,'r--')
    title('Wave_Height_at_"63,5-18"_for_2020')
232 ylabel('Wave_Height_(m)')
    xlabel('Time')
234 datetick('x','mmm','kepticks')
    legend('Raw_Data','Mean','Standard_Deviation');
236

```

```
%%  
238 figure()  
    plot(testT,abs(emf*8))  
240 title('emf_generation_over_one_period_(8_coils,_8_magnets)')  
    xlabel('Time_[s]')  
242 ylabel('Voltage_[V]')  
  
244 figure()  
    plot(testT,emf)  
246 title('emf_generation_over_one_period_(1_coil,_8_magnets)')  
    xlabel('Time_[s]')  
248 ylabel('Voltage_[V]')  
  
250 figure()  
    plot(x2,y2)  
252 hold on  
    plot(x2,-y2)
```

Listing A.4: momentCalc.m: Calculations for moment of Inertia

```

1 close all
  clear all
3 clc

5 %% ***** MOMENT OF INERTIA CALCULATIONS

7 M_magWheel = 0.2;
  M_flyWheel = 0.5;
9 M_axle = 1.0;
  M_magnets = 0.2;
11
  R_magWheel = 0.1;
13 R_flyWheel = 0.0375;
  R_axle = 0.005;
15 R_magnets_COM = 0.091;

17 % * Parallel axis theorem

19 I_magWheel = (1/2)*M_magWheel*R_magWheel^2;
  I_flyWheel = M_flyWheel*R_flyWheel^2; % 1/2 cancels out since there are two of ↩
  ↩them
21 I_axle = M_axle*R_axle^2;
  I_magnet = 8*M_magnets*R_magnets_COM^2;
23
  I_total = I_magWheel + I_flyWheel + I_axle + I_magnet; %Kg m^2

```

Appendix B

Drawings

Figure B.1: Magnetic disk

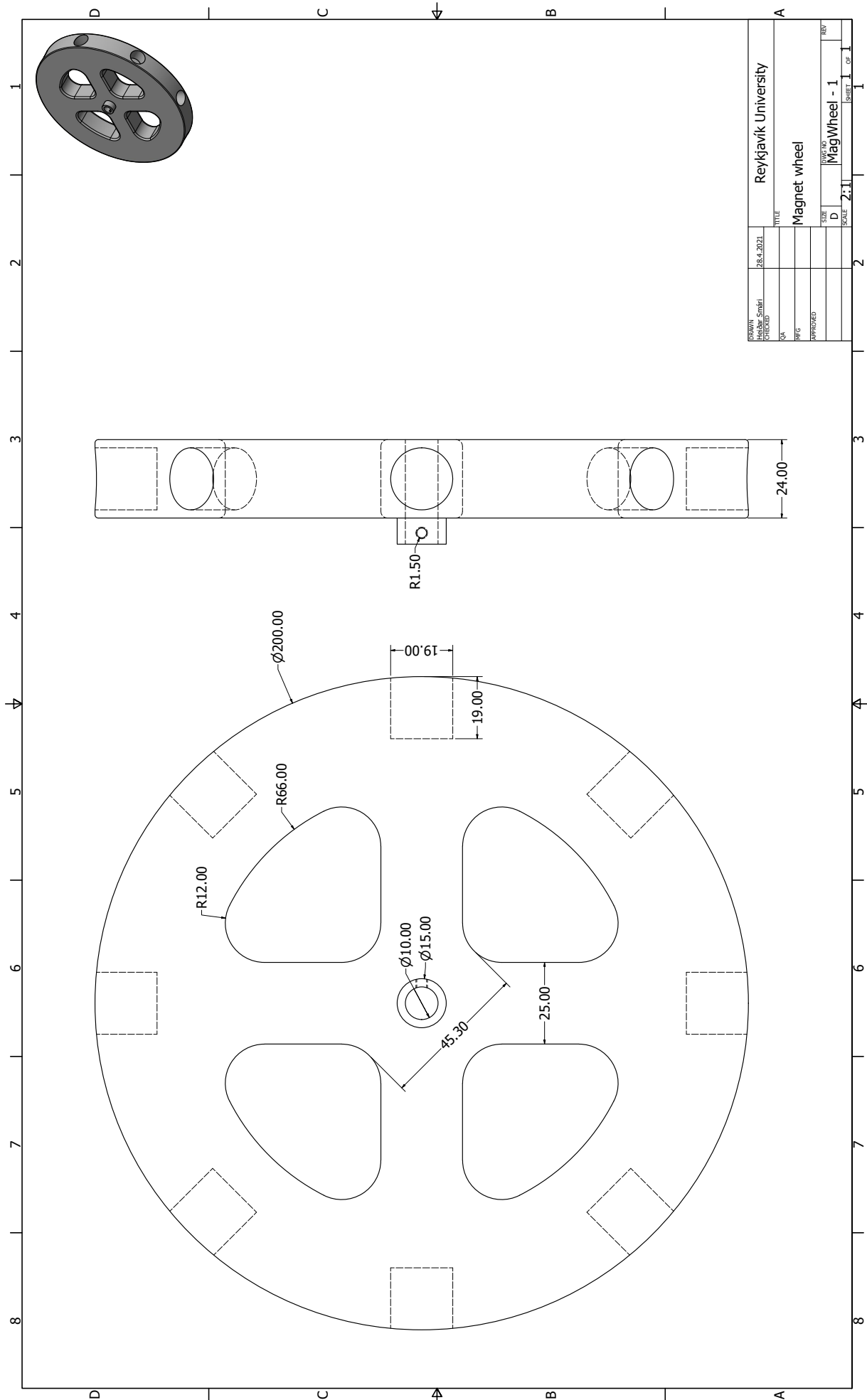


Figure B.2: Axle with Fly-wheels

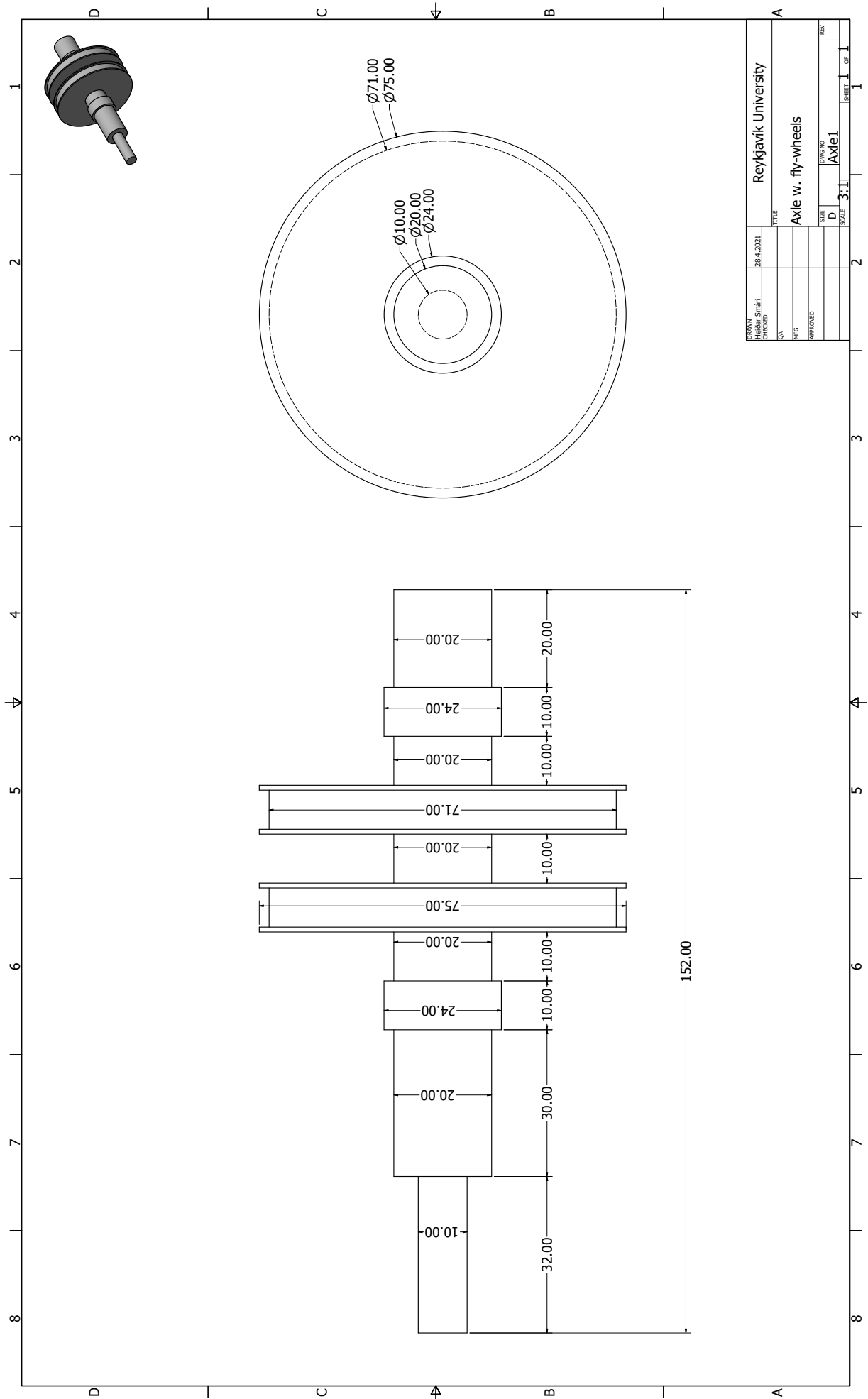


Figure B.3: Coil base

